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PRECISIONSM RESOLUTION TARGETS

Digital Redesign of the NRC Bell 205 Artificial Feel System

by
Arthur William Gubbels, B.Eng

A thesis submitted to the Faculty
of Graduate Studies and Research
in partial fulfillment of the
requirements for the degree of
Master of Engineering

Department of
Mechanical and Aerospace Engineering
Ottawa-Carleton Institute for Mechanical and Aerospace Engineering
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Digital Redesign of the NRC Bell 205 Artificial
Feel System

Submitted by

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in partial fulfillment of the requirements
for the degree of Master of Engineering

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ABSTRACT

An artificial feel system is installed on fly-by-wire aircraft so that pilots experience controller force and position cues similar to those of a conventionally controlled aircraft. Such a system is installed on the National Research Council of Canada's Bell 205 helicopter airborne simulator for control system and flight mechanics experiments. The purpose of this project is to implement a system on the airborne simulator that will remove the existing problems of the analogue system that are hampering research in areas of high gain fly-by-wire control.

This thesis outlines the existing analogue artificial feel system and the difficulties associated with it, including low frequency drift and high gain instability. The requirements, dynamics and simulation model for a digital redesign of the existing controller are described. Next a comprehensive nonlinear simulation of the model following algorithm and the control hardware is discussed. The thesis also covers the testing of the system by varying different controller parameters, and guidelines for choosing an acceptable stick model are developed.

Details of the digital C program design for the target VME processor are outlined. The testing of the system using a single axis stick and a copy of the hardware (actuators, stick, strain gauges, position sensors) installed on the Bell 205 is described. This was done in order to validate the C program and optimize the system before installation. The calibration procedures and other installation details as well as preliminary ground and air testing are described.

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This thesis is dedicated to my wife Irys, our son Mikey,
and my parents Margaret and Cleo.

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NOMENCLATURE

A	Area
C or c	Coefficient
F or f	Force
k	Spring gradient
l	length
M or m	Mass
N	Normal force
ns	Notch size
r	Rudder/pedal position
s	Laplace operator
tl	Throw limits
v	Velocity
x	Lateral stick position
y	Longitudinal stick position
μ	Viscosity
ω_n	Undamped natural frequency
ω_d	Damped natural frequency
ζ	Damping ratio

Subscripts

b	Breakout
k	Kinetic friction
n	Regarding the notch/deadband area
r	Regarding rudder/pedal motion
rat	Ratio of kinetic to static friction
s	Static friction
v	Viscous friction
x	Regarding lateral stick direction
y	Regarding longitudinal stick direction

Special Notations

'	First Derivative
''	Second Derivative

Response Types

a	acceptable
d	Divergent
h	Highly damped
l	Limit cycle
o	Overshoot/oscillation

Acronyms, Designations, and Abbreviations

ACS	Airborne Computing System
ASRA	Advanced Systems Research Aircraft
A/D	Analogue to Digital
D/A	Digital to Analogue
FCC	Flight Control Computer
FCS	Flight Control System
FFS	Force Feel System
FFT	Fast Fourier Transform
FRL	Flight Research Laboratory, part of the Institute for Aerospace Research, National Research Council of Canada
LVDT	Linear Voltage Differential Transformer
NASA	National Aeronautics and Space Administration
PIO	Pilot Induced Oscillation
PSD	Power Spectral Density
SI	System International
USAF	United States Air Force
VME	Versa Module Eurocard (computing system used to run the digital feel system)

CHAPTER 1: INTRODUCTION AND PROBLEM OVERVIEW

1.1 INTRODUCTION

The NRC's Bell 205 Airborne Simulator is a test platform for helicopter control systems design and flight mechanics experiments (Fig [1.1]). Installed in the Bell 205 is a hydraulically powered control loading or 'artificial feel' system designed to give the evaluation pilot a feel for the aircraft through controller force and position cues similar to manually controlled aircraft, even though it is fly-by-wire. Essentially, the system sensed the forces applied by the pilot in 3 axes and processed these through an analogue electronic control system. This thesis outlines the replacement of this with a more versatile digital system. It should be noted that this work on the Bell 205 is preparatory to work that will eventually be performed on ASRA (the Advanced Systems Research Aircraft), a Bell 412 helicopter, which is the Flight Research Laboratory's newest helicopter control system and flight mechanics test platform (Fig [1.2]).

The drive for the digitization of the feel system is a result of inadequacies in the current system, which are described in chapter 2. These problems are preventing experiments that the Flight Research Laboratory (FRL) would like to conduct in the near future. This research involves determining the effects of feel system parameters on helicopter handling qualities. The following sections of this chapter offer some insight into this area of research, however before continuing, it would be appropriate to include a description of the Bell 205 and helicopters in general for the uninitiated reader.

The helicopter is used for a variety of both military and civilian tasks, from general utility and transport rolls to military attack missions. The basic aircraft consists of a main rotor which provides lift, and an anti-torque or tail rotor which prevents the body of the aircraft from spinning around in a direction opposite to that of the main rotor. The helicopter is in general an unstable aircraft, especially in the hover, and requires a diligent pilot to provide careful control. The helicopter is maneuvered by changing the blade pitch angles, either differentially for lateral and longitudinal control, or together for vertical and directional control. The pilot is able to effect these changes through the aircraft hydraulic actuators, which are controlled through hydraulic pilot valves. These pilot valves are actuated by the pilot through cockpit controllers via push rods and bell cranks. Longitudinal and Lateral control is performed through the cyclic stick, while directional control is provided through the pedals. The collective is used to control vertical motion and indirectly engine power through the engine rotational speed governor. A common characteristic of helicopters is that these controls are cross coupled to a fair degree. For example, upward motion of the collective causes the main rotor pitch to increase which effectively increases the lift. With this increase in lift comes an associated increase in drag which manifests itself at the mast as a rise in torque. This then requires the pilot to apply more pedal (tail rotor) to prevent the helicopter from spinning about its vertical axis.

The Bell 205 Airborne Simulator is primarily used for research involving flight mechanics, control systems design, handling qualities experiments, and cockpit technologies development. The left seat is where the safety pilot is located. From this location he/she would control the course of experiments through an array of function

switches and a cockpit terminal. The safety pilot is also responsible for assuming control through the standard Bell 205 control system if a potentially dangerous situation arises. At the right seat is the evaluation pilot's station, where when engaged by the safety pilot, he/she has control of the aircraft through a full authority, fully programmable fly-by-wire (FBW) control system. Essentially with a FBW control system, control signals from the cyclic, collective and pedals are sent to the flight control computer in the form of electric voltages. The flight control computer can then use these signals to develop command signals used to drive the aircraft actuators. With a standard Bell 205 control system, the pilot would feel the force and position cues of the cyclic, pedals and collective as he/she moved the control runs and push rods around. However, this is not the case with FBW aircraft as electric control signals can be generated with a cyclic that does not even move! This, however, is undesirable to the pilot because he/she feels disconnected from the aircraft because of the lack of manipulator force and position cues. Therefore, on the Airborne Simulator a fully programmable force feel system has been installed that can artificially recreate these force and position cues for the pilot.

A final note in this introduction regarding the system of units. Although the author recognizes that SI is the standard system of units used in Canada and thus at Carleton University, Imperial units of measure were used in this project and in this thesis. There are two main reasons for this. First the Bell 205 has a 30 year history of working in Imperial units and has never been converted. Secondly, much of the work done on the Bell 205 is in collaboration with United States partners, particularly the U.S. Army, who require results in Imperial units.

1.2 OVERVIEW OF FORCE FEEL SYSTEM TECHNOLOGY

There are three basic types of force artificial feel systems. The first are mechanical systems such as are installed in many production helicopters like the Bell 412. The second are electro-hydraulic systems controlled by analogue computers. Similar systems are currently installed on the NRC Bell 205 Airborne Simulator, the USAF variable stability NT-33A^[1] and previously on the NASA/Army Ch-47B^[2] variable stability helicopter. These three are examples of programmable feel systems installed on research aircraft where the feel system parameters can be varied. The properties of the analogue systems are outlined in Section 2.1.1. The third type of system is a digitally controlled force feel, the design of which is outlined in this thesis. The implementation of a digitally controlled force feel system in an aircraft may be unique.

For background purposes, the mechanical system as installed on the Bell 412 will be examined. Fig. [1.3] was taken from Ref. [3] and shows the cyclic control system assembly. Parts 18 & 25 are the force gradient assemblies and 19 & 24 are the rotary actuators. Parts 24 & 25 make up the lateral gradient and parts 18 & 19 make up the longitudinal gradient. Fig [1.4] shows a close up of the gradient assembly which consists of a spring loaded piston inside a housing. Before the feel system is engaged, the rotary actuators are free to move and thus the housing and piston move together, supplying no opposing force to the motion caused by pilot input. When the feel system is engaged the rotary actuator holds its position at that point (thus the spring datum position is adjustable) and the housing can no longer move. Now any motion away from this position is opposed

by the spring force applied against the piston relative to the housing. Note that the basic characteristics of the system are not adjustable as they are with the analogue or proposed digital systems. Hence the spring gradient (in lbs/in) is a characteristic of the installed spring and cannot be changed without installing a new spring. Also the mass and friction parameters of the system are just characteristics of the existing mechanical linkage and are not easily changed.

1.3 OVERVIEW OF RESEARCH PAPERS RELEVANT TO ARTIFICIAL FEEL SYSTEM AND HANDLING QUALITIES

1.3.1 HANDLING QUALITIES

Handling qualities have been an important part of aircraft design since the time of the Wright flyer. Indeed it seems that the very first government specifications for handling qualities came at this time:

It [the aircraft] should be sufficiently simple in its construction and operation to permit intelligent man to become proficient in its use within a reasonable length of time.^[4]

Handling Qualities specifications for aircraft today are no longer so simple or appealing, and differ between classes of aircraft. The requirements of most interest for discussion in this paper are those for helicopters given in [5].

The assessment of handling qualities is not a trivial exercise. This must be done through flight testing and pilot evaluation. Pilots will generally fly a set of specified manoeuvres and rate each manoeuvre using a pilot rating scale. The important aspects to consider are:

- Is the aircraft controllable?
- Can the manoeuvre be performed?
- Can it be performed without excessive pilot workload?
- Does the aircraft require modification in order to perform this segment of the mission?

Although a number of rating scales have been suggested^[6], since 1969 the standard used almost universally has been the Cooper-Harper Pilot Rating Scale^[7]. Although not without deficiencies, this scale is clear, simple, and well liked by pilots and engineers. For readers not familiar with the scale or pilot ratings in general, fig [1.5] offers a summary of the Cooper-Harper Scale. However, for a complete understanding of how the scale is used, [6] must be consulted.

Work has been done to attempt to predict handling qualities during the design phase, before building the aircraft^[8]. However, with the advent of fly-by-wire aircraft with increasingly complex control systems, the only way to have a definite assessment of handling qualities is through pilot rating. Aircraft of this type have introduced new causes for classic handling qualities problems, such as Pilot Induced Oscillation (PIO) or the Roll Ratchet phenomenon. PIO in FBW aircraft is generally attributed to excessive time delays between control input and aircraft response, or rate limiting of control components. Several aircraft including the Tornado^[9], the F-18^[10], and the Space Shuttle^[11] have exhibited PIO tendencies during development that had to be remedied.

The Roll Ratchet phenomenon is a problem that can commonly occur with side stick controlled aircraft. It involves an interaction of the pilot's arm/elbow and neuromuscular system and the vibrating, accelerating aircraft environment^[12]. Some authors indicate that it

appears as an oscillation in roll and is distinct from PIO because of its higher frequency. However, others contend that the distinction between PIO and roll ratchet is not that straight forward but may contend that a roll ratchet will continue without the pilot's intentional control of the aircraft while a more classic PIO will occur only when the pilot is trying to control the aircraft.

The problem is that ground based simulation predicts PIO tendencies poorly^[10] and this author has only seen one paper that *claims* prediction of Roll Ratchet in a ground based simulator^[12]. This means that although some predictions of handling qualities can be made through design or ground based simulation, flight testing is absolutely essential in the final handling qualities evaluations during aircraft development.

1.3.2 EFFECT OF FEEL SYSTEM

The primary reason for the digitization of the feel system on the Bell 205 is so that an assessment of the effect of feel system parameters on helicopter handling qualities can be performed. Although a considerable amount of work has been done in this area in the fixed wing world, these results do not necessarily translate well to rotary wing aircraft. Only two authors^{[2][13]}, directly considered this problem, and these will be discussed in detail later in this chapter. In two other earlier papers, the authors examined the effect of feel systems, although only in specific cases. Ref. [14] looked at the design of a programmable force feel system to improve handling qualities of a CH-47B flying with a velocity control system. The author only looked at one specific case and no formal evaluation of handling qualities is given, although some pilot comments are quoted.

Ref. [15] considered at using a constant ratio of stick force to mean load factor² in the pitch axis. This was done to provide a physical cue to the pilot in high speed helicopters. The author states that lack of feel augmentation is one of the obstacles to achieving a 200 knot cruise capability in helicopters. As well, he states:

In the future when vibrations are eliminated, a miscalculated input at high speed could seriously overstress the aircraft before the pilot is aware of it.

This was in reference to the pilot using vibrations as cues to adapt inputs to changing aerodynamics in the absence of stick force cues. It has been over twenty years since this paper was written, and there has yet to be a production helicopter with a cruising speed above 200 knots. As well, vibrations are nowhere near being eliminated from helicopters.

The two aforementioned papers only look at two specific cases. However, in order to get general relations between the artificial feel system and its effect on helicopter handling qualities, the following points must be addressed:

- Manipulator type: is it a conventional centre stick or a sidestick? Is it isometric or does it provide the pilot with position cues?
- Effect of time delays on the system and how they degrade handling qualities.
- The use of force sensing or position sensing sticks and how to include the effect of feel system time delays in the total time delay.
- The effect of feel system parameters like mass, spring gradient, friction, natural frequency and damping.
- Current guidelines for selecting feel system parameters and how adequate they are.

Also one final question must be asked:

- Is there a need for future work in this area and if so what direction should it take?

² Load Factor is defined as the acceleration due to lift expressed as a multiple of the standard acceleration due to gravity

The following parts of this chapter will attempt to address these points.

1.3.3 MANIPULATOR TYPE

There are two basic types of manipulators used in helicopters and high performance aircraft. The centre stick is the conventional configuration, however sidesticks are becoming increasingly common in today's aircraft. Much work has gone into the study of sidesticks for helicopters^{[16][17][18][19][20]} and for fixed wing aircraft^{[1][21]}. However, there are very few production aircraft that use sidesticks. Those that do include the F-16 Falcon and the Airbus 320. The RAH-66 Comanche helicopter comes with 3-axis sidestick controllers for roll, pitch and yaw with a separate collective lever^[22]. It is interesting to note that although the F-16 sidestick is force sensing, in none of the above cases was an isometric stick used. This is because the lack of stick position cues to the pilot degrade his/her perception of the handling qualities of the aircraft. It was found that even very limited controller deflection characteristics are much improved over no motion sticks^{[18][20]}.

Two studies^{[16][19]} look at the effect of different sidestick manipulators on handling qualities. The effects of parameters such as sidestick shape and number of axes controlled by the stick are assessed. However, the effects of stick defining parameters such as mass and spring gradient were not discussed.

Two other studies^{[17][18]} investigated the effects of changing the number of axes controlled by a sidestick and the level of stability and control augmentation on handling qualities. Although one paper^[18] mentions variations in force/deflection characteristics as a

variable in the experiment, only two different levels were used, and the only statement in the results pertaining to this is:

"Critical sidestick design features include the force/deflection characteristics..."

but no more information or observations are given.

In [16][18][19] conventional controls were also flown in the experiments to offer a comparison. In each of these cases, the results were favourable in that little or no degradation in performance or handling qualities occurred through the use of two or three axes sidestick controllers. Some degradation was usually found to occur with four axes integrated sidestick control.

For the remainder of this paper, only conventional centre sticks are considered in detail, as this is the type of manipulator for which the digital feel system is being designed. However, there is no reason why a similar system could not be developed for sidesticks. It would then be possible to conduct an experiment assessing the effects of varying sidestick parameters.

1.3.4 EFFECT OF TIME DELAYS

It is well documented that excessive time delays in flight control systems can seriously degrade aircraft handling qualities. The term 'time delay' is meant to mean the initial delay between pilot input and an aircraft's response to that input. Time delays are introduced by complex modern control systems on advanced aircraft and are usually blamed for problems like pilot induced oscillation (PIO). The worst offender appears to be digital

flight control systems because the power of modern computers encourages increased complexity in control systems design.

The main sources of delay^[23] include digital computational delay which is a pure time delay, data sampling delays, and high order equivalent system time delay. This last case is not actually a time delay, but rather a manner of describing the dynamics that arise from higher order systems. These dynamics are characterized by phase delays caused from the cascading of dynamic elements in the flight control system, such as filters, and can be described as a time delay to simplify the modeling of a system. This is usually the major cause of time delays. Smith and Bailey state that confusion can arise when publishing results regarding handling qualities degradation and time delays if the method by which the time delay was measured is not indicated. There are both frequency domain (known as 'equivalent' time delay) and time domain (known as 'effective' time delay) methods for measuring time delay, and these methods can produce different results if there are low frequency dynamic elements present in the flight control system. The two methods are outlined in the paper^[23], which also confirms that time delay is a significant flying qualities parameter.

An interesting piece by Powers^[24] discusses the PIO tendency of the Space Shuttle in the landing phase. The PIO tendency in this case was attributed to poor visual cues due to cockpit location, the high gain task of landing an unpowered vehicle, and the excessive time delays in the digital flight control system. The paper presents a solution to the problem in the form of an adaptive stick-gain that detects the type of pilot inputs that lead to PIO,

and reduces the longitudinal stick gain so the pilot can maintain control and perform a safe landing.

Two papers by Berry^{[25][26]} examine the effects of pure computational delays on low L/D (lift to drag ratio) landing tasks. The results confirmed that greater time delays degraded handling qualities evaluation on the aircraft, and that the amount of degradation is sensitive to pilot work load and the type of flying task.

Large amounts of research^{[27][28][29][30]} have gone into studying the interaction of time delays and the human operator. The main purpose of these studies has been to develop mathematical models of human pilot behaviour, usually as applied to tracking performance.

Of main interest to the project described in this thesis is the feel system and how it relates to time delays encountered in flight control systems. The force feel system is like any second order dynamic system and has a natural frequency and damping ratio, or two real roots depending on the chosen characteristics. This stick system acts as a pre-filter to the control inputs^[31]. Hence, the stick system can introduce time delays into the flight control system. This concept is subject to much contention in the field of flight control research and is discussed in the next section.

1.3.5 USE OF FORCE SENSING VS. POSITION SENSING STICKS

Cockpit manipulators can send input to flight control systems(FCS) in two ways. Force sensing sticks send force information to the control system. This can be done regardless of whether the stick actually moves. Position sensing sticks use stick position as the input variable. The definition of effective time delay between the two systems and

opinions on how these time delays should be handled vary from author to author. Magdaleno and McRuer^[32] conducted experiments into differences in position and force sensing systems and how they affect human operator performance as far back as 1966. However, it is the more modern papers that look at the effect of time delay that is of most interest here.

In one paper^[33] the authors cite Hess^[34] to support their contention that the feel system is a unique dynamic element in the control system. They state that if position sensing sticks are used then its delay contribution to the flight control system can be potentially reduced through the pilot's inner-most loop closures between stick position and stick force. Essentially, because the pilot has control over both the applied force and the stick position, he/she can compensate for feel system time delays by adding feedforward into controller movement. The authors therefore believe that a position sensing feel system should not be analyzed as an input filter but should be, for the most part, discounted in time delay contributions. The findings of this paper indicate that pilots prefer position sensing sticks over force sensing sticks that have the same equivalent time delay. The findings also indicate that to get the best correlation with time delay requirements as specified in [35] the feel system time delay should not be included in the total time delay for either force or position sensing systems. Bailey^[36] agrees that including feel system dynamics for position sensing systems in total time delay calculations gives poor correlation to the specifications.

In [37] which is a continuation of the work done in [38], the authors state that the use of force sensing as FCS input excludes the feel system dynamic lag from the command path and therefore decreases the effective system time delay. The findings indicated that

pilots preferred force sensing sticks over position sensing sticks, which is opposite to the findings in a previous paper^[33]. This is despite the increased tendency to roll ratchet when using force sensing sticks. The authors also state that "the feel system lag is not transparent to the pilot when displacement sensing is employed." Hence their findings indicated that to get good correlation with time delay requirements, the contribution to time delay of the feel system should be included for position sensing sticks but not for force sensing sticks. The authors support their position in another more extensive work^[39].

It should be noted that a major difference in data acquisition could have contributed to the difference of opinions expressed in the two papers^{[33][37]}. The first set^[33] is flight test data while the second set^[37] is ground based simulator data. This means that the data for one set of experiments^{[37][39]} was acquired in the absence of visual and inertial cues for the pilot, while the data for the other experiments^{[33][36]} was acquired in the NT-33 test aircraft during actual flight.

The situation becomes even more interesting when the latest paper to discuss this controversy^[40] has yet another point of view. This report is actually a collection of data from many different sources^{[2][13][33][38][39][41]} which has been re-analyzed and from which new conclusions are reached. The report draws from both helicopter and fixed wing data, as well as both simulator and flight data. The authors contention is that optimum correlation with the military specifications^[35] is achieved when the feel system dynamics are included in the time delay measurement regardless of whether the command reference was position sensing or force sensing.

It is important to remember that the effect of feel system on pilot ratings is not identical to the effect of adding pure time delay. In [40] it is stated that the manifestation of poor feel system dynamics is distinctly different from that of large time delay. However, in the absence of more specific requirements for feel system characteristics, many researchers use the conservative approach and tend to estimate the effects of the feel system on pilot ratings by considering it to be similar to adding time delay. The absence of guidelines for feel system design highlights a need for more research to better determine the effects of feel system characteristics on handling qualities.

Unfortunately the works cited in this section (except for parts of [40]) all used fixed wing and simulator based data, and there no indication of any differences there might be with regards to time delay if the experiments had been conducted in helicopters. However, it seems likely that had the data been helicopter data, the same confusion as to how to include the effect of time delays would have arisen.

1.3.6 EFFECT OF FEEL SYSTEM PARAMETERS

Feel system parameters including mass, spring gradient and viscous friction, as well as non-linearities such as breakout force, static friction, hard stops, etc. are the defining quantities for the artificial feel system. Changing these parameters changes the stick motion and force cues that are sensed by the pilot. This, in turn, affects the pilot's perception of what the aircraft is doing and how it will react to an input. Thus the feel system parameters do have an effect on aircraft handling qualities as evaluated by the pilot. The question is what values of these parameters makes a good stick, i.e. well liked by the pilot?

There are many references that attempt to answer this question for the purpose of offering guidance when developing feel systems. However most of the work has been done for fixed wing aircraft. Two works^{[21][42]} offer guidance for fighter sidestick controllers, while three others^{[36][39][41]} discuss centre stick characteristics for fixed wing aircraft. However, of primary interest to this work are helicopter handling qualities as they relate to feel systems. There appear to be only two papers which discuss this in detail^{[2][13]}.

The first reference^[2] describes a handling qualities experiment designed to determine the effects of feel system on roll axis handling qualities. The experiment held the spring gradient constant and varied viscous friction and inertia to effect changes in natural frequency and damping ratio. The authors state that inertia rather than natural frequency is the determining parameter with regards to handling qualities. The results suggested that a stick with an inertia between 5 and 7 lbm is a good stick, meaning that the feel system did not have a detrimental effect on the handling qualities of the aircraft. Yet this statement is made without any variation in spring gradient to determine the effects of this. As well, the damping ratios used were around 0.3 or 0.6, both of which are in the normal range. It is certain that there are stick characteristics within this range of inertia but with different spring gradients and damping ratios that would have a negative effect on handling qualities, and thus inertia alone is not enough to specify stick characteristics.

The second reference^[13] is of larger scope and different values of spring gradient, mass, natural frequency and damping ratio was used for a total of 14 different stick models (plus four different isometric sticks). Also, this experiment was not limited to maneuvers in a single axis, and many all axis tasks were evaluated. As this was a preliminary exploratory

study, no definite boundaries for stick parameters were found. However, the results did suggest some general observations that are extremely useful for determining the direction of future studies. Primarily, sticks with an undamped natural frequency of less than 9 rad/s or a damping ratio of less than 0.3 should be avoided. As well spring gradients of at least 9.0 lb/in are acceptable if unreasonable force is not required for maximum displacement. Also, large amounts of overdamping can be tolerated by pilots.

It is certain that the requirements for stick characteristics may be associated with response type, bandwidth, sensitivity and task requirements for the aircraft. Although limited reference to this concept appears in these papers, no hard research was done in order to determine the details of this relationship. This would indicate that considerably more research in this area is required before guidelines on selecting feel system parameters for helicopters can be developed.

1.3.7 CURRENT GUIDELINES FOR THE SELECTION OF FEEL SYSTEM PARAMETERS

There are military standards^[5] which contain some guidelines for the selection of feel system parameters, including allowable breakout forces, spring gradients, and maximum applied forces. How these numbers were determined is classified, however there is evidence to suggest that they were obtained from early 1960's experiments. Thus the values are based on conventional, unaugmented rotorcraft and are not necessarily appropriate for modern helicopters or new designs. Also, no guidance is given for the selection of inertia, damping or stick natural frequency. The document also states the

obvious requirement that the spring gradient may not be negative, due to detrimental effects on aircraft handling qualities.

The only mention of the stick dynamics occurs in the discussion of small amplitude response to control inputs for the pitch (sec. 5.2.1.1) and roll (sec 5.2.5.1) axes. With regards to bandwidth criteria, the document includes this section:

"It is desirable to meet this criterion for both controller force and position inputs. If the bandwidth for force inputs falls outside the specified limits, flight testing should be conducted to determine that the force feel system is not excessively sluggish."

However, the document does not state any criteria for the acceptable or unacceptable dynamic characteristics of helicopter controllers.

In [40] there is some attempt to give some guidance as to design configurations for cockpit manipulators, however it is not overly helpful either:

"Based on the data analyzed in this report, an acceptable feel system is attainable as long as the effective stick natural frequency is above 10 rad/s, or the effective mass is less than 5 lbm, with a stick damping ratio above 0.3. More detailed design guidelines require much more experimental data."

The main problem is that the data for these observations is based on both fixed wing and helicopter data. However, it is stated in this report as well that criteria for rotary wing aircraft do not necessarily coincide with the criteria for fixed wing:

"...the region of acceptable gradients is probably higher for fixed-wing airplanes than for helicopters..."

Thus there is support for separate criteria for each type of aircraft.

1.3.8 NEED FOR FUTURE RESEARCH

As it now stands, there is data from only two limited scope experiments that attempt to describe the effects of feel system characteristics on helicopter handling qualities. This data is by no means in-depth enough to fully describe the effects of the feel system, and thus more experiments are necessary to answer a variety of applicable questions. Among these questions are:

- Does the 9 rad/sec low frequency boundary really exist?
- Is the low damping boundary at $\zeta = 0.3$?
- Is there an absolute limit on acceptable spring gradient or inertia? What are these limits?
- How much overdamping can be tolerated by pilots?
- How important is the stick sensitivity (amount of full stick travel to full actuator travel) to handling qualities?
- Would a non linear stick gradient such as those often used with sidesticks^[19] be better than a linear one?
- Is some dead band desirable or is the absence of a notch[†] better?
- Is damping by viscous friction more desirable than by static and kinetic friction? Or would a combination of friction types be best?
- What guidelines should be used for choosing an appropriate breakout force?
- What would be the effect on the results of using different control systems like rate command or attitude hold on the helicopter?

The above are just some of the questions that must be answered before a complete criterion for the design of force feel systems can be developed.

[†] See Sec. 2.1.4 for a definition of the term 'notch'.

1.4 SCOPE OF WORK

The work will cover the design and installation of a digitally controlled artificial feel system for the NRC Bell 205 airborne simulator. This includes the problem description, outline of the dynamics of the system, the specific requirements of the design, and the reasons for the replacement of the existing system. As well, the generation and testing of a Simulink model of the system is presented. The code for the controller is discussed, along with highlights of the different features that were included in the program. Next a comparison of results between the Simulink output and the controller code output when equivalent forcing functions are used is presented. Finally, there is a discussion of installation problems and procedures, system calibration and optimization, and ground and flight testing.

CHAPTER 2: PHYSICAL PROBLEM DESCRIPTION

2.1 BACKGROUND AND SYSTEM REQUIREMENTS

2.1.1 EXISTING FEEL SYSTEM

The original artificial feel system consisted of the lateral and longitudinal cyclic controls as well as the rudder controls. It did not include the collective, nor are there any plans to include the collective in this system in the future. The lateral and longitudinal cyclic and rudder controls each contain strain gauges to measure the amount of control force. The artificial feel system consisted of two loops of analog computers, as shown in fig [2.1]. The inner loop ran the servo system by accepting position commands, differencing these with the actual position to create an error signal, which was then used to drive the hydraulic servo (Moog) valve, effectively sending the stick to the desired position. The outer loop accepted position and force input and calculated the desired stick position based on user entered parameters using an analog computer. The user entered the desired parameters such as spring gradient in the form of voltage levels controlled by banks analog potentiometers. The servo system is driven by 1000 psi hydraulics and is bounded by a maximum bandwidth frequency of approximately 3.5 Hz closed-loop, or 18 Hz open loop.

Due to the characteristics of analog components such as operational amplifiers, the feel system position and characteristics tended to drift with time. This problem could be brought on by a variety of conditions and, as such, the system had to be periodically recalibrated. In addition, the analog setting controls through banks of potentiometers were not particularly user friendly, nor could accurate values for required parameters be input.

Thus the system suffered from repeatability problems. As well, the analogue model of the dynamics handled the non-linearities of the system poorly. When the stick was pushed to the throw limit representing a mechanical hard stop, the feel of the stick was not realistic. When the stick strikes the stop it should feel like it had been stopped by a structural support element. However, the stick actually oscillated slightly and moved around at the hard stop. Another problem with the original system involved the electronic interaction between the inner and outer control loops. While the two loops were linked together, if the gain on the inner loop control signal to the stick actuator was turned up high enough, the system could go unstable and the stick would begin to move violently. However, if the inner loop was isolated and control signal was provided by way of a signal generator, the inner loop gain could be turned up as high as it was possible with the installed pot on the board, with no signs of instability. One final problem with this system was reliability. The system was over 30 years old and with the large numbers of analog components it was consistently breaking down at the most inopportune times. The complexity of the system made tracking malfunctioning components difficult and time consuming. These problems with the original controller were hampering current research in the area of high gain fly-by-wire control. As such, the suitability of achievable controller characteristics was questioned.

2.1.2 PROPOSED FEEL SYSTEM

The proposed system will replace both analog computer loops with a digital computer system. The new system is best described as model-following, with operation as follows. At each time slice the output of the control stick strain gauges and stick position potentiometers are sampled and converted to units of force and position respectively. The applied force value, together with the preceding time slice values for the stick position and velocity are used in a dynamic model to calculate the current time slice value of desired stick position and velocity. The desired stick position value is then differenced with the actual stick position and this error signal is converted into a drive signal for the hydraulic servo (Moog) valve. The flow of hydraulic fluid into the actuator effectively forces the stick to the desired position.

It is intended that this new system will remove the drift, user interface, repeatability, accuracy, performance and reliability problems of the original system. Proof of these improvements is given in section 5.2.5.

2.1.3 MECHANICAL SYSTEM AND PHYSICAL HARDWARE

The mechanical system consists of components such as the stick, actuators, pedal assembly, hydraulic lines, etc. that were not affected by the changes to the feel system. However, these components are an integral part of the feel system and thus a detailed description of their operation is necessary to make this thesis complete.

The Flight Research Laboratory (FRL) began a feel system design in the mid 1950's for installation on one of its Bell 47G research helicopters. At this time hydraulic actuators

were designed and manufactured for this purpose. In the early 1960's, a working feel system was installed in the Bell 47. After the acquisition of the Bell 205 in 1968, the design was modified to fit in this new machine, and the system was installed in the early 1970's.

The mechanical system consists of the stick assembly, pedal assembly, mounting bracket and three actuator assemblies. Included in the actuator assemblies are position sensors and hydraulic servo valves for each of the three channels, roll, pitch and yaw. The stick assembly is shown in Fig. [2.2], and indicates the location of the longitudinal pivot point and longitudinal actuator attachment point. The lower end of the stick assembly attaches to a mounting bracket as shown in Fig. [2.3]. The complete mounting bracket is shown in Fig. [2.4], with the stick attachment point on the upper surface and the actuator attachments points to the lower right. The entire mounting bracket will pivot to allow for lateral motion of the stick assembly. This motion is performed by activation of the lateral actuator as shown in Fig. [2.5].

The pedal actuation system is displayed in Fig. [2.6], showing the pedal actuator and dual connecting rods. Dual connecting rods are required for the pedal system because as one pedal moves forwards the other must move rearwards an equal amount. A front view of the pedal actuation system is shown in Fig. [2.7], which displays the mounting bolts, pedal stalks, and connecting rod attachment points. A mechanical system assembly diagram showing the actuator layout can be seen in Fig. [2.8]. This figure shows the layout as it would look from the top with all floor panels removed at the evaluation pilot's station. Fig. [2.9] is a picture of a wooden mock-up (which no longer exists) which shows the same information regarding layout but provides better clarity. Figures [2.10], [2.11], and [2.12]

are photographs of the actual installation of the hardware from the rear, side and front respectively. These pictures give the best description of the mechanical portions of the feel system and how they are installed in the floor of the cockpit, aside from in-person inspection.

The pilot grip is located on the top of the stick, as is shown in Fig. [2.2]. A photograph of the grip is shown in Fig. [2.13], which displays the location of various switches. Of particular interest are the 4-way 'coolie hat' switch at the top of the grip, and the force relief button located below the coolie hat in the centre of the grip, just below the pilot's right thumb when flying. These buttons control the feel system trim functions, as will be described later in this thesis. Inside the grip are found the strain gauges which are used to sense the pilot force applied to the grip. The strain gauges can be seen in Fig. [2.14] which shows the inner structure of the grip. The strain gauges appear as patches of fine lines along the square faces of the inner structure, and sense both the lateral and longitudinal forces. The strain gauges form components of an analogue bridge circuit, shown in Fig. [2.15], and the outputs of this circuit are voltages which are proportional to the applied pilot forces. There are two sets of gauges for each channel, the ones in use and spares to offer redundancy in case of problems with the primary set.

Fig. [2.16] shows the rudder pedal (tail collective) assembly including actuator attachment points and pedal stalks. The pedals are fitted on to the pedal stalks as shown in Fig. [2.17]. Both an assembled and disassembled pedal are shown in Fig. [2.18], and the strain gauges are located on the inner surface of the pedal structure.

The feel system hydraulic actuators are relatively simple devices designed and machined at the FRL. The piston area is 1.120 square inches with a maximum stroke of 2.625 inches. Therefore, at the design operating pressure of 1000 psi, the maximum force produced by the actuator is 1120 lbf. A diagram of one of the hydraulic actuators is shown in Fig. [2.19] and was taken from an NRC drawing. For greater clarity, Fig. [2.20] shows a photograph of the actuator and Fig. [2.21] shows a photograph of the same actuator, disassembled. The hydraulic servo (Moog) valve is located on the upper surface of the actuator and can be seen in Fig. [2.19]. This valve directs the flow of hydraulic fluid into the actuator, enabling precise control of the actuator velocity and position. A picture of the hydraulic servo (Moog) valve is given in Fig. [2.22]. This instrument will vary the amount of fluid flow according to a controlling input current. As can be seen in Fig. [2.23] the relationship between current and fluid flow rate is quite linear and very predictable. An analogue current driver is used to control the servo valve by accepting position error voltages which will determine the amount of current that is to flow to the servo valve. A schematic of the current driver is shown in Fig. [2.24].

The above section describes the portions of the feel system hardware that will be incorporated into the new system. There are many other parts of the system including the analogue modeling circuitry that was not described here because it was removed and replaced with the new system as outlined in this thesis.

2.1.4 STICK MODEL REQUIREMENTS

The following stick model requirements were taken from Ref. [43] and are as outlined during a conversation with Murray Morgan on October 4, 1994.

The stick model is required to be representative of a real world physical system and should contain all the nonlinear elements to be found in such systems. The required elements of the model as well as acceptable assumptions about the modeling process are outlined as follows:

INERTIA - The mass of the control runs and stick assembly as is be moved by the pilot. At this stage it is not required to include the effects of aircraft loading, which is assumed to have no bearing on the forces reflected at the pilot's grip, thus a single mass may be used by the controller for each flight test.

SPRING GRADIENT - Variable between zero and 10 lbf/in without affecting closed loop stability.

VISCOUS FRICTION - Force opposing motion and proportional to the velocity. The range should be from zero to approximately 5 lbf/in/sec. If zero is not achievable due to stability considerations then the minimum usable value must be determined.

STATIC FRICTION - Range from zero to 10 lbf.

COULOMB (RUNNING/KINETIC) FRICTION - This may be modeled as a ratio of kinetic to static friction which would range from zero to one, as it is not physically realistic for kinetic friction to be larger than static friction.

NOTCH - Area around neutral where some lost motion is present due to free-play in mechanical linkages. Free-play is a common occurrence in the control systems of older

aircraft and it is desirable to be able to model this for airborne simulation purposes. The extent of the notch is from zero to ± 0.5 in. The notch inertia is any value up to that of the outer model, and enough friction (static or viscous as required) should be present to maintain loop stability. There is not spring gradient while the stick is inside the notch.

BREAKOUT FORCE - The force which must be overcome before the stick will move out of the notch.

THROW LIMITS - The total range of motion at the pilot's grip. This can range from ± 2.0 in to ± 8.0 in.

TRIM - Two stick trim systems and one rudder trim system are required. The four way "coolie hat" switch should change the spring datum position at a constant, user-specified, rate. This rate should be variable from 0.25 to 2.0 in/sec. The other stick trim system consists of a designated button that would have the effect of removing all spring gradients when pressed, and then reinstituting it when the button is released, thus effectively changing the spring datum position. The rudder trim will be performed by use of a thumb wheel. The controller program must have a method by which a pilot selected gain may be placed on the thumb wheel input. This will enable control of the yaw trim system sensitivity.

2.2 SYSTEM DYNAMICS

A simple stick model will be assumed, as shown in Fig.[2.25]. The pilot input force is opposed by inertia, friction, and the spring force.

2.2.1 SYSTEM INPUTS

F_x	Force on lateral cyclic	+ve to right, -ve to left (from pilot's perspective, from zero centre stick position)
F_y	Force on longitudinal cyclic	+ve forward, -ve rearward
F_r	Force on the rudder pedals	-ve depressed right rudder, +ve depressed left rudder

2.2.2 STATES

x	lateral stick position	+ve to right
y	longitudinal stick position	+ve forward
r	rudder position	-ve right rudder depressed

And the corresponding first derivatives of these, the velocities:

$$\dot{x}$$

$$\dot{y}$$

$$\dot{r}$$

2.2.3 STICK MODEL DYNAMICS

Inertia:

M_x lateral mass

M_y longitudinal mass

M_r rudder mass

$$\sum F_x = M_x \ddot{x}$$

Spring gradient:

k_x lateral spring gradient

k_y longitudinal spring gradient

k_r rudder spring gradient

$$F_x = k_x x$$

Static and kinetic (coulomb/running) friction:

N normal force

C_s coefficient of static friction

C_k coefficient of kinetic friction

$$F = C_s N$$

or

$$F = C_k N$$

For our purposes the normal force will be considered to be constant, and hence when these forces apply (case dependent) the frictional forces will also be constant. Static friction only applies when the velocity is zero, otherwise kinetic friction applies. These are nonlinear items which will be accounted for through the use of if/then statements in the controller code. It must be noted that the static frictional forces are normally greater than the kinetic frictional forces (as can be seen in typical coefficient values, C_s & C_k ^[44]). Therefore, the kinetic friction can be modeled as a proportion of static friction, the value of this proportion being between 0 and 1.

Viscous Friction:

F/A	shear stress
μ	viscosity
v/l	velocity gradient

$$\frac{F}{A} = \frac{\mu v}{l}$$

Since A and l are geometric parameters, the viscous friction force is just proportional to velocity through some constant:

$$C_v = \frac{A\mu}{l}$$

By summing the forces in each axis, we can determine the basic state equations in each axis:

$$F_i = M_i \ddot{x} + k_i x + C_{vi} \dot{x}$$

Rearranging:

$$\ddot{x} = \frac{F_v}{M_v} + \frac{k_v x}{M_v} + \frac{C_v \dot{x}}{M_v}$$

In state space form, for all three axes:

$$\begin{Bmatrix} \dot{x} \\ \ddot{x} \end{Bmatrix} = \begin{bmatrix} 0 & 1 \\ -\frac{k_v}{M_v} & -\frac{C_v}{M_v} \end{bmatrix} \begin{Bmatrix} x \\ \dot{x} \end{Bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{M_v} \end{bmatrix} F_v$$

$$\begin{Bmatrix} \dot{y} \\ \ddot{y} \end{Bmatrix} = \begin{bmatrix} 0 & 1 \\ -\frac{k_v}{M_v} & -\frac{C_v}{M_v} \end{bmatrix} \begin{Bmatrix} y \\ \dot{y} \end{Bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{M_v} \end{bmatrix} F_v$$

$$\begin{Bmatrix} \dot{r} \\ \ddot{r} \end{Bmatrix} = \begin{bmatrix} 0 & 1 \\ -\frac{k_r}{M_r} & -\frac{C_r}{M_r} \end{bmatrix} \begin{Bmatrix} r \\ \dot{r} \end{Bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{M_r} \end{bmatrix} F_r$$

In the frequency domain, using transfer functions, the equations become (in one axis only):

$$\frac{x(s)}{F_v(s)} = \frac{1 / M}{s^2 + (C_v / M)s + K / M}$$

This can be written in the standard form for a second order system:

$$\frac{x(s)}{F_v(s)} = \frac{1 / M}{s^2 + 2\zeta\omega_n s + \omega_n^2}$$

thus,

$$\omega_n = \sqrt{(k / M)} \quad \zeta = C_v / 2\sqrt{(kM)}$$

where s is the Laplace operator, ω_n is the natural frequency, and ζ is the damping ratio.

It should be noted that each of the three channels (x, y, r) are completely uncoupled from the others. Even when the stick is out of the notch in one axis it does not necessarily mean that it is out of the notch in the other axis. Hence the state equations for each axis can be written separately. Also, the above dynamic equations ignore the effect of gravity on the grip (Fig. [2.25]). As the stick moves from neutral, and as the aircraft manoeuvres, the mass of the grip will press against the strain gauge. This small force will be mistaken by the controller to be pilot input and will cause the stick to move and control signals to be sent to the aircraft. However it is difficult to compensate for this undesirable effect. It is possible using the aircraft sensors to obtain both the stick position and the aircraft attitude. Using this information and knowing the mass of the grip it is possible to compensate for this destabilizing force. However, inaccuracies in the aircraft attitude sensors combined with the small magnitude of this force and time delays in sensors and calculations would probably result in inaccurate compensation. It is probable that attempting to compensate for this problem would be worse than ignoring it. Also, it should be noted that even a conventional wire-cable system will see gravitational effects on the grip.

For similar reasons, inertial effects of the grip against the strain gauges are not compensated for. However, conventional wire-cable systems will also see this inertial effect, and this is directly comparable to the feel system grip when the mass below the FFS grip is disregarded.

2.2.4 INPUT PARAMETERS

The following parameters will be specified by the user before each flight:

- mass of the system in 3 axes (can be different for each axis)
- spring gradient in 3 axes
- viscous friction coefficients in 3 axes
- Static and kinetic friction parameters in 3 axes
- total throw limits
- breakout force
- notch size
- coolie hat trim rate
- notch mass in 3 axes
- notch frictional coefficients in 3 axes

2.2.5 CONTROL SOLUTION

The proposed digital redesign of the existing system would incorporate a model following controller. Essentially, once the above parameters have been entered into the digital flight computer (by keyboard or disk), the controller will accept the pilot force input from the strain gauges and calculate a new position for the stick and pedals using the governing dynamic equations and an appropriate time step. These position commands will be differenced with the sensed position resulting in an error signal which will be used to

drive the stick to the desired position. Different controllers will be required for each of the following cases:

- 1) When the stick is in the notch.
- 2) When the stick is outside the notch.

In three axes, this will mean that a total of six nonlinear controllers are required to properly model the system.

Note that in the state equations, static and kinetic friction, breakout force and the throw limits are not included. This is because only linear terms were included in the state equations because of the manner in which the nonlinear terms were incorporated in the model. The nonlinear terms will essentially be constant force values in each of their corresponding regimes. Thus by adding appropriate step values of force in the controller at the appropriate times (decided by logic) these cases can be handled satisfactorily.

Trim for the system can be handled simply by updating the spring datum position of the stick by use of either the coolie hat switch or a designated clutch switch.

Essentially the problem is nonlinear, so a different controller must be used for each case. Which controller is being used at a given time will be decided by if/then loops in the digital flight computer. This is similar to an aircraft using different linear flight controllers for different mission segments (ie. different manoeuvres, altitudes, weights, etc).

CHAPTER 3: SIMULATION MODEL

3.1 MODEL BUILD-UP AND TESTING

A dynamic simulation model of the Bell 205's artificial feel system and proposed digital controller was created using Simulink, a sub-program of Matlab. This model was then shown to work correctly by using test values for the different parameters and displaying how these affected the simulation for each model component. The initial test values are given in Table [3.1].

The model was built up in six parts. The first was the basic linear inner model. After this was shown to work, the nonlinear elements were added. These included the throw limits, static and kinetic friction, the breakout force and the notch model. After this, the strain gauge, position sensor and servo were added to the model.

The system was modeled in one axis only. This is because each axis is completely uncoupled from the other two, and the governing dynamic equations are the same in each axis. For each of the simulations, the integration method selected was the Euler method because it most closely resembles the trapezoid method used in the actual controller program. The trapezoid method was selected in order to reduce required computational time to allow the system to run at the required cycle rate. Simulations were performed for 50 sec using a fixed time step of 0.005 sec for good accuracy, as this frequency is well above the bandwidth of the physical system. The main reason for using a fixed time step as opposed to a variable time step is that it will allow a comparison between the simulations and the actual digital system, which will run using a fixed time step.

3.1.1 INNER MODEL

Fig. [3.1] shows the Simulink block diagram for the inner model. The inner model refers to the linear portion of the model, as described in equations on page 32 and contains only linear elements like spring gradient and viscous friction. It is to the inner model that the nonlinear elements are added to develop the complete model. The response to the initial test values is given in Fig. [3.2]. The pilot input for this case and most of the following cases was a square wave form, with a peak value of 2 lbf and a frequency of 0.25 rad/s. The features to note in this figure are the overshoot caused by the inertia and the fact that the model settles to a value of 2-in, which is the steady state case where the pilot force is countered by the spring. The spring has a value of 1 lbf/in, so at 2-in this would be 2 lbf, exactly equal to the pilot input.

In Fig. [3.3], the initial test value for mass had been increased to two slugs. The effect of the inertia was, as expected, to increase the overshoot, and to increase the settling time. In fact it can be seen that for the test input and the increase in inertia, the model no longer has time to settle before the force changes direction. This, of course, depends on the frequency of the forcing function.

In Fig. [3.4], the mass has been returned to its initial value and the viscous friction coefficient has been increased to 2. As expected, the model displays greater damping and inertial effects are not apparent. There is no overshoot and the model peaks at the steady state value. The lower slope for the greater part of the line indicates lower velocities caused by increased friction.

In Fig. [3.5], the viscous friction coefficient is returned to its initial test value and the spring gradient has been increased to 3. This had the effect of altering the steady state value to 0.66-in, as expected. The other apparent effect which was also expected is the more oscillatory nature of the response before settling.

3.1.2 ADDITION OF THROW LIMITS

Fig. [3.6] shows the inclusion of throw limits into the Simulink model. The throw limits are set at 8 inches, and in order to show their effect, the pilot input force must be increased to overcome the spring force. The nonlinear effect of the throw limits caused an interesting problem in the modeling stage, and the normal integrators used before had to be changed to reset-integrators. As the name implies, this allowed the velocity integrator to be reset to zero when the stick strikes the throw limits. As well, the position integrator is set to the value of the throw limits. These changes were made to prevent the system from commanding a position value that exceeds the throw limits and thus to more accurately model the effects of a physical hard stop. This assumes that no bounce of the control off the hardstop would occur. Although this is not entirely accurate, some bounce will occur from the pilot's hand against the grip, which will register in the strain gauges, and thus this phenomenon will be present, if to a lesser degree. Fig. [3.7] shows the effect of a 9 lbf peak pilot input. As expected, the position hangs up on the throw limits. Fig. [3.8] shows the effect of a 7.5 lbf pilot input. Here the system inertia causes the stick to strike the throw limits. After rebounding from the throw limit where the stick velocity was instantaneously zero, the stick arrives at a steady state position near, but not at, the throw limits.

3.1.3 ADDITION OF STATIC AND KINETIC FRICTION

Fig. [3.9] shows the changes to the simulation model with the addition of static and kinetic friction. Static friction applies only when the velocity is very low (less than 0.01 in/s, a value which can easily be changed if this is found to be too fast or slow) and appears as a resisting force to stick motion. Kinetic friction appears in the same way but only applies at velocities above 0.01 in/s. Kinetic friction is always less than static friction and was modeled as a percentage of static friction.

Fig. [3.10] is for comparison purposes and indicates the response with zero friction. Fig. [3.11] shows the response with 1.8 lbs of static friction. The response is over-damped and there is no overshoot. The 2 lbf of pilot input is initially resisted by inertia, spring force, viscous, and kinetic friction. This prevents a large acceleration of the stick. At approximately 1.0-in, the velocity of the stick slows enough that the kinetic friction force is replaced by a larger static friction force. At this point the stick displacement curve changes more slowly, creating the corner in the plot at 1.0-in. The manner in which static friction is modeled allows F_s to be larger than the pilot applied force and thus cause the stick to accelerate. This is physically not possible, and thus the static friction model is only valid when the parameters are set such that this will not be noticeable. This problem can be avoided by not selecting low inertia sticks that would intern cause large accelerations and large differences position between each time step. This problem was fixed in the actual computer code for the force feel system, but it was deemed not a large enough problem to warrant the time required to change the Simulink model as well.

3.1.4 ADDITION OF BREAKOUT FORCE

In Fig. [3.12] it can be seen how the model has changed with the introduction of breakout force (note that the friction portion has been disconnected). Breakout force is a step in restoring force beginning at the edge of the notch and applied constantly outside the notch. It resists stick movement out of the notch and attempts to move the stick back towards the datum position. For the simulation, the breakout has been modeled as an increase in resisting force, outside the notch.

Fig. [3.13] is for comparison purposes and shows the response when the breakout force is set to zero. Fig. [3.14] shows the response when the breakout force is 1 lbf. The presence of the breakout force is indicated by the lower steady state value of 2-in in Fig. [3.14] as opposed to 3-in Fig. [3.13]. Since the spring gradient $k = 0.5$ and the breakout force = 1 lbf, at a value of 2-in the opposing force is 2 lbf, exactly equal to the pilot input.

3.1.5 EFFECT OF MODEL SWITCHING

While the stick is in the notch there will be no spring gradient, and the mass and viscous friction coefficients will be less. This effectively models the situation where in a real system there may be a small amount of free-play in the mechanical linkages. The stick model used while the stick is in the notch is different than the model used when the stick is out of the notch. Thus the controller must switch between stick models as the stick passes in and out of the notch. This was accomplished as shown in Fig. [3.15]. Note that for this simulation, the breakout force as well as the model and notch friction terms have been set to

zero. This magnifies the effect of model switching and allows the reader to see the transition between models more clearly. Fig. [3.16] shows the pilot input corresponding to the outputs in Fig. [3.17], both with the same time scale. This permits a comparison of force vs. reaction. For the simulation, the notch size was set at 4-in. Although this is unusually high in practice, it magnifies the effect so that it can be more easily seen. As well, both the notch and model mass and viscous terms were set to 0.2, and the spring gradient was set to 2.0. Since inside the notch there is no spring gradient present, the position passes through to 4-in where the model switches. Once the model has switched, a restoring spring force is instituted. As expected, the steady state value is 5-in, exactly where the pilot force is equaled by the restoring spring force. It should be noted from the diagram that the spring force (kx) is proportional to the distance from the edge of the notch, not from the zero position. This is more realistic because there is no spring force applied inside the notch.

3.1.6 ADDITION OF STRAIN GAUGE, SERVO, AND POSITION SENSOR

Fig. [3.18] shows the addition of transfer functions which represent the strain gauge, servo and position sensor. The two sensors were modeled as 1/120 sec first order lags and the servo was modeled as a 1/60 sec first order lag. Calculated position is used rather than actual position for calculation of the spring term because the sensor and servo combination would otherwise have the effect of changing the model as seen at the stick by introducing extra phase lag. Therefore, actual position is not used in the calculation of any model parameters. Thus switching for the two models as well as the throw limits are done using

the commanded position and do not wait for the actual position to catch up. The reasoning behind this can be illustrated by using the throw limits as an example. If the switching command were taken off the actual position signal, and if the stick were to approach the stop quickly, the commanded position could be past the throw limits before the model reacts. The fact is, there is no reason to command a position outside the throw limits. The velocity signal used for the calculation of the viscous friction force as well as for some switching was taken from behind the velocity integrator and represents the calculated velocity, not the actual. This was done because taking the derivative of the actual position to acquire the actual velocity is noisy and inaccurate when performed in a digital computer.

For comparison purposes, Fig. [3.19] shows the pilot force input using the same time scale as the simulation. Fig. [3.20] shows the results of the simulation using all of the initial test values, as listed in Table [3.1], and the response is clearly stable.

3.2 SIMULATION

3.2.1 VARIATION OF PARAMETERS

Simulation runs were performed in order to determine how combinations of different parameters would cause the system to react. Initially only the inner model parameters, k , m and C_v were varied, picked within the range of expected operational values. The values that were used are shown in Table [3.2]. It should be noticed that more simulations were performed at smaller values. This was done because the discrete model was expected to be less mathematically stable when the values are small i.e. near zero mass, no restoring spring force and no viscous damping. For the purpose of testing, typical values

were used for the notch and throw limits. The notch was set at 0.25-in, the notch mass and viscous friction coefficients were set equal to those used in the outer model and the throw limits were set at 8-in. This was done to limit the number of combinations of parameters and hence the number of simulations. With the notch parameters set this way the $k=0$ case will be indicative of notch model stability since there is no spring gradient acting on the stick while it is in the notch.

The critically damped cases were tested first. This was done by varying the selected masses and spring gradients in Table [3.2] (except for zero k cases), then calculating the viscous friction coefficient such that the damping ratio was unity. Next, the main simulations were performed using a square wave input, with a 2 lbf peak and 0.25 rad/s (0.0398 Hz) frequency, for a fifty second duration. To determine the effect of other inputs on the stability of the system, a subset of simulations using only the lowest mass was performed using sine inputs. The lowest mass case was selected because it is closest to the mathematically unstable zero ($m=0$) case. The first set of simulations was at the same frequency as before and the second set was performed using a frequency of 12.56 rad/s (2 Hz) for a 2 second duration. The 2 Hz limit was chosen because this is the upper bound on voluntary, controlled human movement capabilities^{[45][46][47]}.

In none of the above cases was the effect of friction or breakout force examined. Thus two more sets of simulations were performed, again using the lowest value of mass. The first set varied the breakout force using values of 1, 1.8, & 3 lbf and the second varied the static friction using the same values. The ratio of kinetic to static friction for this case was 0.75, a typical value. Finally, simulations were performed where a small amount of

noise was introduced after the strain gauge and after the position sensor respectively. Fig. [3.21] shows the location of noise inputs. Note that this figure shows only the location, not the models that were used for simulation, because the simulations were performed for each case separately.

3.2.2 CATEGORIZATION OF RESPONSE

The response of the critically damped simulation is categorized in Table [3.3]. The inner model response type is listed in Table [3.4]. Tables [3.5] & [3.6] contains the response type for the sine wave input, at both the lower and higher frequencies respectively. The response type with the addition of breakout force is listed in Table [3.7], and for static friction in Table [3.8]. Table [3.9] categorizes the response when noise is introduced into the system before the strain gauge and Table [3.10] when noise is added at the position sensor. The response type is categorized as letters which have the following definitions:

a	acceptable
h	highly damped
d	divergent
o	oscillation/overshoot
l	limit cycle

Fig. [3.22] and Fig. [3.23] show examples of acceptable response. Fig. [3.22] has little damping and no spring gradient, and the position has moved to the throw limits where

it remains until the force reverses direction. This case (with no spring gradient) is known as the 'limp noodle' and is preferred by many helicopter pilots. Fig. [3.23] has higher damping, which is a function of viscous friction and can be seen in the manner in which the stick approaches the steady state value. The steady state value is a function of the spring gradient. This response is likely quite acceptable to pilots as well. It must be remembered that "acceptability" is in terms of mathematical behaviour. An acceptable model represents one that is not overdamped, divergent or shows characteristics of limit cycling. However, some of these stick models may be completely unacceptable when tested in a helicopter with a pilot. Conversely an "unacceptable" stick may be quite good when the pilot's arm/neuromuscular system is included in the loop.

Fig. [3.24] shows a highly damped stick model where the viscous friction coefficient was too high to make this an acceptable model. Too much pilot force would be required to achieve a desired reaction, thus leading to pilot fatigue and slow response time. Slow response time can be deadly when flying a helicopter.

Fig. [3.25] shows an example of a divergent response. In this case the model was mathematically unstable and after striking towards the positive throw limits Matlab returned a NAN (Not a Number) error and the calculation of subsequent steps became impossible. It may be asked how increased damping could cause the system to go unstable. This is not a physical phenomenon but rather a numerical anomaly caused by the fact that the system is discrete. Before the first time step, there is no stick velocity, so the viscous frictional forces are zero. However, after the first time slice the stick has a velocity. Since the coefficient of viscous friction is high, it is possible that in combination with a small inertia, the force of

viscous friction is higher than the pilot applied force and causes the stick velocity to change sign, and increase in magnitude. Now the viscous forces for the next time step are even larger because the velocity is larger, and the stick velocity reverses direction once again. This will occur for a discrete number of steps until the integrated position in one time step exceeds Matlab's largest real number, and the NAN error is returned.

Fig. [3.26] shows a stick model response with overshoot and a small amount of oscillation. Although stable, this type of response may be undesirable from a pilot's perspective, especially if the spring gradient is large. It may require the pilot to 'fight' with the stick in order to make the aircraft respond in an appropriate manner. Flight test has revealed that underdamped sticks (damping ratio of less than 0.3) are undesirable.^[14] Underdamped sticks will exhibit overshoot and oscillation.

Fig. [3.27] shows a limit cycle response where the output is bounded but erratic. This is clearly undesirable from a pilot's perspective. Since the servo is driven by a 1000 psi hydraulic system, a limit cycle could cause the stick to oscillate violently, possibly causing serious injury. It should be noted that in the limit cycle response, the indicated output frequency is very high. This however does not take into account the limitations of the hydraulic servo which is bounded to a maximum of approximately 10 Hz.

3.2.3 SIMULATION RESULTS

The output plots are in time domain which is useful to determine at a glance whether or not the system response is acceptable. However, frequency domain parameters such as natural frequency (ω_n) and damping ratio (ζ) are useful to categorize the different responses.

Correlating the results from Tables [3.3] through [3.10] allows some general observations to be made with regards to system response. The critically damped set of simulations all had viscous friction coefficients that were calculated so that the damping ratio was unity. This should have made the response acceptable in all cases. However, as can be seen in the summary of results, Table [3.3], there were some cases where divergence occurred. The divergent occurrences were when the mass was at its smallest value and k at its highest. Here the model was likely most sensitive to small changes in parameters, and the calculation diverged for reasons explained in the previous section making further stepwise calculations impossible.

The inner model response, summarized in Table [3.4], showed a wide variety of response types. Table [3.11] shows the ranges of different parameters for each response type. An acceptable response generally has a relatively low natural frequency range when compared to the other response types, except for the highly damped case. The median damping ratio was unity, and the values of k , C_v and m were never more than three orders of magnitude away from each other, using the same units as indicated in Table [3.1].

The divergent response occurred when the damping ratio was very high (up to 25000) and the median damping ratio was 158. It should be noted that the value for C_v in the divergent case was never less than three orders of magnitude greater than m .

The highly damped case occurred when the damping ratio was high, from 2 to 2500. The natural frequencies for this case were also low, never more than 10 rad/sec. Sticks with an undamped natural frequency less than 9 rad/s should be avoided^[13]. In all the cases, k was considerably smaller in magnitude than the viscous friction coefficient.

The oscillation/overshoot case always has a damping ratio less than 1, as was expected. The value of k is usually much greater than the value of C_v . When the overshoot is small, it may be that the response is acceptable, especially if the mass is small and any oscillation could easily be damped out by the pilot's arm.

The limit cycle case occurred only when the damping ratio was very small, usually in the order of 0.001. In this case k was always a minimum of 10 times larger than C_v and was usually four orders of magnitude higher. The limit cycle is a function of the dynamics of the model and should not be confused with a limit cycle caused by digital precision problems.

A comparison between Tables [3.5] & [3.6] and the first section of Table [3.4], where the mass value is equivalent, shows that input wave shape had little effect on the output in terms of response type. The sine input did cause the limit cycle to start sooner, at slightly higher damping ratios. However, the damping ratios were still well below 1.0 and still fell within the categories listed in Table [3.11]. Otherwise, the response type predicted with the square input was also predicted with the sine input. The frequency of the input had

no effect on the response type, as shown in a comparison of Tables [3.5] & [3.6]. The response type predicted at 0.25 rad/sec (0.04 Hz) was the same at 12.56 rad/sec (2 Hz). Typical responses to sine inputs for 0.04 Hz and 2 Hz are shown in Fig. [3.28] and Fig. [3.29] respectively.

A comparison between Table [3.7] and the first section of Table [3.4] shows how the addition of breakout force can affect the stability of the system. Additions of small amounts of breakout force appear to have little effect on the system. With the addition of 1 lbf of breakout force, the system response type is unchanged from the response type with no breakout force. However, when the breakout force is increased to 1.8 lb, it causes the system to limit cycle at lower values of k . This was expected because breakout force is essentially a step increase in spring force and hence effectively increases the effect of the spring gradient. When the breakout force was increased to 3 lbf, the system limit cycles almost immediately because of the large increase in restoring spring force. Fig. [3.30] and Fig. [3.31] compare two cases, the first with 1 lbf of breakout force, the second with 3 lbf breakout force. Since all the other parameters were the same in each case, it can be seen that the greater breakout force causes the system to limit cycle while the lower F_b retains an acceptable response type.

Table [3.8] shows the effect of adding static friction to the system. Small amounts of static friction such as in the case of 1 lbf and 1.8 lbf had little effect on the predicted response type. Higher static friction as in the 3 lbf case, caused some interesting differences in response type. Fig. [3.32] and Fig. [3.33] compare two cases, the first with 1 lbf static friction and the second with 3 lbf static friction, with all other parameters being the same in

each case. The 1 lbf static friction case clearly exhibits an acceptable response. The 3 lbf F_c case, while being of mathematically acceptable response type, shows some interesting features. Particular to this example is the small step-like feature during transition between throw limits. The reason for this feature which did not occur in any other case is uncertain. As well, there is a thickened line representing the output at the throw limits, which appeared in most of the 3 lbf static friction cases. This is indicative of small limit cycle oscillations at the throw limits caused by transition from static to kinetic friction, and the direction of applied force in a discrete system. When the stick strikes the throw limits the velocity is set to zero and static friction is applied, in a direction opposite to the direction of the velocity in the previous time step. Since the static friction is greater than the applied pilot force the stick is thrown off the stops in one discrete step. However, in the next step the static friction is applied in the opposite direction to counter the new velocity and the stick is thrown to the stops. This cycle repeats until the applied force switches direction, thus causing the small limit cycle at the throw limits. Theoretically, since the static friction is greater than the applied force the position should be held on the lower throw limit no matter the direction of the applied force. However, because of this limit cycle at the throw limit, a reversal in applied force would give the stick enough velocity to overcome static friction, and thus the smaller kinetic friction would apply. Therefore it is possible that the position could move to the other throw limit, as seen in Fig. [3.33]. It must be noted that as stated previously, there is an error in the manner in which the Simulink model handles static friction that allows the static friction to be greater than the pilot's applied force. This is

what has caused the problem as stated above. This problem was fixed in the actual controller code.

Table [3.9] categorizes the response with the addition of strain gauge noise, while Table [3.10] categorizes the response with position sensor noise. This noise appeared to have little effect on system response, except to make the steady state condition appear ripply. Fig. [3.34] and Fig [3.35] show typical output plots with the addition of strain gauge and position sensor noise respectively. It appears that sensor noise will not be a problem with this system.

3.2.4 CHOOSING A STICK MODEL

In deciding upon the parameters to be chosen for a stick model, it must first be determined what characteristics of the stick are desired. Does the pilot want a 'limp noodle' where the spring gradient is zero? This is a valid case and many of the acceptable stick responses do have a spring gradient of zero. Does the pilot want a damped stick, or would he/she prefer almost no friction? Would the pilot like a heavy or near-zero-mass stick? Once the characteristics have been decided upon the different parameters must be chosen. A few guidelines might be helpful in choosing the parameters. Remember, however, that much of this does depend on pilot preference.

The following guidelines are for creating a stick that is mathematically acceptable, that is, not divergent or with tendencies to limit cycle. It must be noted that even though a stick may be mathematically acceptable, it may not be acceptable to the pilot with regards to

feel. Guidelines with respect to pilot preference are limited, and were discussed in section 1.3.7.

To be stable, the model mass should be at least 0.0001 slug. Any less and the stick accelerations will be excessive, and system response may be unstable. Spring gradients as high as 10 or more are acceptable, but high k may cause the stick to limit cycle, and C_v should be sufficiently large so that the damping ratio is high enough to prevent this (the best damping ratios are probably between 0.707 and 1.00). As well, note that if the spring gradient is high, the throw limits will probably need to be small so that excessive force is not required to move the stick through the full range of motion. The viscous damping coefficient should be kept below three in most cases, otherwise the stick model will be slow, and too much pilot force may be required to operate the aircraft effectively. Both C_v and k should be approximately the same order of magnitude (within three orders of magnitude), otherwise the system may be divergent or may limit cycle. It should be noted that the magnitude comparisons as stated above are unit specific.

Once the parameters have been chosen, if the stability or suitability of the stick model are in question, this should be tested using the Simulink model before installation on the helicopter. Otherwise, if the system limit cycles, the stick could cause injury if it unexpectedly moves violently. To assist in the selection of stick models, a complete set of output plots from the Simulink model were given to staff at the FRL.

CHAPTER 4: CONTROLLER PROGRAM

4.1 HARDWARE REQUIREMENTS AND AVAILABLE SYSTEM HARDWARE

The force feel system analogue hardware was replaced with a MVME167 digital computer, running the Motorola MC68040 32-bit processor. This is a local bus system running at 25 MHz with 8 megabytes of DRAM.^[52] A multi-tasking operating system, Microware's OS-9, was used on the system in order to facilitate the operation of several programs at once, including the user interface and the feel system cycle calculation. The force feel system cycle calculation will have priority and thus will be able to interrupt the other program when necessary to perform real-time computations.

Installed in the VME are one A/D board and one D/A board to facilitate the required input and output for the system. The D/A conversion process is done using the Acromag AVME9210 board. This board has 12 bit output resolution with 8 channels of output, 3 of which will be used for the feel system. It is configured to an output voltage range of -10 volts to +10 volts. The A/D conversion function is performed using the Acromag AVME9325 high speed analogue input board. This board has 12 bit resolution and a 5 microsecond per channel throughput rate. The board is configured for 32 single ended inputs, 22 of which are used for the feel system, and is set to read voltages ranging from -10 to +10 volts. This board is used for the discrete switches as well as the force, position and rudder trim thumb wheel inputs. The board's internal clock with triggering feature is also used to control the program cycle timing.

The following is a list of requirements for the computing system, as necessitated by the force feel system module:

Provisions are in place to:

- 1) Complete a computation cycle every 0.0016667 sec (600 Hz). This time interval was dependent upon how fast the computer could calculate a complete cycle of position values for the force feel system.
- 2) Have a method by which the force feel system module can determine if one of eight switches have been thrown.
- 3) Send position command voltages to the servo system in three channels at the same rate the program is calculating these voltages.
- 4) Read the actual position from the position sensors on the stick and rudder pedals for each cycle. It is essential that this information be updated at the same rate at which the force feel system module is running.
- 5) Read the pilot force on the stick and rudder pedals from the strain gauge sensors for each cycle. It is essential that this information be updated at the same rate at which the force feel system module is running.
- 6) Read the state of the 4 coolie hat positions, 1 force relief button, 1 trim/operate switch, and 1 rudder trim thumb wheel.
- 7) Send modified stick position data (not the same as the actual position data) to the flight control computer, or send force data, depending upon whether the system has been selected to run with a regular position sensing, force sensing or isometric stick. The modified stick position data is used as pilot input into the FCC for calculation with the helicopter control laws. It is calculated by subtracting the notch size from the actual stick position and has the effect of preventing the pilot from having any input into the control system while the stick is in the notch. This is to accurately model the case of slop in mechanical linkages where moving the stick in this area would have no effect on control surface position.
- 8) Have access to the aircraft on board terminal and keyboard for user control of the program during flight if necessary. It should be possible to share this terminal with the aircraft flight computer, if necessary, by using a cockpit switch.

SUMMARY: At force feel system cycle rate

1)	Read A/D (16 possible, minimum of 7)	- 3 forces
- 3 positions
- 1 rudder trim
2)	Read discrete switches (16 possible)	- 8 function switches
- 4 coolie hat positions
- 1 force relief button
- 1 trim/operate switch
3)	Output D/A (minimum of 3)	- 3 position commands
4)	Data transfer between FFS and FCC	- serial connection
5)	Service console	- FCC RS 232

4.2 FORCE FEEL SYSTEM PROGRAM

The artificial feel system controller was written in Microware Ultra C because this compiler is recommended for writing real-time programs for use with the OS-9 operating system. A listing of the source code is not provided, however it is available from the author. The code itself was written to follow closely the standards outlined in Ref. [48]. The code was written in three modules: FFS.C, CREATE.C and FEEL.C. As each aspect of the program is described the module where it is located will also be listed for easy reference in case the program is to be modified in the future.

The program consists of two main parts; a portion to implement a user-entered stick model and a part designed for user interface, including file systems and options to create, modify, show and check stick models. The user interface portion is designed to work through any standard terminal, including the one installed in the aircraft. The

implementation part is self contained and the only control the user has is to stop operation, start operation or change stick models. Fig. [4.1] shows a schematic of the program menu structure. In the following sections of this chapter each aspect of the program will be outlined.

4.2.1 MAIN MENU

The program is started by typing "ffs" at the command line of the terminal. This starts the main menu where the user can control the operation of the program. The main menu options include provisions to create, show, modify, load and run stick models. The program runs on a tiered menu structure with options to either move forward or back to the previous menu at each step. As well, it is in the Main menu that the user is given the option to exit the program. (module: FFS.C)

4.2.2 FILE SYSTEM

The file system consists of several subroutines with two functions: save or load stick models. Stick models are saved as text files consisting of the value of each parameter listed in a specified order. This allows the user to create stick models using a text editor if it is found that the create option in this program is insufficient for his/her needs. When models are saved the time and date is included along with a descriptive name for model. This allows the user to determine when the model was last modified and other information indicated by the descriptive name such as natural frequency, damping, etc. The load function turns on a flag to let the program know that a working model has been loaded into

memory. The load function also checks the parameter values to ensure that they are in fact numbers and do not consist of other characters. This function does not check if the values are out of range for a particular parameter, as this is performed by a different routine.

(module: FFS.C)

4.2.3 CREATE OPTION

This option from the main menu allows the user to enter the parameters which define the stick model. Each of these parameters are loaded into memory from the keyboard and a flag is turned on to let the program know that a working model has been loaded into memory. Any previous working model is over-written by this process. After all the parameters have been entered the user is asked to enter a filename for the stick model and then it is written to disk. Afterwards the user is given the option to check the model. If check is selected the model is checked (see section on check), and then control is returned to the main menu. If check is skipped then the program returns to the main menu.

Create allows the user to enter stick models in various ways. These include the standard method where the mass, spring gradient and viscous friction coefficient are entered, and a variety of other cases involving a mix of these parameters along with natural frequency and damping ratio. The natural frequency and damping ratio are only for the linear model and do not take into account the non-linearities such as static friction and breakout force. If the user desires to quit before finishing a model, he/she may enter a negative number to quit without saving and return to the main menu. (module: CREATE.C)

4.2.4 CHECK OPTION

A menu offering the option to check a stick model appears when a model is created, modified, or selected to be loaded into an auxiliary model. If check is skipped, program control is returned to the calling function. If check is selected, various warnings are printed to the screen with regards to the various parameters of the model and how they will affect the implementation of the model. For example, if the model has zero mass in the lateral direction the message "mx is zero and the model will not run" is printed on the screen. Or if the damping ratio is low then a warning about the model tending to oscillate is given. After check is finished, a summary of the number of possible problems is given. Check does not correct any of these problems. If the user desires to correct the problem, the values of parameters can be changed using the modify option from the main menu. (module: CREATE.C)

4.2.5 SHOW OPTION

This option from the main menu allows the user to view stick model parameters on the screen. The user can view the working model, retrieve a model from disk into the working model and view it, or copy a model from an auxiliary model into the working model and view it. (module: FFS.C)

4.2.6 MODIFY OPTION

This option from the main menu allows the user to modify existing models. The user must either modify the working model, load a working model and modify it, or copy a model from the auxiliary models into the working model and modify it. Once one of these options has been selected, the user can select the channel (x,y,r) to modify, and then the parameter. Once the user has modified all the desired parameters, they can exit by selecting the 'back' option. They are then asked to enter a name for the stick model so it can be saved to disk. The user is also given the option to check the model at this point. Afterwards control is returned to the main modify menu, where the user can then back up to the main menu. (module: FFS.C & CREATE.C)

4.2.7 LOAD OPTION

The load option allows the user to load 100 different stick models into memory and store them in an array. These are known as auxiliary models and the user has the option of checking (see sec. 4.2.4) each model as it is loaded. If the user does not wish to spend the time selecting models it is also possible to load up to 100 default models from this menu. The default models are stored on disk as mod1 through mod100, and are **not** checked as they are loaded. The purpose of this function is to allow easy switching between models in flight. Actuation of a set of switches will automatically remove the running model and replace it with the selected auxiliary model. (module: FFS.C)

4.2.8 RUN OPTION

From the run menu it is possible to either implement the working model (the last model loaded into memory) or turn one of the auxiliary models into the working model, then implement it. There is also an option to run the isometric stick at this point if so desired. (module FFS.C) The actual implementation routine for stick models is located in FEEL.C, which forms a component of a separate program which is called by the user interface.

4.2.9 OPTIONAL PROGRAM CONTROL

The program has provisions for program control by other methods than the keyboard. While a model is running it is possible to switch to another auxiliary model by selecting a combination of seven discrete switches which is interpreted by the program as a binary input. By selecting a combination which is the binary equivalent of a specific model number, then this model will be loaded and implemented. It is also possible to add an "x" as a command line argument when starting the program, such as by typing "ffs x". This has the effect of immediately loading the default models and implementing the last model loaded. The program can then be controlled normally from this point. The benefit of this is a quick start up in cases where it is not desired to have complete control over the force feel system. This line could even be added to the regular start up routine for normal flight operations.

4.3 SYSTEM IMPLEMENTATION

4.3.1 SOFTWARE MODELING

The software uses the dynamic equations of motion presented in chapter 2 to calculate stick position from pilot applied force. The non linear elements are handled by the use of if/then statements in the code, since they only apply under certain conditions. for example, to incorporate the throw limits:

IF calculated position > tl

THEN calculated position = tl and calculated velocity = 0

A schematic diagram of the decision structure is shown in Fig. [4.2]. Only one channel is portrayed because the structure is the same for each channel.

The isometric stick is implemented by commanding the neutral stick position, and then sending the pilot force input to the flight control computer. Thus the implementation of the isometric stick is much simpler than the regular feel system.

4.3.2 TRIM SYSTEMS

The function of the trim system is to allow a constant input to be entered by the pilot to hold the aircraft in trim during different phases of flight. In the case of the feel system, the trim function has the effect of changing the spring datum position and thus when the stick is released it will rest at a position with a constant offset from centre. The centre is simply the position where the feedback signal has a value of zero volts.

The cyclic trim system is handled in two ways. The pilot can depress the force release button, removing the spring gradient force. Then the stick is moved to the desired

trim position and the button is released. This position is the new spring datum position. The software handles this by storing the stick position the instant the button is released and uses this as the offset from centre. The second method that can be used for cyclic trim is by way of the "coolie hat" switch. When this switch is pressed the spring datum position is changed at a user specified rate (in in/sec) in the direction that the switch was pressed. The user specified rate is one of the parameters set in the stick model and is usually of the order of 0.5 in/sec. The location of these switches can be seen in Fig. [2.1].

Pedal (yaw) trim is also handled by considering the spring datum position as an offset from centre. However, the amount of offset is set by a thumb wheel on the collective control, as in Fig. [2.1]. The voltage change from centre is detected by the system and the offset is this change multiplied by a user specified gain. This gain is one of the parameters set in the stick model. Note that the trim systems in no way affect the location of the throw limits, as their position is relative to stick and pedal centre. However, the notch is modeled to be around the spring datum position and thus will move as the system is trimmed. The modeling was done this way to satisfy the requirements of the research staff at the FRL, and is based on the behaviour of standard mechanical feel systems installed in production helicopters.

When placed in the trim position, the trim/operate switch will force the stick to the neutral position. At this point the location of the neutral position of the stick and pedals may be manually changed by using the coolie hat or force relief button. This has the effect of summing in a constant voltage with the feedback potentiometer signal, thus changing the stick position where the feedback signal and the datum position sum to a value of zero volts.

This function affects the absolute zero position of the stick and pedals, and thus will also affect the location of software throw limits. The strain gauges may also be zeroed when the system is in trim, to ensure that the force readings from the strain gauges are accurate. When the switch is returned to the operate position, normal operation will resume.

4.3.3 INPUT AND OUTPUT

Output from the computer is required in the form of voltages to drive the servo system. This was achieved through the use of the digital to analogue (D/A) converter board installed in the VME. Input voltages must also be sensed then converted to engineering units such as lbf or inches so that position and force input values can be used by the model at each iteration. As well the state of the various discrete function switches must also be input to the VME. These functions are performed by the analogue to digital (A/D) converter board installed in the computer.

In order for these boards to work with the VME, software drivers must be written for them, and a shell program created to utilize these boards. The rest of this section will describe the system that was designed and implemented by Louis Bolduc, the resident FRL programmer, to perform this function. This part of the system was designed by FRL staff so that all the computing systems installed on the Bell 205 Airborne Simulator and ASRA would have the same system for handling input and output. This would allow consistency between the systems for ease of software upgrades, and for lower training times for FRL staff as familiarity with one system of input/output means familiarity with them all.

The program ACS (Airborne Computing System) controls the input and output functions. This program reads in a configuration file which contains the location and name of the drivers for the A/D and D/A boards. The configuration file also supplies information about location of shared memory, variable names, and cycle iteration. A sample configuration file is given in Appendix A.

The ACS program will update the input and output buffers once per program cycle. The output of each cycle is written to one of three variables, XCOM, YCOM, or RCOM. These represent D/A channels 0,1 and 2 respectively. It is the job of ACS to ensure that the value contained in these variables are sent as a voltage down the appropriate D/A channel.

The input for each cycle is controlled by the calibration file. The calibration file contains variable names as a function of a specific A/D channel. A sample calibration file is shown in Appendix A. It is the job of the ACS program to ensure that the value in a particular variable reflects the engineering value of a particular parameter such as pilot force. Since the line voltages are proportional to real world parameters, the engineering value is found by multiplying by and adding constants to the line voltage of a particular A/D channel, as specified in the calibration file.

4.3.4 PROGRAM OPERATION

Program operation begins with the calling of the user interface by typing 'fts' at the command line. The user may then use any of the options offered by the user interface. After a working model has been loaded into memory, the user may select to run the model. To run the model, the user interface first saves the working model to disk as a file named

'wkmod'. It then calls ACS which loads the appropriate configuration (FEEL.CFG) file. The configuration file tells ACS which calibration file (FEEL.CAL) to use and what the iteration file (FEEL) is called. ACS sets up the shared memory where variable values for input/output are stored.

The program FEEL contains two main functions. The first function is called `feel_init` and is the initialization function. This function is only called once at the beginning of the run and is used to initialize variables and to load the working model parameters from 'wkmod' off the disk. The function `feel_iteration` is called once each cycle by ACS and contains the software that calculates commanded position from pilot input force. It also contains the trim functions and procedures to pass data to the FCC. Initially the code in `feel_iteration` will send the stick to the neutral position for 0.5 secs before beginning operation. This gives an indication to the pilot as to where the neutral position is so that it may be changed by the method stated in sec. 4.3.2 if this position is not acceptable. ACS also has one other function and that is to control the program timing. The A/D board has an accurate real-time clock which is used to send a signal to ACS at 600 Hz. After receiving each pulse, ACS will update the analogue input variables, call `feel_iteration`, wait until `feel_iteration` is finished, then update the D/A command signals. The ACS program will then sleep until the next clock pulse.

Meanwhile, the user interface will have connected to the shared memory and checks every 0.15 seconds the state of the system break switch. If the switch is not depressed then the system continues as normal. However, if the break switch has been depressed then the model switching procedure begins. First the user interface will read the state of the model

selection switches, and convert their binary state to a decimal model number and if the model number is zero, control is returned to the run menu of the user interface. If the model number is not zero but no stick model has been loaded into that particular auxiliary model number then control is also returned to the run menu. However, if this auxiliary model does exist, it is copied to the working model and then implemented.

4.4 FORCE FEEL SYSTEM PROGRAM TESTING

4.4.1 METHODOLOGY

The force feel system program was tested to eliminate any errors in the programming code. This was accomplished in two steps. The first involved modifying the code to include a pilot forcing function equivalent to the 0.25 rad/sec frequency, 2 lbf peak pilot input used with the Simulink model. The code was also modified to store the output position vs. time vector on disk. Next, this computed position output was plotted against the Simulink results for equivalent stick models. Other parameters between the two models were also kept the same for consistency. These included using similar integration schemes and the same time step of 0.005 secs.

The test cases selected for comparison were chosen from each category of response type with the addition of various non-linear elements. To simplify the process, sensor and servo models were excluded, as well as sine inputs and sensor noise. Since the simulations indicated these elements had little effect on system stability, it is felt that this approach is valid.

4.4.2 COMPARISON WITH SIMULINK RESULTS

The correlation between the two models was extremely good. The first test cases selected were linear inner model cases and thus no non-linearities were present. Figs. [4.3], [4.4], [4.5] and [4.6] show these cases, and it is clear that both Simulink and the feel system program produced identical results.

Figs. [4.7] and [4.8] show the results of a comparison between the Simulink model and the FFS program when the nonlinear throw limit element is added. In fig. [4.7] where the position hangs up on the throw limit for the complete cycle, the output of the Simulink model is nearly identical to the FFS program output. However, in fig. [4.8] there is a slight discrepancy between the two. After striking the stop, the stick velocity is set to zero, thus the stick position should fall immediately to a steady state value of 7.5-in ($k=1$ lbf/in) just below the throw limits. This behaviour is exhibited by the FFS program and was verified using a spreadsheet to perform a manual check. However, the Simulink model hangs on to the throw limits for approximately 4 secs before dropping to the appropriate steady state value. The reason for this lag in response is unknown. Manually checking of differences between the Simulink results and the controller code is here, and in other cases, to verify which system was producing the correct result. This was performed by entering the dynamic equations of the system in a spread sheet and integrating manually, using the trapezoid rule. The result was then compared to the controller code and Simulink output to determine which was correct.

Next the effect of model switching is compared, and fig. [4.9] shows the result with a notch size of 4-in. The correlation between the models is excellent and the position traces are nearly identical.

Comparisons for the breakout force cases are shown in figs. [4.10] and [4.11]. Examination of the 1 lbf breakout case in fig. [4.10] shows remarkably similar position traces between the two models, however slight discrepancies do exist. The FFS program produces a nice square waveform for this case with an amplitude of 8-in, which is how the model is supposed to react, as verified by manual computation. However, the Simulink model exhibits a slightly higher steady state value with an overshoot spike at the leading corner of the waveform. These differences are caused by the manner in which the Simulink system was modeled. If the position goes past the throw limits then the position is equal to the throw limits. The spike is caused by the position jumping from just before the throw limits (tl) to well past the throw limits in one cycle, at which point the position for the start of the next cycle becomes equal to the throw limits. Then the force calculation is done and a new position calculated. This will be slightly greater than the throw limits because the applied force is in that direction. Since this is greater than tl, the position is set equal to tl for the start of the next cycle. This condition repeats itself until such time as the applied force reverses. Thus the steady state position output is slightly higher than the throw limits. The FFS program, however, uses if/then logic that states if the commanded position is greater than the throw limits then the commanded position is equal to the throw limits. Thus the position output does not overshoot the throw limits, and the steady state value is equal to tl, as it should be.

Fig. [4.11] shows a comparison for the 3 lbf breakout force case. Both models exhibited limit cycle behaviour as was verified by manual calculation on a spreadsheet. The only difference between the two is that the FFS program does not exceed the throw limits whereas the Simulink model does, for reasons listed in the previous paragraph. However, it must be noted that although discrepancies do exist, both models predicted the same response type.

Fig. [4.12] show a comparison of the results for a model with 1 lbf static friction. The position traces are very similar but again the FFS program gives a steady state value of 8-in which is equal to the throw limits while the Simulink steady state value is slightly greater. This is for the same reasons as outlined previously. Fig. [4.13] shows the two responses for a case with 3 lbf static friction. In this case the FFS program shows the position locked on the throw limits because the applied force cannot overcome the static friction. This is the correct response. However the Simulink model clearly did not handle this case well. For an explanation of the Simulink model response, please see sec. 3.2.3, ref. fig. [3.33]. One might wonder why the position of the FFS model even moves from neutral since the static friction is greater than the applied force. This is because for this case, no static friction was applied in the notch, so the stick would have until the edge of the notch to build up enough velocity to carry it to the lower throw limit, even with the opposition of kinetic friction.

Fig. [4.14] shows an example of a mathematically acceptable response with no spring gradient and very low damping. Again the overshoot of the throw limits and the slightly higher steady state value are evidenced in the Simulink response. Fig. [4.15] shows

another mathematically acceptable response case where both the spring gradient and the damping ratio are equal to 1.0. Here the Simulink model shows a slower rise time to the steady state value than did the FFS program. The reason for this discrepancy is unknown, however the FFS program is exhibiting the correct response as this was verified manually using a spreadsheet.

The next comparison, shown in Fig. [4.16] is for a highly damped response case. The most noticeable difference between the models is the wedge shape formation appearing in the FFS model. This is caused by the presence of the notch around the zero position where the system mass is lower and there is less damping. Therefore there are higher accelerations in the notch and the wedge shaped position trace is formed. This is the correct response and was verified by manual calculation. Why this notch effect is not apparent with the Simulink model is unknown.

Fig. [4.17] exhibits a case where Simulink predicted a divergent response and the FFS program predicted a square wave position trace. The square wave response was verified by manual calculation and the reason for the divergent response of the Simulink model is as explained in section 3.2.2. The reason that the controller code did not diverge is because of the manner in which the throw limits are handled. While the Simulink model will calculate a position that is past the throw limits for one discrete step and then bring the position back to the value of tl , the controller code holds the value at the throw limits and will not let the system go past this value, even for one discrete step. Also, velocity and acceleration are set to zero upon striking the throw limits, and hence the divergent response is prevented. When the Simulink model for this case was run with a smaller ϵ by 2 orders of

magnitude) time step then a similar square waveform to that of the FFS program is exhibited in the response, and thus the problem is numerical.

Fig. [4.18] shows a case of overshoot with oscillation, and the correlation between the two models is excellent.

4.4.3 CONCLUSION REGARDING COMPARISON

The comparison between the FFS code and the Simulink model served to verify that the modeling of a real world mechanical force feel system is accurate. Two different methods of simulation were used and both arrived at nearly identical results for most cases when tested. The discrepancies that did exist between the two models are attributed to small errors in the Simulink model which did not handle some of the non-linearities very well in some of the selected cases. The FFS code was shown to be correct through manual calculation, and thus it is known that the errors are in the Simulink model.

The cases involving no non-linearities produced identical results between the two models. It should be noted that most of the discrepancies between the two models occurred in cases involving worst case conditions. These cases are characterized by models with low mass, high accelerations, abnormally large values of static friction or breakout force, or had either very high or very low damping. These are fringe cases that would almost never be implemented in the helicopter because they could produce controllability problems.

The Simulink model does predict the system response type with great accuracy, and should be considered conservative. In no case did the Simulink model predict a good response when the FFS code indicated a non-acceptable response. Therefore, the Simulink

model is useful for testing suspect stick models before implementing them on the helicopter, so that the pilot or engineer can have an indication of how the stick will react before setting it up to run.

Although the Simulink model could likely be modified to remove the discrepancies between the two models, the amount of time required to do this is not warranted. The Simulink model produces an excellent indication of system response for most cases, and the cases where discrepancies occurred are rarely, if ever, going to be used in the Airborne Simulator. Thus the extra work is not justified, and the time would be better spent perfecting the system upon installation in the Bell 205.

CHAPTER 5: PROGRAM IMPLEMENTATION AND EVALUATION

5.1 IMPLEMENTATION

The VME hardware for the force feel system was installed in the aircraft in January of 1996. A picture of this installation is given in Fig. [5.1]. This process involved several modifications to the aircraft including a significant amount of cabling and rewiring. The chassis, which includes the processor, A/D, D/A boards, power supply and disk drives was bolted into a steel rack. This rack was then attached to the airframe through shock mounts that lower the vibration levels as seen at the computer. As well, the feel system control panel had to be redesigned to include model and program control switches on top of the engage and strain gauge balancing functions. A picture of the new control panel is given in Fig. [5.2]. This panel is the sole source of feel system control in most flights. Unless complete control of the feel system is required through the cockpit terminal during certain experiments, the system is run in the hands-off mode where default models are loaded and the system is run automatically. At this point the switch in the top left corner of the control panel is placed in trim, and the large square engage button is pressed to allow hydraulic fluid to flow into the actuator. The stick will then move to the centre position. Next the small black switch located at the top of the panel between the ammeter and the analog potentiometers is depressed. This activates a sample and hold circuit that removes most of the bias from the strain gauges. Next the rotary switch on the far right of the panel is used to select each channel in turn, and using the corresponding potentiometers, final biases in

the strain gauges are removed using the ammeter as an indication of the balance. When zero amps are reading at the meter, then the gauges are balanced. Once the balancing process is complete, and binary pattern is set in the toggle switches across the bottom of the panel, which represents the desired model number. Next the large black push button switch to the left of this row is pressed to load and implement the desired model. The desired model is now ready to be used and can be activated by moving the switch in the top left corner from the trim position to the operate position.

5.1.1 CALIBRATION OF SYSTEM INPUTS AND OUTPUTS

Calibration of the system was performed using accepted standard techniques and essentially consisted of determining the relationship between sensor output and the physical engineering parameter it is measuring. Strain gauges were calibrated by using hydraulics to hold the stick in an upright position and applying varying levels of force to the grip, inside which the strain gauges are located (ref. Fig. [2.14]). Force was applied in lbs, and measured using a Hunter Spring mechanical force gauge, which was considered accurate enough for this purpose. For each level of applied force, the raw bit reading from the A/D converter was recorded. These were then plotted, and Matlab was used to perform a linear curve fit to the data. The results of this process, for all three axes is shown in Fig. [5.3]. Although a higher order polynomial would have fit the data better, there are several reasons for using a first order fit. These include:

- 1) Strain gauges are generally calibrated using a first order fit.
- 2) Increase in accuracy does not warrant increased computation time.

- 3) It was felt that the increase in accuracy was within the error uncertainty inherent in the calibration process.
- 4) The force gauge only measured up to 30 lbf, and higher pilot inputs are anticipated. It is easy to confidently extrapolate a first order fit, yet it is uncertain how higher order fits will behave when extrapolated. This could be tested, but in light of the above, the work was not justified.

The position sensor calibration was performed by commanding a voltage through the system, and then measuring the distance traveled by the grip from an arbitrary datum. For reasons similar to items 1-3 above, a first order fit to the position data was also used. The results of this calibration, in all three axes, is presented in Fig. [5.4].

5.1.2 OPTIMIZATION OF PERFORMANCE

Testing of the actuator/servo system revealed that the servo gain could be increased high enough to achieve a 60 rad/s bandwidth without instability or hardware problems. This is a factor of three over the original analog system where the system would go unstable if an attempt were made to raise the bandwidth above 20 rad/s. This improvement is reflected in Fig. [5.5], a Bode plot of the servo response at high gain. The increase in bandwidth was ideal as it meant that a much wider range of stick models could be implemented and would be accurately reflected at the stick.

However, it was found that when using this gain in conjunction with stick models that a roughness problem developed. The stick no longer felt smooth when in operation. In order to remove this problem the servo gains had to be lowered to such a level that the achievable performance was reduced to 30 rad/s in the longitudinal channel, 34 rad/s in the lateral channel, and 41 rad/s in the pedals. These are still healthy increases over the original

system, and are reflected in the closed loop Bode plots, Fig [5.6] through [5.8]. The bandwidth as quoted here is based on 90 degrees of phase lag.

5.2 EVALUATION

The purpose of the system evaluation was to ensure that the programmed models were reflected in the output of all three axis. It also verified the accuracy of the calibration procedure, as well this procedure confirmed how the new system removed the problems inherent in the analog system. First ground testing was performed to verify steady state values of position for various force gradients and input forces. Secondly, a number of models were frequency swept and the bode plot of measured values of position for force input was compared to the theoretical. Thirdly, recorded time histories for several models were compared to the Simulink simulation output. The final stage of evaluation involved flight testing to determine the effects of vibration and flight loads. At this point questions of ergonomics were raised and minor code changes performed in order to make the system more user friendly. This section will finish with a discussion of how this system is improved over the analog system.

5.2.1 VERIFICATION OF STEADY STATE RESPONSE

Steady state response can be verified by comparing the theoretical position to the measured position for a set of test cases. For this purpose, three different spring gradients were chosen, and three values of force were applied to each. Only spring gradient need be specified because steady state response is a function of this only. However, for ease of

testing a well damped model was chosen to prevent oscillations around steady state that would make measuring difficult.

The test matrix used is outlined in Table [5.1] along with the measured results for each separate axis. Due to the simple nature of the test, this fairly limited test matrix was deemed adequate to verify the correct operation of the model. The measuring was done using a decimal inch scale and the conditions dictated that accuracies greater than 0.05 inches was not possible. The results presented in Table [5.1] show that in all cases the measured was within 0.05 inches of the theoretical. This serves to show that the calibration procedure was accurate to within 0.05 inches, which is deemed acceptable for this system.

5.2.2 FREQUENCY DOMAIN TESTING

To verify the correct operation and to determine the quality of the model following of the system, nine discrete linear models were tested and subjected to frequency domain analysis. The analysis involved comparing the theoretical Bode plots created in Matlab for six cases to the experimental Bode plots calculated using fast Fourier transform techniques with position and force data acquired using the Airborne Simulator's data acquisition system. The other three cases involved performing a power spectral density (PSD) analysis on the flight test data and comparing the resulting experimental natural frequency to the theoretical natural frequency calculated using equations from section 2.23. It is important to note that the Matlab theoretical analysis here is performed using linear transfer functions and does not involve the Simulink model which contains some errors. The frequency domain test matrix used is given in Table [5.2].

The results of the frequency domain tests are presented in Fig. [5.9] through to Fig. [5.17]. For the Bode plots, the amplitude ratio was normalized to 0 dB in each case to remove the DC offset. This was to allow an accurate comparison of the shape of the plot which is far more important than the DC offset. Differences in offset were caused by calibration errors, differences in calibration between the data acquisition system and the force feel system computers, and the scaling of output. The shape of the curves will reveal match in break points and the slope of the roll off which will indicate the quality of the model following. In some cases the phase curves had to be shifted by 180 degrees to account for sign differences. In fig.[5.9] a breakdown in the FFT computation after 10 rad/s which was indicated by a low value of the coherence function (not presented in this figure) caused the phase to diverge.

In each of the six Bode plots an excellent match between the amplitude ratio curves is exhibited. The phase curves, however, all show increasingly higher lags with the experimental data when compared with the theoretical at higher frequencies. This is a result of working with real hardware and can be attributed to two causes. The minor portion results from digital computational delay, which is a pure time delay. The major portion is caused by the fact that the model is actually in series with the servo/actuator system, which in itself can be modeled as a second order system. The good match in amplitude ratio was possible because as can be seen in Fig. [5.6] through to Fig. [5.8] the servo/actuator systems have a flat amplitude ratio curve out to the frequencies of interest. However, the phase curves are already lagging at these frequencies, and this lag must be directly added to the model lag and thus accounts for the majority of the error. However, the discrepancy in phase is not excessive and is to be expected when working with real hardware. FRL staff

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have deemed that this is acceptable for the Airborne Simulator's feel system, as it is still much improved over the analogue system.

The three PSD analyses have shown a reasonable match between the experimental natural frequencies and the theoretical. For tests 3 and 6 the experimental is 0.5 - 1 rad/sec less than the theoretical. For test 9 the match is much better, and this slight difference is attributed to the fact that a small amount of damping was required to keep the system stable, as strain gauge noise would cause the stick to thrash otherwise. Therefore the stick would not exhibit the undamped natural frequency because damping was present. This, however, can be calculated from:

$$\omega_d = \omega_n \sqrt{1 - \zeta^2}$$

and it was found that although this would account for the entire discrepancy between theoretical and experimentally measured natural frequency for test 9, it only accounted for approximately 20% of the error in tests 3 and 6. Upon revisiting the raw data, it was found that unlike test 9 which had a long stream of smooth oscillations, for tests 3 and 6 more damping was present. This required the oscillations to be manually excited and free oscillation would occur for only 2-3 cycles. This was likely not enough data for the FFT to accurately display the natural frequency. This poor quality of the data is apparent in the height of the peaks of the PSD. In test 9 the peak rises 60 dB at the natural frequency and the analysis clearly determines this quantity effectively. For tests 3 and 6 the strength is only 20-30 dB and the analysis suffers from the poorer data, which accounts for the larger discrepancy between the theoretical and experimental values. It is certain that if these tests

were redone, better results could be obtained. However, this is not possible due to the operational requirements of the aircraft at this time.

5.2.3 TIME DOMAIN TESTING

Time history comparisons between the Simulink model output and the recorded stick position were performed in order to verify the operation of non-linear portions of the model. Four stick models were chosen, each with emphasis on some highly non-linear elements. The models chosen are given in Table [5.3]. The input function for testing was the force time history recorded using the Airborne Simulator's data acquisition system. This was fed to the Simulink model by way of a look-up table.

The results of these comparisons are presented in Fig. [5.18] through to Fig. [5.21]. At first glance it may seem that the match between the theoretical and experimental is not very good. However, it is the shape of the curves that is of most importance and these match quite well, and serve as a final check that the system is operating correctly. The shape was considered to be of greater importance because the magnitude was not expected to match well. The differences that exist between the theoretical and experimental data can be attributed to three main causes.

The first cause involves the data acquisition system. This component is completely separate from the feel system and contains its own force and position calibration curves. These calibrations are different from the ones used in the feel system and would cause different position and force time histories to be recorded than is being used by the feel system for computation. This difference is most apparent in discrepancy between hardstop locations such as in Fig. [5.18], and is the major cause of discrepancy between the curves.

Although it should be possible to remove this effect from the comparison as both calibrations are known, it is not this simple. The location from which the force and position signals are sensed is different between the systems. The data acquisition system senses these quantities after they have undergone signal conditioning which also scales the data, whereas the FFS uses the unconditioned signal, and thus this effect is not easily removed and would involve rewiring and recalibration.

The second cause for the discrepancy involves the use of force trimming. The feel system computer dynamically signal cancels force biases while in trim so that zero force will be read at the stick when the pilot is hands off. The data acquisition system relies solely on the analogue initialization to remove bias and thus is not as accurate and will tend to drift. Therefore the force fed to the theoretical model will be slightly different from that used by the feel system computer, and will cause discrepancy between the curves. This effect is most apparent in the first 3 seconds of Fig [5.19]. Here the experimental line is flat as no force is being applied while the theoretical curve has a slope indicating the presence of a force bias. This would also contribute to some of the small discrepancies in curve shape.

The third cause of the difference between the curves would most likely be responsible for most of the small differences in curve shape. It had been shown previously in sec. 4.4.2 and 4.4.3 that the Simulink model did not handle some of the non-linearities as well as the controller code does. This could manifest itself as problems in correlation between the time histories.

5.2.4 FLIGHT TESTING

Several flight tests were performed using the system to determine the operational suitability of the system. The first two flight tests revealed two major points. The first was that the system performed well despite the vibration rich environment and it was unaffected by flight loads. The second was that it had some major problems with regards to the ergonomics of operation. This led to the conclusion that although the system performance was good, it could not be considered operational until it could be made easy to use in daily operation. Thus some fairly extensive code modifications were made to facilitate a more user friendly pilot/machine interface.

Some of the more major changes included not stopping the control process when changing between auxiliary models and the sensing of when the hydraulics were engaged. This prevented the stick from wandering over to one side which occurred when hydraulics were engaged but the outputs to the hydraulic servo valves were floating because the controller process had shut down to change models. The sensing of hydraulic pressure prevented the system from thrashing upon re-engagement which was caused by the growth of the error signal as the stick moved away from the desired position because there was no hydraulic pressure to send it there. Upon re-engagement the large error signal would cause the stick to thrash, which is a potentially dangerous situation because the actuators supply up to 1120 lbf to the stick assembly. There were also some other more minor changes that removed some small annoyances in the system such as in the manner in which some trimming functions were used and also the way in which changes to change the stick's

absolute centre position (which unlike normal trim will affect the position of the throw limits) were made.

Final flight testing revealed that the system was ergonomically pleasing and could be considered completely operational for flight use. Evaluation by Murray Morgan, the Flight Research Laboratory's helicopter facility manager indicated that the FRL staff involved with helicopter research were pleased with the new system and were happy to accept it as part of the Airborne Simulator research platform. The final stage of the project involved the removal of the analogue chassis and associated hardware, an indication of the finality of this change.

5.2.5 CONFIRMATION OF SYSTEM IMPROVEMENT

In conclusion to this chapter, a discussion of how the digital force feel system has removed the problems associated with the original analog system is appropriate. These problems include performance, repeatability, usability, reliability, low frequency drift, and accuracy. Each of these will be discussed separately.

The performance improvements resulting from the implementation of the digital system were presented earlier in this chapter. These will be summarized here, in terms of closed loop bandwidth for the servo/actuator system. The analog system had a bandwidth, based on 90 degrees of phase lag, of approximately 20 rad/sec. This was raised to 30 rad/sec longitudinally, 34 rad/sec laterally, and 41 rad/sec in the pedals through the implementation of the digital force feel system.

Repeatability of stick models was a problem with the analog system stemming from the manner in which stick models were programmed. Parameters were set using analog

potentiometers and it was impossible to either set exact values of system parameters or to repeat a set of system parameters. This was because the voltage levels used to signify a given parameter could never be set with confidence and thus the value that was desired could not be realized and would change with time. However, with the digital system, exact values of system parameters are entered in numerical form using engineering units, and thus the accuracy with which these values are reflected at the stick are determined by the accuracy of the calibration. Repeatability is ensured because these exact values are stored in digital format and can be reloaded as desired. As well, the slope of the calibration curves is constant and will not change. The intercept of these curves might change slightly but this effect is removed by the controller code which captures this value and removes the bias internally while the stick is in trim.

The user interface with the analog system was poor in that to change a stick model the entire array of analog potentiometers, one for each parameter and each channel, would have to be changed. This was time consuming and difficult to perform in flight. The new system allows models to be changed by using a set of switches that makes in flight control quick and simple. Thus the usability of the digital system is much improved over the analog system.

The original system was over 30 years old and consisted of large numbers of analog components. The system was also famous for breaking down at the most inopportune times, such as immediately prior to or during an important experiment. The large analog component count made tracking down the fault and fixing it difficult and time consuming. However, the digital system has a low component count, and thus tracking down the location of the problem is simpler. As well, fixing the problem is just a matter of removing

and replacing the defective component. Changing an A/D board is far easier than removing and re-soldering an operational amplifier onto a circuit board. Therefore, the reliability of the digital system is much enhanced over that of the analog system.

The low frequency drift of the original system was a function of the high number of analog components such as operational amplifiers. Using high quality components with tight tolerances aided in reducing this, however with so many wired in series and parallel, the effect of low frequency drift was magnified. As digital computers do not drift, the only source of this problem for the new system would be in any analog components still required for the operation of the force feel system. Thus to reduce drift it is desirable to eliminate all analog components, however, this was not possible as some functions could only be performed with analog components. However, it is possible to compensate for much of this drift. Strain gauge signal conditioning requires operational amplifiers to increase the signal strength from the gauges to a level that is within the resolution of the analog to digital converter board. Strain gauges are the major source of drift in the new system, however, the feel system code is designed to determine and remove any force bias in the system while it is in trim. The system is always forced into trim when switching between models, and thus any force bias is removed whenever a new stick model is loaded. Other minor sources of drift would include the amplifier used in the feedback potentiometer circuitry and the current driver board. Drift in the feedback amplifier may change the center location of the stick, but if this is a problem for the pilot he/she can change this location easily to account for this. However, this drift would likely be imperceptible. Drift in the current drive board may affect the gain on conversion of output voltage to current, thus changing the inner loop servo system gain. However, this change would again be imperceptible. The major

problem with drift in the analog system were amplifiers that would affect the values of stick model parameters. This has been eliminated in the digital system as none of the above mentioned sources for drift in the digital system can affect system parameters, and thus the drift problem has been reduced to a level where it can almost be discounted.

In conclusion to this section is a discussion of the accuracy of the system, i.e. how well is the programmed model actually reflected at the grip? As drift can be discounted, then the accuracy can be considered to be time invariant. Therefore the accuracy of the system is completely determined by the accuracy of the calibrations and the limitations of the servo-actuator system. If the model bandwidth is kept well below that of the servo-actuator system (30 rad/s) as most of the model bandwidths will be, then the servo-actuator system will only add a small amount of phase lag to the model which can be considered insignificant for most experiments. Thus the accuracy of the system can effectively be tied solely to the accuracy of the sensor calibrations. Position is accurate to within 0.05 inches and force to within 0.5 lbf. Both of these are the smallest values that can be determined with the calibration equipment, and thus any greater accuracy would require different methods of measuring actual force and position. However, staff at the FRL have determined that this level of accuracy is adequate for the types of experiments that will be run using the system.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

This chapter covers the conclusions that can be drawn from the implementation of the digital force feel system, and also gives some recommendations for future research and development.

6.1 CONCLUSIONS

- 1) Digital control of a high speed mechanical feel system powered by hydraulics is technically feasible.
- 2) The quality of the model following was good when comparing theoretical to measured quantities.
- 3) The digital feel system has solved many problems associated with its analogue predecessor including low frequency drift, high gain instability, usability and repeatability of stick models.
- 4) The system has proved easier to use than the analog system and more reliable. Increased user confidence and greater performance have both been realized.

6.2 RECOMMENDATIONS

The work performed on the Bell 205's feel system has revealed some areas for improvement of the design when considering a next generation feel system on the NRC Bell 412 Advanced Systems Research Aircraft (ASRA). Consideration of the following will

give much improved performance when developing a second generation digital feel system for ASRA. The use of aluminum for stick and pedal structure instead of steel, as well as the use of lighter plastic for the grip material, will result in a mechanical system with less overall mass. This will increase the bandwidth of the system and improve the overall performance. The ASRA fly-by-wire actuators are designed to run using a 3000 psi hydraulic system and it is therefore natural to use the same working pressure for the feel system. This has the advantage that smaller actuators can be used to develop an equivalent amount of force as is used in the Bell 205. Smaller actuators again have less piston mass and thus will also improve the bandwidth of the system, while at the same time requiring a smaller flow rate from the hydraulic system thus preventing large pressure drops because of increased demand flow. One further area of improvement would involve the use LVDTs instead of potentiometers for greater positioning accuracy. From some of the testing that was done, it appears that the smoothness problem which developed at higher gains and limited the bandwidth of the system may have been caused mechanical free play in the system and hysteresis in the linear potentiometers, where the brush must physically touch the outer case. LVDTs, however, are more accurate because they are an inductive device and no moving brush is in contact with the outer case. The use of LVDTs and tighter tolerances in the mechanical system will likely result in allowing for the use of higher loop gains, thus increasing the bandwidth of the system.

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TABLE 3.1: INITIAL PARAMETERS

MATLAB SYMBOL	PARAMETER	DIMENSION	RANGE	INITIAL VALUE
Cv	viscous friction	lbf/in/sec	0-5	0.5
k	spring gradient	lbf/in	0-10	1
m	mass	slug	0.0001-1	0.375
fs	static friction	lbf	0-10	0.5
frat	ratio kinetic/static friction	dimensionless	0-1	0.75
fb	breakout force	lbf	0-5	1
tl	throw limits	in	2-8	8
ns	notch size	in	0-0.5	0.25
Cvn	notch viscous friction	lb/in/sec	0-5	0.4
mn	notch mass	slug	0.0001-1	0.125
fsn	notch static friction	lbf	0-10	0.25
fratn	notch friction ratio	dimensionless	0-1	0.75
p	pilot force input	lbf	-0-50	2 (step, 0.25 rad/s frequency)

TABLE 3.2: PARAMETER VARIATIONS FOR SIMULATION

m (slugs)	k (lb/in)	C_v (lb/in/sec)
0.0001	0	0
0.001	0.0001	0.0001
0.005	0.001	0.001
0.01	0.01	0.01
0.05	0.1	0.1
0.1	1.0	1.0
0.5	5.0	3.0
1.0	10.0	5.0

TABLE 3.3: SIMULATION RESULTS - CRITICALLY DAMPED

mass (slugs)	k (lb/in)	Cv (lb/in/s)	ω_n (rad/s)	ζ	h/in	Cv/h	k/Cv	code	designation
0.0001	0.0001	0.00005	3.46410	1	1	0.5773	1.7320	a	crd1 y1
0.0001	0.001	0.00018	10.9544	1	10	1.8257	5.4772	a	crd1 y2
0.0001	0.01	0.00057	34.6410	1	100	5.7735	17.320	a	crd1 y3
0.0001	0.1	0.00182	109.544	1	1000	18.257	54.772	a	crd1 y4
0.0001	1	0.00577	346.410	1	10000	57.735	173.20	d	crd1 y5
0.0001	5	0.01290	774.596	1	50000	129.09	387.29	d	crd1 y6
0.0001	10	0.01825	1095.44	1	10000	182.57	547.72	d	crd1 y7
0.001	0.0001	0.00018	1.09544	1	0.1	0.1825	0.5477	a	crd2 y1
0.001	0.001	0.00057	3.46410	1	1	0.5773	1.7320	a	crd2 y2
0.001	0.01	0.00182	10.9544	1	10	1.8257	5.4772	a	crd2 y3
0.001	0.1	0.00577	34.6410	1	100	5.7735	17.320	a	crd2 y4
0.001	1	0.01825	109.544	1	1000	18.257	54.772	a	crd2 y5
0.001	5	0.04082	244.948	1	5000	40.824	122.47	d	crd2 y6
0.001	10	0.05773	346.410	1	10000	57.735	173.20	d	crd2 y7
0.005	0.0001	0.00040	0.48989	1	0.02	0.0816	0.2449	a	crd3 y1
0.005	0.001	0.00129	1.54919	1	0.2	0.2581	0.7745	a	crd3 y2
0.005	0.01	0.00408	4.89897	1	2	0.8164	2.4494	a	crd3 y3
0.005	0.1	0.01290	15.4919	1	20	2.5819	7.7459	a	crd3 y4
0.005	1	0.04082	48.9897	1	200	8.1649	24.494	a	crd3 y5
0.005	5	0.09128	109.544	1	1000	18.257	54.772	a	crd3 y6
0.005	10	0.12909	154.919	1	2000	25.819	77.459	a	crd3 y7
0.01	0.0001	0.00057	0.34641	1	0.01	0.0577	0.1732	a	crd4 y1
0.01	0.001	0.00182	1.09544	1	0.1	0.1825	0.5477	a	crd4 y2
0.01	0.01	0.00577	3.46410	1	1	0.5773	1.7320	a	crd4 y3
0.01	0.1	0.01825	10.9544	1	10	1.8257	5.4772	a	crd4 y4
0.01	1	0.05773	34.6410	1	100	5.7735	17.320	a	crd4 y5
0.01	5	0.12909	77.4596	1	500	12.909	38.729	a	crd4 y6
0.01	10	0.18257	109.544	1	1000	18.257	54.772	a	crd4 y7
0.05	0.0001	0.00129	0.15491	1	0.002	0.0258	0.0774	a	crd5 y1
0.05	0.001	0.00408	0.48989	1	0.02	0.0816	0.2449	a	crd5 y2
0.05	0.01	0.01290	1.54919	1	0.2	0.2581	0.7745	a	crd5 y3
0.05	0.1	0.04082	4.89897	1	2	0.8164	2.4494	a	crd5 y4
0.05	1	0.12909	15.4919	1	20	2.5819	7.7459	a	crd5 y5
0.05	5	0.28867	34.6410	1	100	5.7735	17.320	a	crd5 y6
0.05	10	0.40824	48.9897	1	200	8.1649	24.494	a	crd5 y7

TABLE 3.3: SIMULATION RESULTS - CRITICALLY DAMPED

mass (slug)	k (lb/in)	Cv (lb/in/s)	ωn (rad/s)	ζ	k/m	Cv/m	k/Cv	code	designation
0.1	0.0001	0.00182	0.10954	1	0.001	0.0182	0.0547	a	crd6 y1
0.1	0.001	0.00577	0.34641	1	0.01	0.0577	0.1732	a	crd6 y2
0.1	0.01	0.01825	1.09544	1	0.1	0.1825	0.5477	a	crd6 y3
0.1	0.1	0.05773	3.46410	1	1	0.5773	1.7320	a	crd6 y4
0.1	1	0.18257	10.9544	1	10	1.8257	5.4772	a	crd6 y5
0.1	5	0.40824	24.4948	1	50	4.0824	12.247	a	crd6 y6
0.1	10	0.57735	34.6410	1	100	5.7735	17.320	a	crd6 y7
0.5	0.0001	0.00408	0.04898	1	0.000	0.0081	0.0244	a	crd7 y1
0.5	0.001	0.01290	0.15491	1	0.002	0.0258	0.0774	a	crd7 y2
0.5	0.01	0.04082	0.48989	1	0.02	0.0816	0.2449	a	crd7 y3
0.5	0.1	0.12909	1.54919	1	0.2	0.2581	0.7745	a	crd7 y4
0.5	1	0.40824	4.89897	1	2	0.8164	2.4494	a	crd7 y5
0.5	5	0.91287	10.9544	1	10	1.8257	5.4772	a	crd7 y6
0.5	10	1.29099	15.4919	1	20	2.5819	7.7459	a	crd7 y7
1	0.0001	0.00577	0.03464	1	0.000	0.0057	0.0173	a	crd8 y1
1	0.001	0.01825	0.10954	1	0.001	0.0182	0.0547	a	crd8 y2
1	0.01	0.05773	0.34641	1	0.01	0.0577	0.1732	a	crd8 y3
1	0.1	0.18257	1.09544	1	0.1	0.1825	0.5477	a	crd8 y4
1	1	0.57735	3.46410	1	1	0.5773	1.7320	a	crd8 y5
1	5	1.29099	7.74596	1	5	1.2909	3.8729	a	crd8 y6
1	10	1.82574	10.9544	1	10	1.8257	5.4772	a	crd8 y7

TABLE 3.4: SIMULATION RESULTS - INNER MODEL RESPONSE

mass (slug)	k (lb/in)	Cv (lb/in/s)	ω_n (rad/s)	ζ	k/m	Cv/m	k/Cv	code	designation
0.0001	0	0	0	#DIV 0!	0	0	#DIV 0!	a	sim11 y1
0.0001	0	0.0001	0	#DIV 0!	0	1	0	a	sim11 y2
0.0001	0	0.001	0	#DIV 0!	0	10	0	a	sim11 y3
0.0001	0	0.01	0	#DIV 0!	0	100	0	d	sim11 y4
0.0001	0	0.1	0	#DIV 0!	0	1000	0	d	sim11 y5
0.0001	0	1	0	#DIV 0!	0	10000	0	d	sim11 y6
0.0001	0	3	0	#DIV 0!	0	30000	0	d	sim11 y7
0.0001	0	5	0	#DIV 0!	0	50000	0	d	sim11 y8
0.0001	0.0001	0	3.46410	0	1	0	#DIV 0!	a	sim12 y1
0.0001	0.0001	0.0001	3.46410	1.732	1	1	1	a	sim12 y2
0.0001	0.0001	0.001	3.46410	17.32	1	10	0.1	a	sim12 y3
0.0001	0.0001	0.01	3.46410	173.2	1	100	0.01	d	sim12 y4
0.0001	0.0001	0.1	3.46410	1732.0	1	1000	0.001	d	sim12 y5
0.0001	0.0001	1	3.46410	17320.5	1	10000	0.0001	d	sim12 y6
0.0001	0.0001	3	3.46410	51961.5	1	30000	3.33333	d	sim12 y7
0.0001	0.0001	5	3.46410	86602.5	1	50000	0.00002	d	sim12 y8
0.0001	0.001	0	10.9544	0	10	0	#DIV 0!	a	sim13 y1
0.0001	0.001	0.0001	10.9544	0.547	10	1	10	a	sim13 y2
0.0001	0.001	0.001	10.9544	5.477	10	10	1	a	sim13 y3
0.0001	0.001	0.01	10.9544	54.77	10	100	0.1	d	sim13 y4
0.0001	0.001	0.1	10.9544	547.7	10	1000	0.01	d	sim13 y5
0.0001	0.001	1	10.9544	5477.2	10	10000	0.001	d	sim13 y6
0.0001	0.001	3	10.9544	16431.6	10	30000	0.00033	d	sim13 y7
0.0001	0.001	5	10.9544	27386.1	10	50000	0.0002	d	sim13 y8
0.0001	0.01	0	34.6410	0	100	0	#DIV 0!	a	sim14 y1
0.0001	0.01	0.0001	34.6410	0.173	100	1	100	a	sim14 y2
0.0001	0.01	0.001	34.6410	1.732	100	10	10	a	sim14 y3
0.0001	0.01	0.01	34.6410	17.32	100	100	1	d	sim14 y4
0.0001	0.01	0.1	34.6410	173.2	100	1000	0.1	d	sim14 y5
0.0001	0.01	1	34.6410	1732.0	100	10000	0.01	d	sim14 y6
0.0001	0.01	3	34.6410	5196.1	100	30000	0.00333	d	sim14 y7
0.0001	0.01	5	34.6410	8660.2	100	50000	0.002	d	sim14 y8
0.0001	0.1	0	109.544	0	1000	0	#DIV 0!	a	sim15 y1
0.0001	0.1	0.0001	109.544	0.054	1000	1	1000	a	sim15 y2
0.0001	0.1	0.001	109.544	0.547	1000	10	100	a	sim15 y3

TABLE 3.4: SIMULATION RESULTS - INNER MODEL RESPONSE

mms (slug)	k (lb/in)	C_v (lb/in/s)	ω_n (rad/s)	ζ	l/m	C_v/m	k/C_v	code	designation
0.0001	0.1	0.01	109.544	5.477	1000	100	10	d	sim15 y4
0.0001	0.1	0.1	109.544	54.77	1000	1000	1	d	sim15 y5
0.0001	0.1	1	109.544	547.7	1000	10000	0.1	d	sim15 y6
0.0001	0.1	3	109.544	1643.1	1000	30000	0.03333	d	sim15 y7
0.0001	0.1	5	109.544	2738.6	1000	50000	0.02	d	sim15 y8
0.0001	1	0	346.410	0	10000	0	#DIV/0!	d	sim16 y1
0.0001	1	0.0001	346.410	0.017	10000	1	10000	d	sim16 y2
0.0001	1	0.001	346.410	0.173	10000	10	1000	d	sim16 y3
0.0001	1	0.01	346.410	1.732	10000	100	100	d	sim16 y4
0.0001	1	0.1	346.410	17.32	10000	1000	10	d	sim16 y5
0.0001	1	1	346.410	173.2	10000	10000	1	d	sim16 y6
0.0001	1	3	346.410	519.6	10000	30000	0.33333	d	sim16 y7
0.0001	1	5	346.410	866.0	10000	50000	0.2	d	sim16 y8
0.0001	5	0	774.596	0	50000	0	#DIV/0!	d	sim17 y1
0.0001	5	0.0001	774.596	0.007	50000	1	50000	d	sim17 y2
0.0001	5	0.001	774.596	0.077	50000	10	5000	d	sim17 y3
0.0001	5	0.01	774.596	0.774	50000	100	500	d	sim17 y4
0.0001	5	0.1	774.596	7.745	50000	1000	50	d	sim17 y5
0.0001	5	1	774.596	77.45	50000	10000	5	d	sim17 y6
0.0001	5	3	774.596	232.3	50000	30000	1.66666	d	sim17 y7
0.0001	5	5	774.596	387.2	50000	50000	1	d	sim17 y8
0.0001	10	0	1095.44	0	100000	0	#DIV/0!	d	sim18 y1
0.0001	10	0.0001	1095.44	0.005	100000	1	100000	d	sim18 y2
0.0001	10	0.001	1095.44	0.054	100000	10	10000	d	sim18 y3
0.0001	10	0.01	1095.44	0.547	100000	100	1000	d	sim18 y4
0.0001	10	0.1	1095.44	5.477	100000	1000	100	d	sim18 y5
0.0001	10	1	1095.44	54.77	100000	10000	10	d	sim18 y6
0.0001	10	3	1095.44	164.3	100000	30000	3.33333	d	sim18 y7
0.0001	10	5	1095.44	273.8	100000	50000	2	d	sim18 y8
0.001	0	0	0	#DIV/0!	0	0	#DIV/0!	a	sim21 y1
0.001	0	0.0001	0	#DIV/0!	0	0.1	0	a	sim21 y2
0.001	0	0.001	0	#DIV/0!	0	1	0	a	sim21 y3
0.001	0	0.01	0	#DIV/0!	0	10	0	a	sim21 y4
0.001	0	0.1	0	#DIV/0!	0	100	0	d	sim21 y5
0.001	0	1	0	#DIV/0!	0	1000	0	d	sim21 y6

TABLE 3.4: SIMULATION RESULTS - INNER MODEL RESPONSE

m/m_0 (slug)	k (lb/in)	C_v (lb/in/s)	ω_n (rad/s)	ζ	l/m	C_w/m	l/C_v	code	designation
0.001	0	3	0	#DIV/0!	0	3000	0	d	sim21 y7
0.001	0	5	0	#DIV/0!	0	5000	0	d	sim21 y8
0.001	0.0001	0	1.09544	0	0.1	0	#DIV/0!	a	sim22 y1
0.001	0.0001	0.0001	1.09544	0.547	0.1	0.1	1	a	sim22 y2
0.001	0.0001	0.001	1.09544	5.477	0.1	1	0.1	a	sim22 y3
0.001	0.0001	0.01	1.09544	54.77	0.1	10	0.01	a	sim22 y4
0.001	0.0001	0.1	1.09544	547.7	0.1	100	0.001	d	sim22 y5
0.001	0.0001	1	1.09544	5477.2	0.1	1000	0.0001	d	sim22 y6
0.001	0.0001	3	1.09544	16431.6	0.1	3000	3.33333	d	sim22 y7
0.001	0.0001	5	1.09544	27386.1	0.1	5000	0.00002	d	sim22 y8
0.001	0.001	0	3.46410	0	1	0	#DIV/0!	a	sim23 y1
0.001	0.001	0.0001	3.46410	0.173	1	0.1	10	a	sim23 y2
0.001	0.001	0.001	3.46410	1.732	1	1	1	a	sim23 y3
0.001	0.001	0.01	3.46410	17.32	1	10	0.1	a	sim23 y4
0.001	0.001	0.1	3.46410	173.2	1	100	0.01	d	sim23 y5
0.001	0.001	1	3.46410	1732.0	1	1000	0.001	d	sim23 y6
0.001	0.001	3	3.46410	5196.1	1	3000	0.00033	d	sim23 y7
0.001	0.001	5	3.46410	8660.2	1	5000	0.0002	d	sim23 y8
0.001	0.01	0	10.9544	0	10	0	#DIV/0!	a	sim24 y1
0.001	0.01	0.0001	10.9544	0.054	10	0.1	100	a	sim24 y2
0.001	0.01	0.001	10.9544	0.547	10	1	10	a	sim24 y3
0.001	0.01	0.01	10.9544	5.477	10	10	1	a	sim24 y4
0.001	0.01	0.1	10.9544	54.77	10	100	0.1	d	sim24 y5
0.001	0.01	1	10.9544	547.7	10	1000	0.01	d	sim24 y6
0.001	0.01	3	10.9544	1643.1	10	3000	0.00333	d	sim24 y7
0.001	0.01	5	10.9544	2738.6	10	5000	0.002	d	sim24 y8
0.001	0.1	0	34.6410	0	100	0	#DIV/0!	a	sim25 y1
0.001	0.1	0.0001	34.6410	0.017	100	0.1	1000	a	sim25 y2
0.001	0.1	0.001	34.6410	0.173	100	1	100	a	sim25 y3
0.001	0.1	0.01	34.6410	1.732	100	10	10	a	sim25 y4
0.001	0.1	0.1	34.6410	17.32	100	100	1	d	sim25 y5
0.001	0.1	1	34.6410	173.2	100	1000	0.1	d	sim25 y6
0.001	0.1	3	34.6410	519.6	100	3000	0.03333	d	sim25 y7
0.001	0.1	5	34.6410	866.0	100	5000	0.02	d	sim25 y8
0.001	1	0	109.544	0	1000	0	#DIV/0!	l	sim26 y1

TABLE 3.4: SIMULATION RESULTS - INNER MODEL RESPONSE

mass (slug)	k (lb/in)	Cv (lb/in/s)	ω_n (rad/s)	ζ	l/m	Cv/m	k/Cv	code	designation
0.001	1	0.0001	109.544	0.005	1000	0.1	10000	l	sim26 y2
0.001	1	0.001	109.544	0.054	1000	1	1000	l	sim26 y3
0.001	1	0.01	109.544	0.547	1000	10	100	l	sim26 y4
0.001	1	0.1	109.544	5.477	1000	100	10	d	sim26 y5
0.001	1	1	109.544	54.77	1000	1000	1	d	sim26 y6
0.001	1	3	109.544	164.3	1000	3000	0.33333	d	sim26 y7
0.001	1	5	109.544	273.8	1000	5000	0.2	d	sim26 y8
0.001	5	0	244.948	0	5000	0	#DIV/0!	l	sim27 y1
0.001	5	0.0001	244.948	0.002	5000	0.1	50000	l	sim27 y2
0.001	5	0.001	244.948	0.024	5000	1	5000	l	sim27 y3
0.001	5	0.01	244.948	0.244	5000	10	500	l	sim27 y4
0.001	5	0.1	244.948	2.449	5000	100	50	d	sim27 y5
0.001	5	1	244.948	24.49	5000	1000	5	d	sim27 y6
0.001	5	3	244.948	73.48	5000	3000	1.66666	d	sim27 y7
0.001	5	5	244.948	122.4	5000	5000	1	d	sim27 y8
0.001	10	0	346.410	0	10000	0	#DIV/0!	d	sim28 y1
0.001	10	0.0001	346.410	0.001	10000	0.1	100000	d	sim28 y2
0.001	10	0.001	346.410	0.017	10000	1	10000	d	sim28 y3
0.001	10	0.01	346.410	0.173	10000	10	1000	d	sim28 y4
0.001	10	0.1	346.410	1.732	10000	100	100	d	sim28 y5
0.001	10	1	346.410	17.32	10000	1000	10	d	sim28 y6
0.001	10	3	346.410	51.96	10000	3000	3.33333	d	sim28 y7
0.001	10	5	346.410	86.60	10000	5000	2	d	sim28 y8
0.005	0	0	0	#DIV/0!	0	0	#DIV/0!	a	sim31 y1
0.005	0	0.0001	0	#DIV/0!	0	0.02	0	a	sim31 y2
0.005	0	0.001	0	#DIV/0!	0	0.2	0	a	sim31 y3
0.005	0	0.01	0	#DIV/0!	0	2	0	a	sim31 y4
0.005	0	0.1	0	#DIV/0!	0	20	0	a	sim31 y5
0.005	0	1	0	#DIV/0!	0	200	0	d	sim31 y6
0.005	0	3	0	#DIV/0!	0	600	0	d	sim31 y7
0.005	0	5	0	#DIV/0!	0	1000	0	d	sim31 y8
0.005	0.0001	0	0.48989	0	0.02	0	#DIV/0!	a	sim32 y1
0.005	0.0001	0.0001	0.48989	0.244	0.02	0.02	1	a	sim32 y2
0.005	0.0001	0.001	0.48989	2.449	0.02	0.2	0.1	a	sim32 y3
0.005	0.0001	0.01	0.48989	24.49	0.02	2	0.01	a	sim32 y4

TABLE 3.4: SIMULATION RESULTS - INNER MODEL RESPONSE

mass (slug)	k (lb/in)	Cv (lb/in/s)	sm (rad/s)	ζ	l/m	Cv/m	l/Cv	code	designation
0.005	0.0001	0.1	0.48989	244.9	0.02	20	0.001	a	sim32 y5
0.005	0.0001	1	0.48989	2449.4	0.02	200	0.0001	d	sim32 y6
0.005	0.0001	3	0.48989	7348.4	0.02	600	3.33333	d	sim32 y7
0.005	0.0001	5	0.48989	12247.4	0.02	1000	0.00002	d	sim32 y8
0.005	0.001	0	1.54919	0	0.2	0	#DIV/0!	a	sim33 y1
0.005	0.001	0.0001	1.54919	0.077	0.2	0.02	10	a	sim33 y2
0.005	0.001	0.001	1.54919	0.774	0.2	0.2	1	a	sim33 y3
0.005	0.001	0.01	1.54919	7.745	0.2	2	0.1	a	sim33 y4
0.005	0.001	0.1	1.54919	77.45	0.2	20	0.01	a	sim33 y5
0.005	0.001	1	1.54919	774.5	0.2	200	0.001	d	sim33 y6
0.005	0.001	3	1.54919	2323.7	0.2	600	0.00033	d	sim33 y7
0.005	0.001	5	1.54919	3872.9	0.2	1000	0.0002	d	sim33 y8
0.005	0.01	0	4.89897	0	2	0	#DIV/0!	a	sim34 y1
0.005	0.01	0.0001	4.89897	0.024	2	0.02	100	a	sim34 y2
0.005	0.01	0.001	4.89897	0.244	2	0.2	10	a	sim34 y3
0.005	0.01	0.01	4.89897	2.449	2	2	1	a	sim34 y4
0.005	0.01	0.1	4.89897	24.49	2	20	0.1	a	sim34 y5
0.005	0.01	1	4.89897	244.9	2	200	0.01	d	sim34 y6
0.005	0.01	3	4.89897	734.8	2	600	0.00333	d	sim34 y7
0.005	0.01	5	4.89897	1224.7	2	1000	0.002	d	sim34 y8
0.005	0.1	0	15.4919	0	20	0	#DIV/0!	a	sim35 y1
0.005	0.1	0.0001	15.4919	0.007	20	0.02	1000	a	sim35 y2
0.005	0.1	0.001	15.4919	0.077	20	0.2	100	a	sim35 y3
0.005	0.1	0.01	15.4919	0.774	20	2	10	a	sim35 y4
0.005	0.1	0.1	15.4919	7.745	20	20	1	a	sim35 y5
0.005	0.1	1	15.4919	77.45	20	200	0.1	d	sim35 y6
0.005	0.1	3	15.4919	232.3	20	600	0.03333	d	sim35 y7
0.005	0.1	5	15.4919	387.2	20	1000	0.02	d	sim35 y8
0.005	1	0	48.9897	0	200	0	#DIV/0!	l	sim36 y1
0.005	1	0.0001	48.9897	0.002	200	0.02	10000	l	sim36 y2
0.005	1	0.001	48.9897	0.024	200	0.2	1000	l	sim36 y3
0.005	1	0.01	48.9897	0.244	200	2	100	l	sim36 y4
0.005	1	0.1	48.9897	2.449	200	20	10	o	sim36 y5
0.005	1	1	48.9897	24.49	200	200	1	d	sim36 y6
0.005	1	3	48.9897	73.48	200	600	0.33333	d	sim36 y7

TABLE 3.4: SIMULATION RESULTS - INNER MODEL RESPONSE

mass (slug)	k (lb/in)	Cv (lb/in/s)	ω_n (rad/s)	ζ	l/m	C_w/m	k/C_v	code	designation
0.005	1	5	48.9897	122.4	200	1000	0.2	d	sim36 y8
0.005	5	0	109.544	0	1000	0	#DIV/0!	l	sim37 y1
0.005	5	0.0001	109.544	0.001	1000	0.02	50000	l	sim37 y2
0.005	5	0.001	109.544	0.010	1000	0.2	5000	l	sim37 y3
0.005	5	0.01	109.544	0.109	1000	2	500	l	sim37 y4
0.005	5	0.1	109.544	1.095	1000	20	50	l	sim37 y5
0.005	5	1	109.544	10.95	1000	200	5	d	sim37 y6
0.005	5	3	109.544	32.86	1000	600	1.66666	d	sim37 y7
0.005	5	5	109.544	54.77	1000	1000	1	d	sim37 y8
0.005	10	0	154.919	0	2000	0	#DIV/0!	l	sim38 y1
0.005	10	0.0001	154.919	0.000	2000	0.02	100000	l	sim38 y2
0.005	10	0.001	154.919	0.007	2000	0.2	10000	l	sim38 y3
0.005	10	0.01	154.919	0.077	2000	2	1000	l	sim38 y4
0.005	10	0.1	154.919	0.774	2000	20	100	o	sim38 y5
0.005	10	1	154.919	7.745	2000	200	10	d	sim38 y6
0.005	10	3	154.919	23.23	2000	600	3.33333	d	sim38 y7
0.005	10	5	154.919	38.72	2000	1000	2	d	sim38 y8
0.01	0	0	0	#DIV/0!	0	0	#DIV/0!	a	sim41 y1
0.01	0	0.0001	0	#DIV/0!	0	0.01	0	a	sim41 y2
0.01	0	0.001	0	#DIV/0!	0	0.1	0	a	sim41 y3
0.01	0	0.01	0	#DIV/0!	0	1	0	a	sim41 y4
0.01	0	0.1	0	#DIV/0!	0	10	0	a	sim41 y5
0.01	0	1	0	#DIV/0!	0	100	0	d	sim41 y6
0.01	0	3	0	#DIV/0!	0	300	0	d	sim41 y7
0.01	0	5	0	#DIV/0!	0	500	0	d	sim41 y8
0.01	0.0001	0	0.34641	0	0.01	0	#DIV/0!	a	sim42 y1
0.01	0.0001	0.0001	0.34641	0.173	0.01	0.01	1	a	sim42 y2
0.01	0.0001	0.001	0.34641	1.732	0.01	0.1	0.1	a	sim42 y3
0.01	0.0001	0.01	0.34641	17.32	0.01	1	0.01	a	sim42 y4
0.01	0.0001	0.1	0.34641	173.2	0.01	10	0.001	a	sim42 y5
0.01	0.0001	1	0.34641	1732.0	0.01	100	0.0001	d	sim42 y6
0.01	0.0001	3	0.34641	5196.1	0.01	300	3.33333	d	sim42 y7
0.01	0.0001	5	0.34641	8660.2	0.01	500	0.00002	d	sim42 y8
0.01	0.001	0	1.09544	0	0.1	0	#DIV/0!	a	sim43 y1
0.01	0.001	0.0001	1.09544	0.054	0.1	0.01	10	a	sim43 y2

TABLE 3.4: SIMULATION RESULTS - INNER MODEL RESPONSE

mass (slug)	k (lb/in)	Cv (lb/in/s)	cm (rad/s)	ζ	h/m	Cv/m	h/Cv	code	designation
0.01	0.001	0.001	1.09544	0.547	0.1	0.1	1	a	sim43 y3
0.01	0.001	0.01	1.09544	5.477	0.1	1	0.1	a	sim43 y4
0.01	0.001	0.1	1.09544	54.77	0.1	10	0.01	a	sim43 y5
0.01	0.001	1	1.09544	547.7	0.1	100	0.001	d	sim43 y6
0.01	0.001	3	1.09544	1643.1	0.1	300	0.00033	d	sim43 y7
0.01	0.001	5	1.09544	2738.6	0.1	500	0.0002	d	sim43 y8
0.01	0.01	0	3.46410	0	1	0	#DIV 0!	a	sim44 y1
0.01	0.01	0.0001	3.46410	0.017	1	0.01	100	a	sim44 y2
0.01	0.01	0.001	3.46410	0.173	1	0.1	10	a	sim44 y3
0.01	0.01	0.01	3.46410	1.732	1	1	1	a	sim44 y4
0.01	0.01	0.1	3.46410	17.32	1	10	0.1	a	sim44 y5
0.01	0.01	1	3.46410	173.2	1	100	0.01	d	sim44 y6
0.01	0.01	3	3.46410	519.6	1	300	0.00333	d	sim44 y7
0.01	0.01	5	3.46410	866.0	1	500	0.002	d	sim44 y8
0.01	0.1	0	10.9544	0	10	0	#DIV 0!	a	sim45 y1
0.01	0.1	0.0001	10.9544	0.005	10	0.01	1000	a	sim45 y2
0.01	0.1	0.001	10.9544	0.054	10	0.1	100	a	sim45 y3
0.01	0.1	0.01	10.9544	0.547	10	1	10	a	sim45 y4
0.01	0.1	0.1	10.9544	5.477	10	10	1	a	sim45 y5
0.01	0.1	1	10.9544	54.77	10	100	0.1	d	sim45 y6
0.01	0.1	3	10.9544	164.3	10	300	0.03333	d	sim45 y7
0.01	0.1	5	10.9544	273.8	10	500	0.02	d	sim45 y8
0.01	1	0	34.6410	0	100	0	#DIV 0!	l	sim46 y1
0.01	1	0.0001	34.6410	0.001	100	0.01	10000	l	sim46 y2
0.01	1	0.001	34.6410	0.017	100	0.1	1000	l	sim46 y3
0.01	1	0.01	34.6410	0.173	100	1	100	l	sim46 y4
0.01	1	0.1	34.6410	1.732	100	10	10	a	sim46 y5
0.01	1	1	34.6410	17.32	100	100	1	d	sim46 y6
0.01	1	3	34.6410	51.96	100	300	0.33333	d	sim46 y7
0.01	1	5	34.6410	86.60	100	500	0.2	d	sim46 y8
0.01	5	0	77.4596	0	500	0	#DIV 0!	l	sim47 y1
0.01	5	0.0001	77.4596	0.000	500	0.01	50000	l	sim47 y2
0.01	5	0.001	77.4596	0.007	500	0.1	5000	l	sim47 y3
0.01	5	0.01	77.4596	0.077	500	1	500	l	sim47 y4
0.01	5	0.1	77.4596	0.774	500	10	50	o	sim47 y5

TABLE 3.4: SIMULATION RESULTS - INNER MODEL RESPONSE

$\omega_{\text{res}} \text{ (rad/s)}$	$k \text{ (lb/in)}$	$C_v \text{ (lb/in/s)}$	$\omega_n \text{ (rad/s)}$	ζ	k/m	C_v/m	k/C_v	code	designation
0.01	5	1	77.4596	7.745	500	100	5	d	sim47 y6
0.01	5	3	77.4596	23.23	500	300	1.66666	d	sim47 y7
0.01	5	5	77.4596	38.72	500	500	1	d	sim47 y8
0.01	10	0	109.544	0	1000	0	#DIV/0!	l	sim48 y1
0.01	10	0.0001	109.544	0.000	1000	0.01	100000	l	sim48 y2
0.01	10	0.001	109.544	0.005	1000	0.1	10000	l	sim48 y3
0.01	10	0.01	109.544	0.054	1000	1	1000	l	sim48 y4
0.01	10	0.1	109.544	0.547	1000	10	100	l	sim48 y5
0.01	10	1	109.544	5.477	1000	100	10	d	sim48 y6
0.01	10	3	109.544	16.43	1000	300	3.33333	d	sim48 y7
0.01	10	5	109.544	27.38	1000	500	2	d	sim48 y8
0.05	0	0	0	#DIV/0!	0	0	#DIV/0!	a	sim51 y1
0.05	0	0.0001	0	#DIV/0!	0	0.002	0	a	sim51 y2
0.05	0	0.001	0	#DIV/0!	0	0.02	0	a	sim51 y3
0.05	0	0.01	0	#DIV/0!	0	0.2	0	a	sim51 y4
0.05	0	0.1	0	#DIV/0!	0	2	0	a	sim51 y5
0.05	0	1	0	#DIV/0!	0	20	0	a	sim51 y6
0.05	0	3	0	#DIV/0!	0	60	0	d	sim51 y7
0.05	0	5	0	#DIV/0!	0	100	0	d	sim51 y8
0.05	0.0001	0	0.15491	0	0.002	0	#DIV/0!	a	sim52 y1
0.05	0.0001	0.0001	0.15491	0.077	0.002	0.002	1	a	sim52 y2
0.05	0.0001	0.001	0.15491	0.774	0.002	0.02	0.1	a	sim52 y3
0.05	0.0001	0.01	0.15491	7.745	0.002	0.2	0.01	a	sim52 y4
0.05	0.0001	0.1	0.15491	77.45	0.002	2	0.001	a	sim52 y5
0.05	0.0001	1	0.15491	774.5	0.002	20	0.0001	a	sim52 y6
0.05	0.0001	3	0.15491	2323.7	0.002	60	3.33333	d	sim52 y7
0.05	0.0001	5	0.15491	3872.9	0.002	100	0.00002	d	sim52 y8
0.05	0.001	0	0.48989	0	0.02	0	#DIV/0!	a	sim53 y1
0.05	0.001	0.0001	0.48989	0.024	0.02	0.002	10	a	sim53 y2
0.05	0.001	0.001	0.48989	0.244	0.02	0.02	1	a	sim53 y3
0.05	0.001	0.01	0.48989	2.449	0.02	0.2	0.1	a	sim53 y4
0.05	0.001	0.1	0.48989	24.49	0.02	2	0.01	a	sim53 y5
0.05	0.001	1	0.48989	244.9	0.02	20	0.001	a	sim53 y6
0.05	0.001	3	0.48989	734.8	0.02	60	0.00033	d	sim53 y7
0.05	0.001	5	0.48989	1224.7	0.02	100	0.0002	d	sim53 y8

TABLE 3.4: SIMULATION RESULTS - INNER MODEL RESPONSE

mass (slugs)	k (lb/in)	Cv (lb/in/s)	ω_n (rad/s)	ζ	h/m	Cv/m	k/Cv	code	designation
0.05	0.01	0	1.54919	0	0.2	0	#DIV 0!	a	sim54 y1
0.05	0.01	0.0001	1.54919	0.007	0.2	0.002	100	a	sim54 y2
0.05	0.01	0.001	1.54919	0.077	0.2	0.02	10	a	sim54 y3
0.05	0.01	0.01	1.54919	0.774	0.2	0.2	1	a	sim54 y4
0.05	0.01	0.1	1.54919	7.745	0.2	2	0.1	a	sim54 y5
0.05	0.01	1	1.54919	77.45	0.2	20	0.01	a	sim54 y6
0.05	0.01	3	1.54919	232.3	0.2	60	0.00333	d	sim54 y7
0.05	0.01	5	1.54919	387.2	0.2	100	0.002	d	sim54 y8
0.05	0.1	0	4.89897	0	2	0	#DIV 0!	a	sim55 y1
0.05	0.1	0.0001	4.89897	0.002	2	0.002	1000	a	sim55 y2
0.05	0.1	0.001	4.89897	0.024	2	0.02	100	a	sim55 y3
0.05	0.1	0.01	4.89897	0.244	2	0.2	10	a	sim55 y4
0.05	0.1	0.1	4.89897	2.449	2	2	1	a	sim55 y5
0.05	0.1	1	4.89897	24.49	2	20	0.1	a	sim55 y6
0.05	0.1	3	4.89897	73.48	2	60	0.03333	d	sim55 y7
0.05	0.1	5	4.89897	122.4	2	100	0.02	d	sim55 y8
0.05	1	0	15.4919	0	20	0	#DIV 0!	l	sim56 y1
0.05	1	0.0001	15.4919	0.000	20	0.002	10000	l	sim56 y2
0.05	1	0.001	15.4919	0.007	20	0.02	1000	l	sim56 y3
0.05	1	0.01	15.4919	0.077	20	0.2	100	l	sim56 y4
0.05	1	0.1	15.4919	0.774	20	2	10	a	sim56 y5
0.05	1	1	15.4919	7.745	20	20	1	a	sim56 y6
0.05	1	3	15.4919	23.23	20	60	0.33333	d	sim56 y7
0.05	1	5	15.4919	38.72	20	100	0.2	d	sim56 y8
0.05	5	0	34.6410	0	100	0	#DIV 0!	l	sim57 y1
0.05	5	0.0001	34.6410	0.000	100	0.002	50000	l	sim57 y2
0.05	5	0.001	34.6410	0.003	100	0.02	5000	l	sim57 y3
0.05	5	0.01	34.6410	0.034	100	0.2	500	l	sim57 y4
0.05	5	0.1	34.6410	0.346	100	2	50	l	sim57 y5
0.05	5	1	34.6410	3.464	100	20	5	a	sim57 y6
0.05	5	3	34.6410	10.39	100	60	1.66666	a	sim57 y7
0.05	5	5	34.6410	17.32	100	100	1	a	sim57 y8
0.05	10	0	48.9897	0	200	0	#DIV 0!	l	sim58 y1
0.05	10	0.0001	48.9897	0.000	200	0.002	100000	l	sim58 y2
0.05	10	0.001	48.9897	0.002	200	0.02	10000	l	sim58 y3

TABLE 3.4: SIMULATION RESULTS - INNER MODEL RESPONSE

$\omega_{\text{res}} (\text{rad/s})$	$k (\text{lb/in})$	$C_v (\text{lb/in/s})$	$\omega_n (\text{rad/s})$	ζ	h/in	C_{win}	k/C_v	code	designation
0.05	10	0.01	48.9897	0.024	200	0.2	1000	l	sim58 y4
0.05	10	0.1	48.9897	0.244	200	2	100	l	sim58 y5
0.05	10	1	48.9897	2.449	200	20	10	a	sim58 y6
0.05	10	3	48.9897	7.348	200	60	3.33333	d	sim58 y7
0.05	10	5	48.9897	12.24	200	100	2	d	sim58 y8
0.1	0	0	0	#DIV/0!	0	0	#DIV/0!	a	sim61 y1
0.1	0	0.0001	0	#DIV/0!	0	0.001	0	a	sim61 y2
0.1	0	0.001	0	#DIV/0!	0	0.01	0	a	sim61 y3
0.1	0	0.01	0	#DIV/0!	0	0.1	0	a	sim61 y4
0.1	0	0.1	0	#DIV/0!	0	1	0	a	sim61 y5
0.1	0	1	0	#DIV/0!	0	10	0	a	sim61 y6
0.1	0	3	0	#DIV/0!	0	30	0	h	sim61 y7
0.1	0	5	0	#DIV/0!	0	50	0	d	sim61 y8
0.1	0.0001	0	0.10954	0	0.001	0	#DIV/0!	a	sim62 y1
0.1	0.0001	0.0001	0.10954	0.054	0.001	0.001	1	a	sim62 y2
0.1	0.0001	0.001	0.10954	0.547	0.001	0.01	0.1	a	sim62 y3
0.1	0.0001	0.01	0.10954	5.477	0.001	0.1	0.01	a	sim62 y4
0.1	0.0001	0.1	0.10954	54.77	0.001	1	0.001	a	sim62 y5
0.1	0.0001	1	0.10954	547.7	0.001	10	0.0001	a	sim62 y6
0.1	0.0001	3	0.10954	1643.1	0.001	30	3.33333	h	sim62 y7
0.1	0.0001	5	0.10954	2738.6	0.001	50	0.00002	d	sim62 y8
0.1	0.001	0	0.34641	0	0.01	0	#DIV/0!	a	sim63 y1
0.1	0.001	0.0001	0.34641	0.017	0.01	0.001	10	a	sim63 y2
0.1	0.001	0.001	0.34641	0.173	0.01	0.01	1	a	sim63 y3
0.1	0.001	0.01	0.34641	1.732	0.01	0.1	0.1	a	sim63 y4
0.1	0.001	0.1	0.34641	17.32	0.01	1	0.01	a	sim63 y5
0.1	0.001	1	0.34641	173.2	0.01	10	0.001	a	sim63 y6
0.1	0.001	3	0.34641	519.6	0.01	30	0.00033	h	sim63 y7
0.1	0.001	5	0.34641	866.0	0.01	50	0.0002	d	sim63 y8
0.1	0.01	0	1.09544	0	0.1	0	#DIV/0!	a	sim64 y1
0.1	0.01	0.0001	1.09544	0.005	0.1	0.001	100	a	sim64 y2
0.1	0.01	0.001	1.09544	0.054	0.1	0.01	10	a	sim64 y3
0.1	0.01	0.01	1.09544	0.547	0.1	0.1	1	a	sim64 y4
0.1	0.01	0.1	1.09544	5.477	0.1	1	0.1	a	sim64 y5
0.1	0.01	1	1.09544	54.77	0.1	10	0.01	a	sim64 y6

TABLE 3.4: SIMULATION RESULTS - INNER MODEL RESPONSE

mass (slug)	k (lb/in)	Cv (lb/in/s)	am (rad/s)	ζ	lcm	Cvcm	lc/Cv	code	designation
0.1	0.01	3	1.09544	164.3	0.1	30	0.00333	h	sim64 y7
0.1	0.01	5	1.09544	273.8	0.1	50	0.002	d	sim64 y8
0.1	0.1	0	3.46410	0	1	0	#DIV/0!	a	sim65 y1
0.1	0.1	0.0001	3.46410	0.001	1	0.001	1000	a	sim65 y2
0.1	0.1	0.001	3.46410	0.017	1	0.01	100	a	sim65 y3
0.1	0.1	0.01	3.46410	0.173	1	0.1	10	a	sim65 y4
0.1	0.1	0.1	3.46410	1.732	1	1	1	a	sim65 y5
0.1	0.1	1	3.46410	17.32	1	10	0.1	a	sim65 y6
0.1	0.1	3	3.46410	51.96	1	30	0.03333	h	sim65 y7
0.1	0.1	5	3.46410	86.60	1	50	0.02	d	sim65 y8
0.1	1	0	10.9544	0	10	0	#DIV/0!	l	sim66 y1
0.1	1	0.0001	10.9544	0.000	10	0.001	10000	l	sim66 y2
0.1	1	0.001	10.9544	0.005	10	0.01	1000	l	sim66 y3
0.1	1	0.01	10.9544	0.054	10	0.1	100	l	sim66 y4
0.1	1	0.1	10.9544	0.547	10	1	10	o	sim66 y5
0.1	1	1	10.9544	5.477	10	10	1	a	sim66 y6
0.1	1	3	10.9544	16.43	10	30	0.33333	h	sim66 y7
0.1	1	5	10.9544	27.38	10	50	0.2	d	sim66 y8
0.1	5	0	24.4948	0	50	0	#DIV/0!	l	sim67 y1
0.1	5	0.0001	24.4948	0.000	50	0.001	50000	l	sim67 y2
0.1	5	0.001	24.4948	0.002	50	0.01	5000	l	sim67 y3
0.1	5	0.01	24.4948	0.024	50	0.1	500	l	sim67 y4
0.1	5	0.1	24.4948	0.244	50	1	50	l	sim67 y5
0.1	5	1	24.4948	2.449	50	10	5	o	sim67 y6
0.1	5	3	24.4948	7.348	50	30	1.66666	a	sim67 y7
0.1	5	5	24.4948	12.24	50	50	1	d	sim67 y8
0.1	10	0	34.6410	0	100	0	#DIV/0!	l	sim68 y1
0.1	10	0.0001	34.6410	0.000	100	0.001	100000	l	sim68 y2
0.1	10	0.001	34.6410	0.001	100	0.01	10000	l	sim68 y3
0.1	10	0.01	34.6410	0.017	100	0.1	1000	l	sim68 y4
0.1	10	0.1	34.6410	0.173	100	1	100	l	sim68 y5
0.1	10	1	34.6410	1.732	100	10	10	o	sim68 y6
0.1	10	3	34.6410	5.196	100	30	3.33333	a	sim68 y7
0.1	10	5	34.6410	8.660	100	50	2	d	sim68 y8
0.5	0	0	0	#DIV/0!	0	0	#DIV/0!	a	sim71 y1

TABLE 3.4: SIMULATION RESULTS - INNER MODEL RESPONSE

mass (slug)	k (lb/in)	Cv (lb/in/s)	cm (rad/s)	ζ	h/m	Cv/m	h/Cv	code	designation
0.5	0	0.0001	0	#DIV/0!	0	0.0002	0	a	sim71 y2
0.5	0	0.001	0	#DIV/0!	0	0.002	0	a	sim71 y3
0.5	0	0.01	0	#DIV/0!	0	0.02	0	a	sim71 y4
0.5	0	0.1	0	#DIV/0!	0	0.2	0	a	sim71 y5
0.5	0	1	0	#DIV/0!	0	2	0	a	sim71 y6
0.5	0	3	0	#DIV/0!	0	6	0	h	sim71 y7
0.5	0	5	0	#DIV/0!	0	10	0	h	sim71 y8
0.5	0.0001	0	0.04898	0	0.0002	0	#DIV/0!	a	sim72 y1
0.5	0.0001	0.0001	0.04898	0.024	0.0002	0.0002	1	a	sim72 y2
0.5	0.0001	0.001	0.04898	0.244	0.0002	0.002	0.1	a	sim72 y3
0.5	0.0001	0.01	0.04898	2.449	0.0002	0.02	0.01	a	sim72 y4
0.5	0.0001	0.1	0.04898	24.49	0.0002	0.2	0.001	a	sim72 y5
0.5	0.0001	1	0.04898	244.9	0.0002	2	0.0001	a	sim72 y6
0.5	0.0001	3	0.04898	734.8	0.0002	6	3.33333	h	sim72 y7
0.5	0.0001	5	0.04898	1224.7	0.0002	10	0.00002	h	sim72 y8
0.5	0.001	0	0.15491	0	0.002	0	#DIV/0!	a	sim73 y1
0.5	0.001	0.0001	0.15491	0.007	0.002	0.0002	10	a	sim73 y2
0.5	0.001	0.001	0.15491	0.077	0.002	0.002	1	a	sim73 y3
0.5	0.001	0.01	0.15491	0.774	0.002	0.02	0.1	a	sim73 y4
0.5	0.001	0.1	0.15491	7.745	0.002	0.2	0.01	a	sim73 y5
0.5	0.001	1	0.15491	77.45	0.002	2	0.001	a	sim73 y6
0.5	0.001	3	0.15491	232.3	0.002	6	0.00033	h	sim73 y7
0.5	0.001	5	0.15491	387.2	0.002	10	0.0002	h	sim73 y8
0.5	0.01	0	0.48989	0	0.02	0	#DIV/0!	a	sim74 y1
0.5	0.01	0.0001	0.48989	0.002	0.02	0.0002	100	a	sim74 y2
0.5	0.01	0.001	0.48989	0.024	0.02	0.002	10	a	sim74 y3
0.5	0.01	0.01	0.48989	0.244	0.02	0.02	1	a	sim74 y4
0.5	0.01	0.1	0.48989	2.449	0.02	0.2	0.1	a	sim74 y5
0.5	0.01	1	0.48989	24.49	0.02	2	0.01	a	sim74 y6
0.5	0.01	3	0.48989	73.48	0.02	6	0.00333	h	sim74 y7
0.5	0.01	5	0.48989	122.4	0.02	10	0.002	h	sim74 y8
0.5	0.1	0	1.54919	0	0.2	0	#DIV/0!	a	sim75 y1
0.5	0.1	0.0001	1.54919	0.000	0.2	0.0002	1000	a	sim75 y2
0.5	0.1	0.001	1.54919	0.007	0.2	0.002	100	a	sim75 y3
0.5	0.1	0.01	1.54919	0.077	0.2	0.02	10	a	sim75 y4

TABLE 3.4: SIMULATION RESULTS - INNER MODEL RESPONSE

mass (slugs)	k (lb/in)	Cv (lb/in/s)	cm (rad/s)	ζ	h/m	Cv/m	k/Cv	code	designation
0.5	0.1	0.1	1.54919	0.774	0.2	0.2	1	a	sim75 y5
0.5	0.1	1	1.54919	7.745	0.2	2	0.1	a	sim75 y6
0.5	0.1	3	1.54919	23.23	0.2	6	0.03333	h	sim75 y7
0.5	0.1	5	1.54919	38.72	0.2	10	0.02	h	sim75 y8
0.5	1	0	4.89897	0	2	0	#DIV/0!	l	sim76 y1
0.5	1	0.0001	4.89897	0.000	2	0.0002	10000	l	sim76 y2
0.5	1	0.001	4.89897	0.002	2	0.002	1000	l	sim76 y3
0.5	1	0.01	4.89897	0.024	2	0.02	100	l	sim76 y4
0.5	1	0.1	4.89897	0.244	2	0.2	10	o	sim76 y5
0.5	1	1	4.89897	2.449	2	2	1	a	sim76 y6
0.5	1	3	4.89897	7.348	2	6	0.33333	h	sim76 y7
0.5	1	5	4.89897	12.24	2	10	0.2	h	sim76 y8
0.5	5	0	10.9544	0	10	0	#DIV/0!	l	sim77 y1
0.5	5	0.0001	10.9544	0.000	10	0.0002	50000	l	sim77 y2
0.5	5	0.001	10.9544	0.001	10	0.002	5000	l	sim77 y3
0.5	5	0.01	10.9544	0.010	10	0.02	500	l	sim77 y4
0.5	5	0.1	10.9544	0.109	10	0.2	50	l	sim77 y5
0.5	5	1	10.9544	1.095	10	2	5	a	sim77 y6
0.5	5	3	10.9544	3.286	10	6	1.66666	a	sim77 y7
0.5	5	5	10.9544	5.477	10	10	1	a	sim77 y8
0.5	10	0	15.4919	0	20	0	#DIV/0!	l	sim78 y1
0.5	10	0.0001	15.4919	7.745	20	0.0002	100000	l	sim78 y2
0.5	10	0.001	15.4919	0.000	20	0.002	10000	l	sim78 y3
0.5	10	0.01	15.4919	0.007	20	0.02	1000	l	sim78 y4
0.5	10	0.1	15.4919	0.077	20	0.2	100	l	sim78 y5
0.5	10	1	15.4919	0.774	20	2	10	o	sim78 y6
0.5	10	3	15.4919	2.323	20	6	3.33333	a	sim78 y7
0.5	10	5	15.4919	3.872	20	10	2	a	sim78 y8
1	0	0	0	#DIV/0!	0	0	#DIV/0!	a	sim81 y1
1	0	0.0001	0	#DIV/0!	0	0.0001	0	a	sim81 y2
1	0	0.001	0	#DIV/0!	0	0.001	0	a	sim81 y3
1	0	0.01	0	#DIV/0!	0	0.01	0	a	sim81 y4
1	0	0.1	0	#DIV/0!	0	0.1	0	a	sim81 y5
1	0	1	0	#DIV/0!	0	1	0	a	sim81 y6
1	0	3	0	#DIV/0!	0	3	0	h	sim81 y7

TABLE 3.4: SIMULATION RESULTS - INNER MODEL RESPONSE

mass (slugs)	k (lb/in)	Cv (lb/in/s)	cm (rad/s)	ζ	lcm	Cvcm	k/Cv	code	designation
1	0	5	0	#DIV/0!	0	5	0	h	sim81 y8
1	0.0001	0	0.03464	0	0.0001	0	#DIV/0!	a	sim82 y1
1	0.0001	0.0001	0.03464	0.017	0.0001	0.0001	1	a	sim82 y2
1	0.0001	0.001	0.03464	0.173	0.0001	0.001	0.1	a	sim82 y3
1	0.0001	0.01	0.03464	1.732	0.0001	0.01	0.01	a	sim82 y4
1	0.0001	0.1	0.03464	17.32	0.0001	0.1	0.001	a	sim82 y5
1	0.0001	1	0.03464	173.2	0.0001	1	0.0001	a	sim82 y6
1	0.0001	3	0.03464	519.6	0.0001	3	3.33333	h	sim82 y7
1	0.0001	5	0.03464	866.0	0.0001	5	0.00002	h	sim82 y8
1	0.001	0	0.10954	0	0.001	0	#DIV/0!	a	sim83 y1
1	0.001	0.0001	0.10954	0.005	0.001	0.0001	10	a	sim83 y2
1	0.001	0.001	0.10954	0.054	0.001	0.001	1	a	sim83 y3
1	0.001	0.01	0.10954	0.547	0.001	0.01	0.1	a	sim83 y4
1	0.001	0.1	0.10954	5.477	0.001	0.1	0.01	a	sim83 y5
1	0.001	1	0.10954	54.77	0.001	1	0.001	a	sim83 y6
1	0.001	3	0.10954	164.3	0.001	3	0.00033	h	sim83 y7
1	0.001	5	0.10954	273.8	0.001	5	0.0002	h	sim83 y8
1	0.01	0	0.34641	0	0.01	0	#DIV/0!	a	sim84 y1
1	0.01	0.0001	0.34641	0.001	0.01	0.0001	100	a	sim84 y2
1	0.01	0.001	0.34641	0.017	0.01	0.001	10	a	sim84 y3
1	0.01	0.01	0.34641	0.173	0.01	0.01	1	a	sim84 y4
1	0.01	0.1	0.34641	1.732	0.01	0.1	0.1	a	sim84 y5
1	0.01	1	0.34641	17.32	0.01	1	0.01	a	sim84 y6
1	0.01	3	0.34641	51.96	0.01	3	0.00333	h	sim84 y7
1	0.01	5	0.34641	86.60	0.01	5	0.002	h	sim84 y8
1	0.1	0	1.09544	0	0.1	0	#DIV/0!	a	sim85 y1
1	0.1	0.0001	1.09544	0.000	0.1	0.0001	1000	a	sim85 y2
1	0.1	0.001	1.09544	0.005	0.1	0.001	100	a	sim85 y3
1	0.1	0.01	1.09544	0.054	0.1	0.01	10	a	sim85 y4
1	0.1	0.1	1.09544	0.547	0.1	0.1	1	a	sim85 y5
1	0.1	1	1.09544	5.477	0.1	1	0.1	a	sim85 y6
1	0.1	3	1.09544	16.43	0.1	3	0.03333	h	sim85 y7
1	0.1	5	1.09544	27.38	0.1	5	0.02	h	sim85 y8
1	1	0	3.46410	0	1	0	#DIV/0!	l	sim86 y1
1	1	0.0001	3.46410	0.000	1	0.0001	10000	l	sim86 y2

TABLE 3.4: SIMULATION RESULTS - INNER MODEL RESPONSE

ω_{nat} (rad/s)	k (lb/in)	C_v (lb/in/s)	ω_n (rad/s)	ζ	h/ω_n	C_v/ω_n	h/C_v	code	designation
1	1	0.001	3.46410	0.001	1	0.001	1000	l	sim86 y3
1	1	0.01	3.46410	0.017	1	0.01	100	l	sim86 y4
1	1	0.1	3.46410	0.173	1	0.1	10	o	sim86 y5
1	1	1	3.46410	1.732	1	1	1	a	sim86 y6
1	1	3	3.46410	5.196	1	3	0.33333	h	sim86 y7
1	1	5	3.46410	8.660	1	5	0.2	h	sim86 y8
1	5	0	7.74596	0	5	0	#DIV/0!	l	sim87 y1
1	5	0.0001	7.74596	7.745	5	0.0001	50000	l	sim87 y2
1	5	0.001	7.74596	0.000	5	0.001	5000	l	sim87 y3
1	5	0.01	7.74596	0.007	5	0.01	500	l	sim87 y4
1	5	0.1	7.74596	0.077	5	0.1	50	l	sim87 y5
1	5	1	7.74596	0.774	5	1	5	o	sim87 y6
1	5	3	7.74596	2.323	5	3	1.66666	a	sim87 y7
1	5	5	7.74596	3.872	5	5	1	a	sim87 y8
1	10	0	10.9544	0	10	0	#DIV/0!	l	sim88 y1
1	10	0.0001	10.9544	5.477	10	0.0001	100000	l	sim88 y2
1	10	0.001	10.9544	0.000	10	0.001	10000	l	sim88 y3
1	10	0.01	10.9544	0.005	10	0.01	1000	l	sim88 y4
1	10	0.1	10.9544	0.054	10	0.1	100	l	sim88 y5
1	10	1	10.9544	0.547	10	1	10	o	sim88 y6
1	10	3	10.9544	1.643	10	3	3.33333	a	sim88 y7
1	10	5	10.9544	2.738	10	5	2	a	sim88 y8

TABLE 3.5: SIMULATION RESULTS - SINE INPUT, 0.04 HERTZ

mass (slug)	k (lb/in)	Cv (lb/in/s)	am (rad/s)	ζ	h/m	Cwh	h/Cv	code	designation
0.0001	0	0	0	#DIV/0!	0	0	#DIV/0!	a	sim1a1 y1
0.0001	0	0.0001	0	#DIV/0!	0	1	0	a	sim1a1 y2
0.0001	0	0.001	0	#DIV/0!	0	10	0	a	sim1a1 y3
0.0001	0	0.01	0	#DIV/0!	0	100	0	d	sim1a1 y4
0.0001	0	0.1	0	#DIV/0!	0	1000	0	d	sim1a1 y5
0.0001	0	1	0	#DIV/0!	0	10000	0	d	sim1a1 y6
0.0001	0	3	0	#DIV/0!	0	30000	0	d	sim1a1 y7
0.0001	0	5	0	#DIV/0!	0	50000	0	d	sim1a1 y8
0.0001	0.0001	0	3.4641016	0	1	0	#DIV/0!	a	sim1a2 y1
0.0001	0.0001	0.0001	3.4641016	1.73205	1	1	1	a	sim1a2 y2
0.0001	0.0001	0.001	3.4641016	17.3205	1	10	0.1	a	sim1a2 y3
0.0001	0.0001	0.01	3.4641016	173.205	1	100	0.01	d	sim1a2 y4
0.0001	0.0001	0.1	3.4641016	1732.05	1	1000	0.001	d	sim1a2 y5
0.0001	0.0001	1	3.4641016	17320.5	1	10000	0.0001	d	sim1a2 y6
0.0001	0.0001	3	3.4641016	51961.5	1	30000	3.33333	d	sim1a2 y7
0.0001	0.0001	5	3.4641016	86602.5	1	50000	0.00002	d	sim1a2 y8
0.0001	0.001	0	10.954451	0	10	0	#DIV/0!	a	sim1a3 y1
0.0001	0.001	0.0001	10.954451	0.54772	10	1	10	a	sim1a3 y2
0.0001	0.001	0.001	10.954451	5.47722	10	10	1	a	sim1a3 y3
0.0001	0.001	0.01	10.954451	54.7722	10	100	0.1	d	sim1a3 y4
0.0001	0.001	0.1	10.954451	547.722	10	1000	0.01	d	sim1a3 y5
0.0001	0.001	1	10.954451	5477.22	10	10000	0.001	d	sim1a3 y6
0.0001	0.001	3	10.954451	16431.6	10	30000	0.00033	d	sim1a3 y7
0.0001	0.001	5	10.954451	27386.1	10	50000	0.0002	d	sim1a3 y8
0.0001	0.01	0	34.641016	0	100	0	#DIV/0!	a	sim1a4 y1
0.0001	0.01	0.0001	34.641016	0.17320	100	1	100	a	sim1a4 y2
0.0001	0.01	0.001	34.641016	1.73205	100	10	10	a	sim1a4 y3
0.0001	0.01	0.01	34.641016	17.3205	100	100	1	d	sim1a4 y4
0.0001	0.01	0.1	34.641016	173.205	100	1000	0.1	d	sim1a4 y5
0.0001	0.01	1	34.641016	1732.05	100	10000	0.01	d	sim1a4 y6
0.0001	0.01	3	34.641016	5196.15	100	30000	0.00333	d	sim1a4 y7
0.0001	0.01	5	34.641016	8660.25	100	50000	0.002	d	sim1a4 y8
0.0001	0.1	0	109.54451	0	1000	0	#DIV/0!	l	sim1a5 y1
0.0001	0.1	0.0001	109.54451	0.05477	1000	1	1000	l	sim1a5 y2
0.0001	0.1	0.001	109.54451	0.54772	1000	10	100	a	sim1a5 y3
0.0001	0.1	0.01	109.54451	5.47722	1000	100	10	d	sim1a5 y4

TABLE 3.5: SIMULATION RESULTS - SINE INPUT, 0.04 HERTZ

mass (slugs)	k (lb/in)	Cv (lb/in/s)	cm (rad/s)	ζ	h/m	Cv/m	k/Cv	code	designation
0.0001	0.1	0.1	109.54451	54.7722	1000	1000	1	d	sim1a5 y5
0.0001	0.1	1	109.54451	547.722	1000	10000	0.1	d	sim1a5 y6
0.0001	0.1	3	109.54451	1643.16	1000	30000	0.03333	d	sim1a5 y7
0.0001	0.1	5	109.54451	2738.61	1000	50000	0.02	d	sim1a5 y8
0.0001	1	0	346.41016	0	10000	0	#DIV/0!	d	sim1a6 y1
0.0001	1	0.0001	346.41016	0.01732	10000	1	10000	d	sim1a6 y2
0.0001	1	0.001	346.41016	0.17320	10000	10	1000	d	sim1a6 y3
0.0001	1	0.01	346.41016	1.73205	10000	100	100	d	sim1a6 y4
0.0001	1	0.1	346.41016	17.3205	10000	1000	10	d	sim1a6 y5
0.0001	1	1	346.41016	173.205	10000	10000	1	d	sim1a6 y6
0.0001	1	3	346.41016	519.615	10000	30000	0.33333	d	sim1a6 y7
0.0001	1	5	346.41016	866.025	10000	50000	0.2	d	sim1a6 y8
0.0001	5	0	774.59666	0	50000	0	#DIV/0!	d	sim1a7 y1
0.0001	5	0.0001	774.59666	0.00774	50000	1	50000	d	sim1a7 y2
0.0001	5	0.001	774.59666	0.07745	50000	10	5000	d	sim1a7 y3
0.0001	5	0.01	774.59666	0.77459	50000	100	500	d	sim1a7 y4
0.0001	5	0.1	774.59666	7.74596	50000	1000	50	d	sim1a7 y5
0.0001	5	1	774.59666	77.4596	50000	10000	5	d	sim1a7 y6
0.0001	5	3	774.59666	232.379	50000	30000	1.66666	d	sim1a7 y7
0.0001	5	5	774.59666	387.298	50000	50000	1	d	sim1a7 y8
0.0001	10	0	1095.4451	0	100000	0	#DIV/0!	d	sim1a8 y1
0.0001	10	0.0001	1095.4451	0.00547	100000	1	100000	d	sim1a8 y2
0.0001	10	0.001	1095.4451	0.05477	100000	10	10000	d	sim1a8 y3
0.0001	10	0.01	1095.4451	0.54772	100000	100	1000	d	sim1a8 y4
0.0001	10	0.1	1095.4451	5.47722	100000	1000	100	d	sim1a8 y5
0.0001	10	1	1095.4451	54.7722	100000	10000	10	d	sim1a8 y6
0.0001	10	3	1095.4451	164.316	100000	30000	3.33333	d	sim1a8 y7
0.0001	10	5	1095.4451	273.861	100000	50000	2	d	sim1a8 y8

TABLE 3.6: SIMULATION RESULTS - SINE INPUT, 2 HERTZ

mass (slug)	k (lb/in)	Cv (lb/in/s)	ωn (rad/s)	ζ	h/m	C/ωn	k/Cv	code	designation
0.0001	0	0	0	#DIV/0!	0	0	#DIV/0!	a	sim1b1 y1
0.0001	0	0.0001	0	#DIV/0!	0	1	0	a	sim1b1 y2
0.0001	0	0.001	0	#DIV/0!	0	10	0	a	sim1b1 y3
0.0001	0	0.01	0	#DIV/0!	0	100	0	d	sim1b1 y4
0.0001	0	0.1	0	#DIV/0!	0	1000	0	d	sim1b1 y5
0.0001	0	1	0	#DIV/0!	0	10000	0	d	sim1b1 y6
0.0001	0	3	0	#DIV/0!	0	30000	0	d	sim1b1 y7
0.0001	0	5	0	#DIV/0!	0	50000	0	d	sim1b1 y8
0.0001	0.0001	0	3.4641016	0	1	0	#DIV/0!	a	sim1b2 y1
0.0001	0.0001	0.0001	3.4641016	1.73205	1	1	1	a	sim1b2 y2
0.0001	0.0001	0.001	3.4641016	17.3205	1	10	0.1	a	sim1b2 y3
0.0001	0.0001	0.01	3.4641016	173.205	1	100	0.01	d	sim1b2 y4
0.0001	0.0001	0.1	3.4641016	1732.05	1	1000	0.001	d	sim1b2 y5
0.0001	0.0001	1	3.4641016	17320.5	1	10000	0.0001	d	sim1b2 y6
0.0001	0.0001	3	3.4641016	51961.5	1	30000	3.33333	d	sim1b2 y7
0.0001	0.0001	5	3.4641016	86602.5	1	50000	0.00002	d	sim1b2 y8
0.0001	0.001	0	10.954451	0	10	0	#DIV/0!	a	sim1b3 y1
0.0001	0.001	0.0001	10.954451	0.54772	10	1	10	a	sim1b3 y2
0.0001	0.001	0.001	10.954451	5.47722	10	10	1	a	sim1b3 y3
0.0001	0.001	0.01	10.954451	54.7722	10	100	0.1	d	sim1b3 y4
0.0001	0.001	0.1	10.954451	547.722	10	1000	0.01	d	sim1b3 y5
0.0001	0.001	1	10.954451	5477.22	10	10000	0.001	d	sim1b3 y6
0.0001	0.001	3	10.954451	16431.6	10	30000	0.00033	d	sim1b3 y7
0.0001	0.001	5	10.954451	27386.1	10	50000	0.0002	d	sim1b3 y8
0.0001	0.01	0	34.641016	0	100	0	#DIV/0!	a	sim1b4 y1
0.0001	0.01	0.0001	34.641016	0.17320	100	1	100	a	sim1b4 y2
0.0001	0.01	0.001	34.641016	1.73205	100	10	10	a	sim1b4 y3
0.0001	0.01	0.01	34.641016	17.3205	100	100	1	d	sim1b4 y4
0.0001	0.01	0.1	34.641016	173.205	100	1000	0.1	d	sim1b4 y5
0.0001	0.01	1	34.641016	1732.05	100	10000	0.01	d	sim1b4 y6
0.0001	0.01	3	34.641016	5196.15	100	30000	0.00333	d	sim1b4 y7
0.0001	0.01	5	34.641016	8660.25	100	50000	0.002	d	sim1b4 y8
0.0001	0.1	0	109.54451	0	1000	0	#DIV/0!	a	sim1b5 y1
0.0001	0.1	0.0001	109.54451	0.05477	1000	1	1000	a	sim1b5 y2
0.0001	0.1	0.001	109.54451	0.54772	1000	10	100	a	sim1b5 y3
0.0001	0.1	0.01	109.54451	5.47722	1000	100	10	d	sim1b5 y4

TABLE 3.6: SIMULATION RESULTS - SINE INPUT, 2 HERTZ

mass (slug)	k (lb/in)	Cv (lb/in/s)	ω_n (rad/s)	ζ	h/m	Cv/m	k/Cv	code	designation
0.0001	0.1	0.1	109.54451	54.7722	1000	1000	1	d	sim1b5 y5
0.0001	0.1	1	109.54451	547.722	1000	10000	0.1	d	sim1b5 y6
0.0001	0.1	3	109.54451	1643.16	1000	30000	0.03333	d	sim1b5 y7
0.0001	0.1	5	109.54451	2738.61	1000	50000	0.02	d	sim1b5 y8
0.0001	1	0	346.41016	0	10000	0	#DIV/0!	d	sim1b6 y1
0.0001	1	0.0001	346.41016	0.01732	10000	1	10000	d	sim1b6 y2
0.0001	1	0.001	346.41016	0.17320	10000	10	1000	d	sim1b6 y3
0.0001	1	0.01	346.41016	1.73205	10000	100	100	d	sim1b6 y4
0.0001	1	0.1	346.41016	17.3205	10000	1000	10	d	sim1b6 y5
0.0001	1	1	346.41016	173.205	10000	10000	1	d	sim1b6 y6
0.0001	1	3	346.41016	519.615	10000	30000	0.33333	d	sim1b6 y7
0.0001	1	5	346.41016	866.025	10000	50000	0.2	d	sim1b6 y8
0.0001	5	0	774.59666	0	50000	0	#DIV/0!	d	sim1b7 y1
0.0001	5	0.0001	774.59666	0.00774	50000	1	50000	d	sim1b7 y2
0.0001	5	0.001	774.59666	0.07745	50000	10	5000	d	sim1b7 y3
0.0001	5	0.01	774.59666	0.77459	50000	100	500	d	sim1b7 y4
0.0001	5	0.1	774.59666	7.74596	50000	1000	50	d	sim1b7 y5
0.0001	5	1	774.59666	77.4596	50000	10000	5	d	sim1b7 y6
0.0001	5	3	774.59666	232.379	50000	30000	1.66666	d	sim1b7 y7
0.0001	5	5	774.59666	387.298	50000	50000	1	d	sim1b7 y8
0.0001	10	0	1095.4451	0	100000	0	#DIV/0!	d	sim1b8 y1
0.0001	10	0.0001	1095.4451	0.00547	100000	1	100000	d	sim1b8 y2
0.0001	10	0.001	1095.4451	0.05477	100000	10	10000	d	sim1b8 y3
0.0001	10	0.01	1095.4451	0.54772	100000	100	1000	d	sim1b8 y4
0.0001	10	0.1	1095.4451	5.47722	100000	1000	100	d	sim1b8 y5
0.0001	10	1	1095.4451	54.7722	100000	10000	10	d	sim1b8 y6
0.0001	10	3	1095.4451	164.316	100000	30000	3.33333	d	sim1b8 y7
0.0001	10	5	1095.4451	273.861	100000	50000	2	d	sim1b8 y8

TABLE 3.7: SIMULATION RESULTS - 1.0 lbf BREAKOUT FORCE

mass (slugs)	k (lb/in)	Cv (lb/in/s)	con (rad/s)	ζ	h/m	Cwm	h/Cv	code	designation
0.0001	0	0	0	#DIV/0!	0	0	#DIV/0!	a	sim1e1 y1
0.0001	0	0.0001	0	#DIV/0!	0	1	0	a	sim1e1 y2
0.0001	0	0.001	0	#DIV/0!	0	10	0	a	sim1e1 y3
0.0001	0	0.01	0	#DIV/0!	0	100	0	d	sim1e1 y4
0.0001	0	0.1	0	#DIV/0!	0	1000	0	d	sim1e1 y5
0.0001	0	1	0	#DIV/0!	0	10000	0	d	sim1e1 y6
0.0001	0	3	0	#DIV/0!	0	30000	0	d	sim1e1 y7
0.0001	0	5	0	#DIV/0!	0	50000	0	d	sim1e1 y8
0.0001	0.0001	0	3.4641016	0	1	0	#DIV/0!	a	sim1e2 y1
0.0001	0.0001	0.0001	3.4641016	1.73205	1	1	1	a	sim1e2 y2
0.0001	0.0001	0.001	3.4641016	17.3205	1	10	0.1	a	sim1e2 y3
0.0001	0.0001	0.01	3.4641016	173.205	1	100	0.01	d	sim1e2 y4
0.0001	0.0001	0.1	3.4641016	1732.05	1	1000	0.001	d	sim1e2 y5
0.0001	0.0001	1	3.4641016	17320.5	1	10000	0.0001	d	sim1e2 y6
0.0001	0.0001	3	3.4641016	51961.5	1	30000	3.33333	d	sim1e2 y7
0.0001	0.0001	5	3.4641016	86602.5	1	50000	0.00002	d	sim1e2 y8
0.0001	0.001	0	10.954451	0	10	0	#DIV/0!	a	sim1e3 y1
0.0001	0.001	0.0001	10.954451	0.54772	10	1	10	a	sim1e3 y2
0.0001	0.001	0.001	10.954451	5.47722	10	10	1	a	sim1e3 y3
0.0001	0.001	0.01	10.954451	54.7722	10	100	0.1	d	sim1e3 y4
0.0001	0.001	0.1	10.954451	547.722	10	1000	0.01	d	sim1e3 y5
0.0001	0.001	1	10.954451	5477.22	10	10000	0.001	d	sim1e3 y6
0.0001	0.001	3	10.954451	16431.6	10	30000	0.00033	d	sim1e3 y7
0.0001	0.001	5	10.954451	27386.1	10	50000	0.0002	d	sim1e3 y8
0.0001	0.01	0	34.641016	0	100	0	#DIV/0!	a	sim1e4 y1
0.0001	0.01	0.0001	34.641016	0.17320	100	1	100	a	sim1e4 y2
0.0001	0.01	0.001	34.641016	1.73205	100	10	10	a	sim1e4 y3
0.0001	0.01	0.01	34.641016	17.3205	100	100	1	d	sim1e4 y4
0.0001	0.01	0.1	34.641016	173.205	100	1000	0.1	d	sim1e4 y5
0.0001	0.01	1	34.641016	1732.05	100	10000	0.01	d	sim1e4 y6
0.0001	0.01	3	34.641016	5196.15	100	30000	0.00333	d	sim1e4 y7
0.0001	0.01	5	34.641016	8660.25	100	50000	0.002	d	sim1e4 y8
0.0001	0.1	0	109.54451	0	1000	0	#DIV/0!	a	sim1e5 y1
0.0001	0.1	0.0001	109.54451	0.05477	1000	1	1000	a	sim1e5 y2
0.0001	0.1	0.001	109.54451	0.54772	1000	10	100	a	sim1e5 y3

TABLE 3.7: SIMULATION RESULTS - 1.0 lbf BREAKOUT FORCE

mm (deg)	k (lb/in)	Cv (lb/in/h)	am (rad/s)	ζ	h/m	Cwm	h/Cv	code	designation
0.0001	0.1	0.01	109.54451	5.47722	1000	100	10	d	simle5 y4
0.0001	0.1	0.1	109.54451	5.47722	1000	1000	1	d	simle5 y5
0.0001	0.1	1	109.54451	5.47722	1000	10000	0.1	d	simle5 y6
0.0001	0.1	3	109.54451	1643.16	1000	30000	0.03333	d	simle5 y7
0.0001	0.1	5	109.54451	2738.61	1000	50000	0.02	d	simle5 y8
0.0001	1	0	346.41016	0	10000	0	#DIV/0!	d	simle6 y1
0.0001	1	0.0001	346.41016	0.01732	10000	1	10000	d	simle6 y2
0.0001	1	0.001	346.41016	0.17320	10000	10	1000	d	simle6 y3
0.0001	1	0.01	346.41016	1.73205	10000	100	100	d	simle6 y4
0.0001	1	0.1	346.41016	17.3205	10000	1000	10	d	simle6 y5
0.0001	1	1	346.41016	173.205	10000	10000	1	d	simle6 y6
0.0001	1	3	346.41016	519.615	10000	30000	0.33333	d	simle6 y7
0.0001	1	5	346.41016	866.025	10000	50000	0.2	d	simle6 y8
0.0001	5	0	774.59666	0	50000	0	#DIV/0!	d	simle7 y1
0.0001	5	0.0001	774.59666	0.00774	50000	1	50000	d	simle7 y2
0.0001	5	0.001	774.59666	0.07745	50000	10	5000	d	simle7 y3
0.0001	5	0.01	774.59666	0.77459	50000	100	500	d	simle7 y4
0.0001	5	0.1	774.59666	7.74596	50000	1000	50	d	simle7 y5
0.0001	5	1	774.59666	77.4596	50000	10000	5	d	simle7 y6
0.0001	5	3	774.59666	232.379	50000	30000	1.66666	d	simle7 y7
0.0001	5	5	774.59666	387.298	50000	50000	1	d	simle7 y8
0.0001	10	0	1095.4451	0	100000	0	#DIV/0!	d	simle8 y1
0.0001	10	0.0001	1095.4451	0.00547	100000	1	100000	d	simle8 y2
0.0001	10	0.001	1095.4451	0.05477	100000	10	10000	d	simle8 y3
0.0001	10	0.01	1095.4451	0.54772	100000	100	1000	d	simle8 y4
0.0001	10	0.1	1095.4451	5.47722	100000	1000	100	d	simle8 y5
0.0001	10	1	1095.4451	54.7722	100000	10000	10	d	simle8 y6
0.0001	10	3	1095.4451	164.316	100000	30000	3.33333	d	simle8 y7
0.0001	10	5	1095.4451	273.861	100000	50000	2	d	simle8 y8

TABLE 3.7: SIMULATION RESULTS - 1.8 lbf BREAKOUT FORCE

mm (deg)	Is (lb/in)	Cv (lb/in/s)	cm (rad/s)	ζ	Is/m	Cv/m	Is/Cv	code	designation
0.0001	0	0	0	#DIV/0!	0	0	#DIV/0!	a	sim1e21 y1
0.0001	0	0.0001	0	#DIV/0!	0	1	0	a	sim1e21 y2
0.0001	0	0.001	0	#DIV/0!	0	10	0	a	sim1e21 y3
0.0001	0	0.01	0	#DIV/0!	0	100	0	d	sim1e21 y4
0.0001	0	0.1	0	#DIV/0!	0	1000	0	d	sim1e21 y5
0.0001	0	1	0	#DIV/0!	0	10000	0	d	sim1e21 y6
0.0001	0	3	0	#DIV/0!	0	30000	0	d	sim1e21 y7
0.0001	0	5	0	#DIV/0!	0	50000	0	d	sim1e21 y8
0.0001	0.0001	0	3.4641016	0	1	0	#DIV/0!	a	sim1e22 y1
0.0001	0.0001	0.0001	3.4641016	1.73205	1	1	1	a	sim1e22 y2
0.0001	0.0001	0.001	3.4641016	17.3205	1	10	0.1	a	sim1e22 y3
0.0001	0.0001	0.01	3.4641016	173.205	1	100	0.01	d	sim1e22 y4
0.0001	0.0001	0.1	3.4641016	1732.05	1	1000	0.001	d	sim1e22 y5
0.0001	0.0001	1	3.4641016	17320.5	1	10000	0.0001	d	sim1e22 y6
0.0001	0.0001	3	3.4641016	51961.5	1	30000	3.33333	d	sim1e22 y7
0.0001	0.0001	5	3.4641016	86602.5	1	50000	0.00002	d	sim1e22 y8
0.0001	0.001	0	10.954451	0	10	0	#DIV/0!	a	sim1e23 y1
0.0001	0.001	0.0001	10.954451	0.54772	10	1	10	a	sim1e23 y2
0.0001	0.001	0.001	10.954451	5.47722	10	10	1	a	sim1e23 y3
0.0001	0.001	0.01	10.954451	54.7722	10	100	0.1	d	sim1e23 y4
0.0001	0.001	0.1	10.954451	547.722	10	1000	0.01	d	sim1e23 y5
0.0001	0.001	1	10.954451	5477.22	10	10000	0.001	d	sim1e23 y6
0.0001	0.001	3	10.954451	16431.6	10	30000	0.00033	d	sim1e23 y7
0.0001	0.001	5	10.954451	27386.1	10	50000	0.0002	d	sim1e23 y8
0.0001	0.01	0	34.641016	0	100	0	#DIV/0!	a	sim1e24 y1
0.0001	0.01	0.0001	34.641016	0.17320	100	1	100	a	sim1e24 y2
0.0001	0.01	0.001	34.641016	1.73205	100	10	10	a	sim1e24 y3
0.0001	0.01	0.01	34.641016	17.3205	100	100	1	d	sim1e24 y4
0.0001	0.01	0.1	34.641016	173.205	100	1000	0.1	d	sim1e24 y5
0.0001	0.01	1	34.641016	1732.05	100	10000	0.01	d	sim1e24 y6
0.0001	0.01	3	34.641016	5196.15	100	30000	0.00333	d	sim1e24 y7
0.0001	0.01	5	34.641016	8660.25	100	50000	0.002	d	sim1e24 y8
0.0001	0.1	0	109.54451	0	1000	0	#DIV/0!	a	sim1e25 y1
0.0001	0.1	0.0001	109.54451	0.05477	1000	1	1000	a	sim1e25 y2
0.0001	0.1	0.001	109.54451	0.54772	1000	10	100	a	sim1e25 y3

TABLE 3.7: SIMULATION RESULTS - 1.8 lbf BREAKOUT FORCE

mass (slugs)	k (lb/in)	Cv (lb/in/s)	cm (rad/s)	ζ	h/in	Cwin	h/Cv	code	designation
0.0001	0.1	0.01	109.54451	5.4772	1000	100	10	d	sim1e25 y4
0.0001	0.1	0.1	109.54451	54.772	1000	1000	1	d	sim1e25 y5
0.0001	0.1	1	109.54451	547.72	1000	10000	0.1	d	sim1e25 y6
0.0001	0.1	3	109.54451	1643.1	1000	30000	0.03333	d	sim1e25 y7
0.0001	0.1	5	109.54451	2738.6	1000	50000	0.02	d	sim1e25 y8
0.0001	1	0	346.41016	0	10000	0	#DIV/0!	d	sim1e26 y1
0.0001	1	0.0001	346.41016	0.0173	10000	1	10000	d	sim1e26 y2
0.0001	1	0.001	346.41016	0.1732	10000	10	1000	d	sim1e26 y3
0.0001	1	0.01	346.41016	1.7320	10000	100	100	d	sim1e26 y4
0.0001	1	0.1	346.41016	17.320	10000	1000	10	d	sim1e26 y5
0.0001	1	1	346.41016	173.20	10000	10000	1	d	sim1e26 y6
0.0001	1	3	346.41016	519.61	10000	30000	0.33333	d	sim1e26 y7
0.0001	1	5	346.41016	866.02	10000	50000	0.2	d	sim1e26 y8
0.0001	5	0	774.59666	0	50000	0	#DIV/0!	d	sim1e27 y1
0.0001	5	0.0001	774.59666	0.0077	50000	1	50000	d	sim1e27 y2
0.0001	5	0.001	774.59666	0.0774	50000	10	5000	d	sim1e27 y3
0.0001	5	0.01	774.59666	0.7745	50000	100	500	d	sim1e27 y4
0.0001	5	0.1	774.59666	7.7459	50000	1000	50	d	sim1e27 y5
0.0001	5	1	774.59666	77.459	50000	10000	5	d	sim1e27 y6
0.0001	5	3	774.59666	232.37	50000	30000	1.66666	d	sim1e27 y7
0.0001	5	5	774.59666	387.29	50000	50000	1	d	sim1e27 y8
0.0001	10	0	1095.4451	0	100000	0	#DIV/0!	d	sim1e28 y1
0.0001	10	0.0001	1095.4451	0.0054	100000	1	100000	d	sim1e28 y2
0.0001	10	0.001	1095.4451	0.0547	100000	10	10000	d	sim1e28 y3
0.0001	10	0.01	1095.4451	0.5477	100000	100	1000	d	sim1e28 y4
0.0001	10	0.1	1095.4451	5.4772	100000	1000	100	d	sim1e28 y5
0.0001	10	1	1095.4451	54.772	100000	10000	10	d	sim1e28 y6
0.0001	10	3	1095.4451	164.31	100000	30000	3.33333	d	sim1e28 y7
0.0001	10	5	1095.4451	273.86	100000	50000	2	d	sim1e28 y8

TABLE 3.7: SIMULATION RESULTS - 3.0 lbf BREAKOUT FORCE

mass (slug)	k (lb/in)	Cv (lb/in/s)	cm (rad/s)	ζ	lc/in	Cv/in	lc/Cv	code	designation
0.0001	0	0	0	#DIV/0!	0	0	#DIV/0!	l	simle31 y1
0.0001	0	0.0001	0	#DIV/0!	0	1	0	l	simle31 y2
0.0001	0	0.001	0	#DIV/0!	0	10	0	l	simle31 y3
0.0001	0	0.01	0	#DIV/0!	0	100	0	d	simle31 y4
0.0001	0	0.1	0	#DIV/0!	0	1000	0	d	simle31 y5
0.0001	0	1	0	#DIV/0!	0	10000	0	d	simle31 y6
0.0001	0	3	0	#DIV/0!	0	30000	0	d	simle31 y7
0.0001	0	5	0	#DIV/0!	0	50000	0	d	simle31 y8
0.0001	0.0001	0	3.4641016	0	1	0	#DIV/0!	l	simle32 y1
0.0001	0.0001	0.0001	3.4641016	1.7320	1	1	1	l	simle32 y2
0.0001	0.0001	0.001	3.4641016	17.320	1	10	0.1	l	simle32 y3
0.0001	0.0001	0.01	3.4641016	173.20	1	100	0.01	d	simle32 y4
0.0001	0.0001	0.1	3.4641016	1732.0	1	1000	0.001	d	simle32 y5
0.0001	0.0001	1	3.4641016	17320.	1	10000	0.0001	d	simle32 y6
0.0001	0.0001	3	3.4641016	51961.	1	30000	3.33333	d	simle32 y7
0.0001	0.0001	5	3.4641016	86602.	1	50000	0.00002	d	simle32 y8
0.0001	0.001	0	10.954451	0	10	0	#DIV/0!	l	simle33 y1
0.0001	0.001	0.0001	10.954451	0.5477	10	1	10	l	simle33 y2
0.0001	0.001	0.001	10.954451	5.4772	10	10	1	l	simle33 y3
0.0001	0.001	0.01	10.954451	54.772	10	100	0.1	d	simle33 y4
0.0001	0.001	0.1	10.954451	547.72	10	1000	0.01	d	simle33 y5
0.0001	0.001	1	10.954451	5477.2	10	10000	0.001	d	simle33 y6
0.0001	0.001	3	10.954451	16431.	10	30000	0.00033	d	simle33 y7
0.0001	0.001	5	10.954451	27386.	10	50000	0.0002	d	simle33 y8
0.0001	0.01	0	34.641016	0	100	0	#DIV/0!	l	simle34 y1
0.0001	0.01	0.0001	34.641016	0.1732	100	1	100	l	simle34 y2
0.0001	0.01	0.001	34.641016	1.7320	100	10	10	l	simle34 y3
0.0001	0.01	0.01	34.641016	17.320	100	100	1	d	simle34 y4
0.0001	0.01	0.1	34.641016	173.20	100	1000	0.1	d	simle34 y5
0.0001	0.01	1	34.641016	1732.0	100	10000	0.01	d	simle34 y6
0.0001	0.01	3	34.641016	5196.1	100	30000	0.00333	d	simle34 y7
0.0001	0.01	5	34.641016	8660.2	100	50000	0.002	d	simle34 y8
0.0001	0.1	0	109.54451	0	1000	0	#DIV/0!	l	simle35 y1
0.0001	0.1	0.0001	109.54451	0.0547	1000	1	1000	l	simle35 y2
0.0001	0.1	0.001	109.54451	0.5477	1000	10	100	l	simle35 y3

TABLE 3.7: SIMULATION RESULTS - 3.0 lbf BREAKOUT FORCE

mass (slug)	k (lb/in)	Cv (lb/in/s)	am (rad/s)	ζ	l/m		l/Cv	code	designation
0.0001	0.1	0.01	109.54451	5.4772	1000	100	10	d	sim1e35 y4
0.0001	0.1	0.1	109.54451	54.772	1000	1000	1	d	sim1e35 y5
0.0001	0.1	1	109.54451	547.72	1000	10000	0.1	d	sim1e35 y6
0.0001	0.1	3	109.54451	1643.1	1000	30000	0.03333	d	sim1e35 y7
0.0001	0.1	5	109.54451	2738.6	1000	50000	0.02	d	sim1e35 y8
0.0001	1	0	346.41016	0	10000	0	#DIV/0!	d	sim1e36 y1
0.0001	1	0.0001	346.41016	0.0173	10000	1	10000	d	sim1e36 y2
0.0001	1	0.001	346.41016	0.1732	10000	10	1000	d	sim1e36 y3
0.0001	1	0.01	346.41016	1.7320	10000	100	100	d	sim1e36 y4
0.0001	1	0.1	346.41016	17.320	10000	1000	10	d	sim1e36 y5
0.0001	1	1	346.41016	173.20	10000	10000	1	d	sim1e36 y6
0.0001	1	3	346.41016	519.61	10000	30000	0.33333	d	sim1e36 y7
0.0001	1	5	346.41016	866.02	10000	50000	0.2	d	sim1e36 y8
0.0001	5	0	774.59666	0	50000	0	#DIV/0!	d	sim1e37 y1
0.0001	5	0.0001	774.59666	0.0077	50000	1	50000	d	sim1e37 y2
0.0001	5	0.001	774.59666	0.0774	50000	10	5000	d	sim1e37 y3
0.0001	5	0.01	774.59666	0.7745	50000	100	500	d	sim1e37 y4
0.0001	5	0.1	774.59666	7.7459	50000	1000	50	d	sim1e37 y5
0.0001	5	1	774.59666	77.459	50000	10000	5	d	sim1e37 y6
0.0001	5	3	774.59666	232.37	50000	30000	1.66666	d	sim1e37 y7
0.0001	5	5	774.59666	387.29	50000	50000	1	d	sim1e37 y8
0.0001	10	0	1095.4451	0	100000	0	#DIV/0!	d	sim1e38 y1
0.0001	10	0.0001	1095.4451	0.0054	100000	1	100000	d	sim1e38 y2
0.0001	10	0.001	1095.4451	0.0547	100000	10	10000	d	sim1e38 y3
0.0001	10	0.01	1095.4451	0.5477	100000	100	1000	d	sim1e38 y4
0.0001	10	0.1	1095.4451	5.4772	100000	1000	100	d	sim1e38 y5
0.0001	10	1	1095.4451	54.772	100000	10000	10	d	sim1e38 y6
0.0001	10	3	1095.4451	164.31	100000	30000	3.33333	d	sim1e38 y7
0.0001	10	5	1095.4451	273.86	100000	50000	2	d	sim1e38 y8

TABLE 3.8: SIMULATION RESULTS - 1.0 lbf STATIC FRICTION

mass (slug)	k (lb/in)	Cv (lb/in/s)	cm (rad/s)	ζ	h/m		h/Cv	code	designation
0.0001	0	0	0	#DIV/0!	0	0	#DIV/0!	a	sim1f1 y1
0.0001	0	0.0001	0	#DIV/0!	0	1	0	a	sim1f1 y2
0.0001	0	0.001	0	#DIV/0!	0	10	0	a	sim1f1 y3
0.0001	0	0.01	0	#DIV/0!	0	100	0	d	sim1f1 y4
0.0001	0	0.1	0	#DIV/0!	0	1000	0	d	sim1f1 y5
0.0001	0	1	0	#DIV/0!	0	10000	0	d	sim1f1 y6
0.0001	0	3	0	#DIV/0!	0	30000	0	d	sim1f1 y7
0.0001	0	5	0	#DIV/0!	0	50000	0	d	sim1f1 y8
0.0001	0.0001	0	3.4641016	0	1	0	#DIV/0!	a	sim1f2 y1
0.0001	0.0001	0.0001	3.4641016	1.7320	1	1	1	a	sim1f2 y2
0.0001	0.0001	0.001	3.4641016	17.320	1	10	0.1	a	sim1f2 y3
0.0001	0.0001	0.01	3.4641016	173.20	1	100	0.01	d	sim1f2 y4
0.0001	0.0001	0.1	3.4641016	1732.0	1	1000	0.001	d	sim1f2 y5
0.0001	0.0001	1	3.4641016	17320.	1	10000	0.0001	d	sim1f2 y6
0.0001	0.0001	3	3.4641016	51961.	1	30000	3.33333	d	sim1f2 y7
0.0001	0.0001	5	3.4641016	86602.	1	50000	0.00002	d	sim1f2 y8
0.0001	0.001	0	10.954451	0	10	0	#DIV/0!	a	sim1f3 y1
0.0001	0.001	0.0001	10.954451	0.5477	10	1	10	a	sim1f3 y2
0.0001	0.001	0.001	10.954451	5.4772	10	10	1	a	sim1f3 y3
0.0001	0.001	0.01	10.954451	54.772	10	100	0.1	d	sim1f3 y4
0.0001	0.001	0.1	10.954451	547.72	10	1000	0.01	d	sim1f3 y5
0.0001	0.001	1	10.954451	5477.2	10	10000	0.001	d	sim1f3 y6
0.0001	0.001	3	10.954451	16431.	10	30000	0.00033	d	sim1f3 y7
0.0001	0.001	5	10.954451	27386.	10	50000	0.0002	d	sim1f3 y8
0.0001	0.01	0	34.641016	0	100	0	#DIV/0!	a	sim1f4 y1
0.0001	0.01	0.0001	34.641016	0.1732	100	1	100	a	sim1f4 y2
0.0001	0.01	0.001	34.641016	1.7320	100	10	10	a	sim1f4 y3
0.0001	0.01	0.01	34.641016	17.320	100	100	1	d	sim1f4 y4
0.0001	0.01	0.1	34.641016	173.20	100	1000	0.1	d	sim1f4 y5
0.0001	0.01	1	34.641016	1732.0	100	10000	0.01	d	sim1f4 y6
0.0001	0.01	3	34.641016	5196.1	100	30000	0.00333	d	sim1f4 y7
0.0001	0.01	5	34.641016	8660.2	100	50000	0.002	d	sim1f4 y8
0.0001	0.1	0	109.54451	0	1000	0	#DIV/0!	a	sim1f5 y1
0.0001	0.1	0.0001	109.54451	0.0547	1000	1	1000	a	sim1f5 y2
0.0001	0.1	0.001	109.54451	0.5477	1000	10	100	a	sim1f5 y3

TABLE 3.8: SIMULATION RESULTS - 1.0 lbf STATIC FRICTION

mass (slugs)	k (lb/in)	Cv (lb/in/s)	ω_n (rad/s)	ζ	b/m		b/Cv	code	designation
0.0001	0.1	0.01	109.54451	5.47722	1000	100	10	d	sim1f5 y4
0.0001	0.1	0.1	109.54451	54.7722	1000	1000	1	d	sim1f5 y5
0.0001	0.1	1	109.54451	547.722	1000	10000	0.1	d	sim1f5 y6
0.0001	0.1	3	109.54451	1643.16	1000	30000	0.03333	d	sim1f5 y7
0.0001	0.1	5	109.54451	2738.61	1000	50000	0.02	d	sim1f5 y8
0.0001	1	0	346.41016	0	10000	0	#DIV/0!	d	sim1f6 y1
0.0001	1	0.0001	346.41016	0.01732	10000	1	10000	d	sim1f6 y2
0.0001	1	0.001	346.41016	0.17320	10000	10	1000	d	sim1f6 y3
0.0001	1	0.01	346.41016	1.73205	10000	100	100	d	sim1f6 y4
0.0001	1	0.1	346.41016	17.3205	10000	1000	10	d	sim1f6 y5
0.0001	1	1	346.41016	173.205	10000	10000	1	d	sim1f6 y6
0.0001	1	3	346.41016	519.615	10000	30000	0.33333	d	sim1f6 y7
0.0001	1	5	346.41016	866.025	10000	50000	0.2	d	sim1f6 y8
0.0001	5	0	774.59666	0	50000	0	#DIV/0!	d	sim1f7 y1
0.0001	5	0.0001	774.59666	0.00774	50000	1	50000	d	sim1f7 y2
0.0001	5	0.001	774.59666	0.07745	50000	10	5000	d	sim1f7 y3
0.0001	5	0.01	774.59666	0.77459	50000	100	500	d	sim1f7 y4
0.0001	5	0.1	774.59666	7.74596	50000	1000	50	d	sim1f7 y5
0.0001	5	1	774.59666	77.4596	50000	10000	5	d	sim1f7 y6
0.0001	5	3	774.59666	232.379	50000	30000	1.66666	d	sim1f7 y7
0.0001	5	5	774.59666	387.298	50000	50000	1	d	sim1f7 y8
0.0001	10	0	1095.4451	0	100000	0	#DIV/0!	d	sim1f8 y1
0.0001	10	0.0001	1095.4451	0.00547	100000	1	100000	d	sim1f8 y2
0.0001	10	0.001	1095.4451	0.05477	100000	10	10000	d	sim1f8 y3
0.0001	10	0.01	1095.4451	0.54772	100000	100	1000	d	sim1f8 y4
0.0001	10	0.1	1095.4451	5.47722	100000	1000	100	d	sim1f8 y5
0.0001	10	1	1095.4451	54.7722	100000	10000	10	d	sim1f8 y6
0.0001	10	3	1095.4451	164.316	100000	30000	3.33333	d	sim1f8 y7
0.0001	10	5	1095.4451	273.861	100000	50000	2	d	sim1f8 y8

TABLE 3.8: SIMULATION RESULTS - 1.8 lbf STATIC FRICTION

mass (slug)	k (lb/in)	Cv (lb/in/s)	ω_n (rad/s)	ζ	l/m	Cv/m	k/Cv	code	designation
0.0001	0	0	0	#DIV/0!	0	0	#DIV/0!	a	sim1f21 y1
0.0001	0	0.0001	0	#DIV/0!	0	1	0	a	sim1f21 y2
0.0001	0	0.001	0	#DIV/0!	0	10	0	a	sim1f21 y3
0.0001	0	0.01	0	#DIV/0!	0	100	0	d	sim1f21 y4
0.0001	0	0.1	0	#DIV/0!	0	1000	0	d	sim1f21 y5
0.0001	0	1	0	#DIV/0!	0	10000	0	d	sim1f21 y6
0.0001	0	3	0	#DIV/0!	0	30000	0	d	sim1f21 y7
0.0001	0	5	0	#DIV/0!	0	50000	0	d	sim1f21 y8
0.0001	0.0001	0	3.4641016	0	1	0	#DIV/0!	a	sim1f22 y1
0.0001	0.0001	0.0001	3.4641016	1.73205	1	1	1	a	sim1f22 y2
0.0001	0.0001	0.001	3.4641016	17.3205	1	10	0.1	a	sim1f22 y3
0.0001	0.0001	0.01	3.4641016	173.205	1	100	0.01	d	sim1f22 y4
0.0001	0.0001	0.1	3.4641016	1732.05	1	1000	0.001	d	sim1f22 y5
0.0001	0.0001	1	3.4641016	17320.5	1	10000	0.0001	d	sim1f22 y6
0.0001	0.0001	3	3.4641016	51961.5	1	30000	3.33333	d	sim1f22 y7
0.0001	0.0001	5	3.4641016	86602.5	1	50000	0.00002	d	sim1f22 y8
0.0001	0.001	0	10.954451	0	10	0	#DIV/0!	a	sim1f23 y1
0.0001	0.001	0.0001	10.954451	0.54772	10	1	10	a	sim1f23 y2
0.0001	0.001	0.001	10.954451	5.47722	10	10	1	a	sim1f23 y3
0.0001	0.001	0.01	10.954451	54.7722	10	100	0.1	d	sim1f23 y4
0.0001	0.001	0.1	10.954451	547.722	10	1000	0.01	d	sim1f23 y5
0.0001	0.001	1	10.954451	5477.22	10	10000	0.001	d	sim1f23 y6
0.0001	0.001	3	10.954451	16431.6	10	30000	0.00033	d	sim1f23 y7
0.0001	0.001	5	10.954451	27386.1	10	50000	0.0002	d	sim1f23 y8
0.0001	0.01	0	34.641016	0	100	0	#DIV/0!	a	sim1f24 y1
0.0001	0.01	0.0001	34.641016	0.17320	100	1	100	a	sim1f24 y2
0.0001	0.01	0.001	34.641016	1.73205	100	10	10	a	sim1f24 y3
0.0001	0.01	0.01	34.641016	17.3205	100	100	1	d	sim1f24 y4
0.0001	0.01	0.1	34.641016	173.205	100	1000	0.1	d	sim1f24 y5
0.0001	0.01	1	34.641016	1732.05	100	10000	0.01	d	sim1f24 y6
0.0001	0.01	3	34.641016	5196.15	100	30000	0.00333	d	sim1f24 y7
0.0001	0.01	5	34.641016	8660.25	100	50000	0.002	d	sim1f24 y8
0.0001	0.1	0	109.54451	0	1000	0	#DIV/0!	a	sim1f25 y1
0.0001	0.1	0.0001	109.54451	0.05477	1000	1	1000	a	sim1f25 y2
0.0001	0.1	0.001	109.54451	0.54772	1000	10	100	a	sim1f25 y3

TABLE 3.8: SIMULATION RESULTS - 1.8 lbf STATIC FRICTION

mass (slug)	k (lb/in)	Cv (lb/in/s)	ω_n (rad/s)	ζ	k/m	Cv/m	k/Cv	code	designation
0.0001	0.1	0.01	109.54451	5.47722	1000	100	10	d	sim1f25 y4
0.0001	0.1	0.1	109.54451	54.7722	1000	1000	1	d	sim1f25 y5
0.0001	0.1	1	109.54451	547.722	1000	10000	0.1	d	sim1f25 y6
0.0001	0.1	3	109.54451	1643.16	1000	30000	0.03333	d	sim1f25 y7
0.0001	0.1	5	109.54451	2738.61	1000	50000	0.02	d	sim1f25 y8
0.0001	1	0	346.41016	0	10000	0	#DIV/0!	d	sim1f26 y1
0.0001	1	0.0001	346.41016	0.01732	10000	1	10000	d	sim1f26 y2
0.0001	1	0.001	346.41016	0.17320	10000	10	1000	d	sim1f26 y3
0.0001	1	0.01	346.41016	1.73205	10000	100	100	d	sim1f26 y4
0.0001	1	0.1	346.41016	17.3205	10000	1000	10	d	sim1f26 y5
0.0001	1	1	346.41016	173.205	10000	10000	1	d	sim1f26 y6
0.0001	1	3	346.41016	519.615	10000	30000	0.33333	d	sim1f26 y7
0.0001	1	5	346.41016	866.025	10000	50000	0.2	d	sim1f26 y8
0.0001	5	0	774.59666	0	50000	0	#DIV/0!	d	sim1f27 y1
0.0001	5	0.0001	774.59666	0.00774	50000	1	50000	d	sim1f27 y2
0.0001	5	0.001	774.59666	0.07745	50000	10	5000	d	sim1f27 y3
0.0001	5	0.01	774.59666	0.77459	50000	100	500	d	sim1f27 y4
0.0001	5	0.1	774.59666	7.74596	50000	1000	50	d	sim1f27 y5
0.0001	5	1	774.59666	77.4596	50000	10000	5	d	sim1f27 y6
0.0001	5	3	774.59666	232.379	50000	30000	1.66666	d	sim1f27 y7
0.0001	5	5	774.59666	387.298	50000	50000	1	d	sim1f27 y8
0.0001	10	0	1095.4451	0	100000	0	#DIV/0!	d	sim1f28 y1
0.0001	10	0.0001	1095.4451	0.00547	100000	1	100000	d	sim1f28 y2
0.0001	10	0.001	1095.4451	0.05477	100000	10	10000	d	sim1f28 y3
0.0001	10	0.01	1095.4451	0.54772	100000	100	1000	d	sim1f28 y4
0.0001	10	0.1	1095.4451	5.47722	100000	1000	100	d	sim1f28 y5
0.0001	10	1	1095.4451	54.7722	100000	10000	10	d	sim1f28 y6
0.0001	10	3	1095.4451	164.316	100000	30000	3.33333	d	sim1f28 y7
0.0001	10	5	1095.4451	273.861	100000	50000	2	d	sim1f28 y8

TABLE 3.8: SIMULATION RESULTS - 3.0 lbf STATIC FRICTION

mass (slug)	k (lb/in)	Cv (lb/in/s)	am (rad/s)	ζ	l/m	Cwm	l/Cv	code	designation
0.0001	0	0	0	#DIV/0!	0	0	#DIV/0!	l	sim1f31 y1
0.0001	0	0.0001	0	#DIV/0!	0	1	0	l	sim1f31 y2
0.0001	0	0.001	0	#DIV/0!	0	10	0	l	sim1f31 y3
0.0001	0	0.01	0	#DIV/0!	0	100	0	d	sim1f31 y4
0.0001	0	0.1	0	#DIV/0!	0	1000	0	d	sim1f31 y5
0.0001	0	1	0	#DIV/0!	0	10000	0	d	sim1f31 y6
0.0001	0	3	0	#DIV/0!	0	30000	0	d	sim1f31 y7
0.0001	0	5	0	#DIV/0!	0	50000	0	d	sim1f31 y8
0.0001	0.0001	0	3.4641016	0	1	0	#DIV/0!	l	sim1f32 y1
0.0001	0.0001	0.0001	3.4641016	1.73205	1	1	1	l	sim1f32 y2
0.0001	0.0001	0.001	3.4641016	17.3205	1	10	0.1	l	sim1f32 y3
0.0001	0.0001	0.01	3.4641016	173.205	1	100	0.01	d	sim1f32 y4
0.0001	0.0001	0.1	3.4641016	1732.05	1	1000	0.001	d	sim1f32 y5
0.0001	0.0001	1	3.4641016	17320.5	1	10000	0.0001	d	sim1f32 y6
0.0001	0.0001	3	3.4641016	51961.5	1	30000	3.33333	d	sim1f32 y7
0.0001	0.0001	5	3.4641016	86602.5	1	50000	0.00002	d	sim1f32 y8
0.0001	0.001	0	10.954451	0	10	0	#DIV/0!	l	sim1f33 y1
0.0001	0.001	0.0001	10.954451	0.54772	10	1	10	l	sim1f33 y2
0.0001	0.001	0.001	10.954451	5.47722	10	10	1	l	sim1f33 y3
0.0001	0.001	0.01	10.954451	54.7722	10	100	0.1	d	sim1f33 y4
0.0001	0.001	0.1	10.954451	547.722	10	1000	0.01	d	sim1f33 y5
0.0001	0.001	1	10.954451	5477.22	10	10000	0.001	d	sim1f33 y6
0.0001	0.001	3	10.954451	16431.6	10	30000	0.00033	d	sim1f33 y7
0.0001	0.001	5	10.954451	27386.1	10	50000	0.0002	d	sim1f33 y8
0.0001	0.01	0	34.641016	0	100	0	#DIV/0!	l	sim1f34 y1
0.0001	0.01	0.0001	34.641016	0.17320	100	1	100	l	sim1f34 y2
0.0001	0.01	0.001	34.641016	1.73205	100	10	10	l	sim1f34 y3
0.0001	0.01	0.01	34.641016	17.3205	100	100	1	d	sim1f34 y4
0.0001	0.01	0.1	34.641016	173.205	100	1000	0.1	d	sim1f34 y5
0.0001	0.01	1	34.641016	1732.05	100	10000	0.01	d	sim1f34 y6
0.0001	0.01	3	34.641016	5196.15	100	30000	0.00333	d	sim1f34 y7
0.0001	0.01	5	34.641016	8660.25	100	50000	0.002	d	sim1f34 y8
0.0001	0.1	0	109.54451	0	1000	0	#DIV/0!	l	sim1f35 y1
0.0001	0.1	0.0001	109.54451	0.05477	1000	1	1000	l	sim1f35 y2
0.0001	0.1	0.001	109.54451	0.54772	1000	10	100	l	sim1f35 y3

TABLE 3.8: SIMULATION RESULTS - 3.0 lbf STATIC FRICTION

mass (slug)	k (lb/in)	Cv (lb/in/s)	ω_n (rad/s)	ζ	h/in	Cwin	h/Cv	code	designation
0.0001	0.1	0.01	109.54451	5.47722	1000	100	10	d	sim1f35 y4
0.0001	0.1	0.1	109.54451	54.7722	1000	1000	1	d	sim1f35 y5
0.0001	0.1	1	109.54451	547.722	1000	10000	0.1	d	sim1f35 y6
0.0001	0.1	3	109.54451	1643.16	1000	30000	0.03333	d	sim1f35 y7
0.0001	0.1	5	109.54451	2738.61	1000	50000	0.02	d	sim1f35 y8
0.0001	1	0	346.41016	0	10000	0	#DIV/0!	d	sim1f36 y1
0.0001	1	0.0001	346.41016	0.01732	10000	1	10000	d	sim1f36 y2
0.0001	1	0.001	346.41016	0.17320	10000	10	1000	d	sim1f36 y3
0.0001	1	0.01	346.41016	1.73205	10000	100	100	d	sim1f36 y4
0.0001	1	0.1	346.41016	17.3205	10000	1000	10	d	sim1f36 y5
0.0001	1	1	346.41016	173.205	10000	10000	1	d	sim1f36 y6
0.0001	1	3	346.41016	519.615	10000	30000	0.33333	d	sim1f36 y7
0.0001	1	5	346.41016	866.025	10000	50000	0.2	d	sim1f36 y8
0.0001	5	0	774.59666	0	50000	0	#DIV/0!	d	sim1f37 y1
0.0001	5	0.0001	774.59666	0.00774	50000	1	50000	d	sim1f37 y2
0.0001	5	0.001	774.59666	0.07745	50000	10	5000	d	sim1f37 y3
0.0001	5	0.01	774.59666	0.77459	50000	100	500	d	sim1f37 y4
0.0001	5	0.1	774.59666	7.74596	50000	1000	50	d	sim1f37 y5
0.0001	5	1	774.59666	77.4596	50000	10000	5	d	sim1f37 y6
0.0001	5	3	774.59666	232.379	50000	30000	1.66666	d	sim1f37 y7
0.0001	5	5	774.59666	387.298	50000	50000	1	d	sim1f37 y8
0.0001	10	0	1095.4451	0	100000	0	#DIV/0!	d	sim1f38 y1
0.0001	10	0.0001	1095.4451	0.00547	100000	1	100000	d	sim1f38 y2
0.0001	10	0.001	1095.4451	0.05477	100000	10	10000	d	sim1f38 y3
0.0001	10	0.01	1095.4451	0.54772	100000	100	1000	d	sim1f38 y4
0.0001	10	0.1	1095.4451	5.47722	100000	1000	100	d	sim1f38 y5
0.0001	10	1	1095.4451	54.7722	100000	10000	10	d	sim1f38 y6
0.0001	10	3	1095.4451	164.316	100000	30000	3.33333	d	sim1f38 y7
0.0001	10	5	1095.4451	273.861	100000	50000	2	d	sim1f38 y8

TABLE 3.9: SIMULATION RESULTS - STRAIN GAUGE NOISE

mass (slug)	k (lb/in)	Cv (lb/in/s)	ω_n (rad/s)	ζ	k/m	Cv/m	k/Cv	code	designation
0.0001	0	0	0	#DIV/0!	0	0	#DIV/0!	a	sim1c1 y1
0.0001	0	0.0001	0	#DIV/0!	0	1	0	a	sim1c1 y2
0.0001	0	0.001	0	#DIV/0!	0	10	0	a	sim1c1 y3
0.0001	0	0.01	0	#DIV/0!	0	100	0	d	sim1c1 y4
0.0001	0	0.1	0	#DIV/0!	0	1000	0	d	sim1c1 y5
0.0001	0	1	0	#DIV/0!	0	10000	0	d	sim1c1 y6
0.0001	0	3	0	#DIV/0!	0	30000	0	d	sim1c1 y7
0.0001	0	5	0	#DIV/0!	0	50000	0	d	sim1c1 y8
0.0001	0.0001	0	3.4641016	0	1	0	#DIV/0!	a	sim1c2 y1
0.0001	0.0001	0.0001	3.4641016	1.73205	1	1	1	a	sim1c2 y2
0.0001	0.0001	0.001	3.4641016	17.3205	1	10	0.1	a	sim1c2 y3
0.0001	0.0001	0.01	3.4641016	173.205	1	100	0.01	d	sim1c2 y4
0.0001	0.0001	0.1	3.4641016	1732.05	1	1000	0.001	d	sim1c2 y5
0.0001	0.0001	1	3.4641016	17320.5	1	10000	0.0001	d	sim1c2 y6
0.0001	0.0001	3	3.4641016	51961.5	1	30000	3.33333	d	sim1c2 y7
0.0001	0.0001	5	3.4641016	86602.5	1	50000	0.00002	d	sim1c2 y8
0.0001	0.001	0	10.954451	0	10	0	#DIV/0!	a	sim1c3 y1
0.0001	0.001	0.0001	10.954451	0.54772	10	1	10	a	sim1c3 y2
0.0001	0.001	0.001	10.954451	5.47722	10	10	1	a	sim1c3 y3
0.0001	0.001	0.01	10.954451	54.7722	10	100	0.1	d	sim1c3 y4
0.0001	0.001	0.1	10.954451	547.722	10	1000	0.01	d	sim1c3 y5
0.0001	0.001	1	10.954451	5477.22	10	10000	0.001	d	sim1c3 y6
0.0001	0.001	3	10.954451	16431.6	10	30000	0.00033	d	sim1c3 y7
0.0001	0.001	5	10.954451	27386.1	10	50000	0.0002	d	sim1c3 y8
0.0001	0.01	0	34.641016	0	100	0	#DIV/0!	a	sim1c4 y1
0.0001	0.01	0.0001	34.641016	0.17320	100	1	100	a	sim1c4 y2
0.0001	0.01	0.001	34.641016	1.73205	100	10	10	a	sim1c4 y3
0.0001	0.01	0.01	34.641016	17.3205	100	100	1	d	sim1c4 y4
0.0001	0.01	0.1	34.641016	173.205	100	1000	0.1	d	sim1c4 y5
0.0001	0.01	1	34.641016	1732.05	100	10000	0.01	d	sim1c4 y6
0.0001	0.01	3	34.641016	5196.15	100	30000	0.00333	d	sim1c4 y7
0.0001	0.01	5	34.641016	8660.25	100	50000	0.002	d	sim1c4 y8
0.0001	0.1	0	109.54451	0	1000	0	#DIV/0!	a	sim1c5 y1
0.0001	0.1	0.0001	109.54451	0.05477	1000	1	1000	a	sim1c5 y2
0.0001	0.1	0.001	109.54451	0.54772	1000	10	100	a	sim1c5 y3

TABLE 3.9: SIMULATION RESULTS - STRAIN GAUGE NOISE

mass (slug)	k (lb/in)	Cv (lb/in/s)	am (rad/s)	ζ	l/m	Cw/m	l/Cv	code	designation
0.0001	0.1	0.01	109.54451	5.47722	1000	100	10	d	sim1e5 y4
0.0001	0.1	0.1	109.54451	54.7722	1000	1000	1	d	sim1e5 y5
0.0001	0.1	1	109.54451	547.722	1000	10000	0.1	d	sim1e5 y6
0.0001	0.1	3	109.54451	1643.16	1000	30000	0.03333	d	sim1e5 y7
0.0001	0.1	5	109.54451	2738.61	1000	50000	0.02	d	sim1e5 y8
0.0001	1	0	346.41016	0	10000	0	#DIV/0!	d	sim1e6 y1
0.0001	1	0.0001	346.41016	0.01732	10000	1	10000	d	sim1e6 y2
0.0001	1	0.001	346.41016	0.17320	10000	10	1000	d	sim1e6 y3
0.0001	1	0.01	346.41016	1.73205	10000	100	100	d	sim1e6 y4
0.0001	1	0.1	346.41016	17.3205	10000	1000	10	d	sim1e6 y5
0.0001	1	1	346.41016	173.205	10000	10000	1	d	sim1e6 y6
0.0001	1	3	346.41016	519.615	10000	30000	0.33333	d	sim1e6 y7
0.0001	1	5	346.41016	866.025	10000	50000	0.2	d	sim1e6 y8
0.0001	5	0	774.59666	0	50000	0	#DIV/0!	d	sim1e7 y1
0.0001	5	0.0001	774.59666	0.00774	50000	1	50000	d	sim1e7 y2
0.0001	5	0.001	774.59666	0.07745	50000	10	5000	d	sim1e7 y3
0.0001	5	0.01	774.59666	0.77459	50000	100	500	d	sim1e7 y4
0.0001	5	0.1	774.59666	7.74596	50000	1000	50	d	sim1e7 y5
0.0001	5	1	774.59666	77.4596	50000	10000	5	d	sim1e7 y6
0.0001	5	3	774.59666	232.379	50000	30000	1.66666	d	sim1e7 y7
0.0001	5	5	774.59666	387.298	50000	50000	1	d	sim1e7 y8
0.0001	10	0	1095.4451	0	100000	0	#DIV/0!	d	sim1e8 y1
0.0001	10	0.0001	1095.4451	0.00547	100000	1	100000	d	sim1e8 y2
0.0001	10	0.001	1095.4451	0.05477	100000	10	10000	d	sim1e8 y3
0.0001	10	0.01	1095.4451	0.54772	100000	100	1000	d	sim1e8 y4
0.0001	10	0.1	1095.4451	5.47722	100000	1000	100	d	sim1e8 y5
0.0001	10	1	1095.4451	54.7722	100000	10000	10	d	sim1e8 y6
0.0001	10	3	1095.4451	164.316	100000	30000	3.33333	d	sim1e8 y7
0.0001	10	5	1095.4451	273.861	100000	50000	2	d	sim1e8 y8

TABLE 3.10: SIMULATION RESULTS - POSITION SENSOR NOISE

mass (slug)	k (lb/in)	Cv (lb/in/s)	cm (rad/s)	ζ	l/in	Cv/in	l/Cv	code	designation
0.0001	0	0	0	#DIV/0!	0	0	#DIV/0!	a	sim1d1 y1
0.0001	0	0.0001	0	#DIV/0!	0	1	0	a	sim1d1 y2
0.0001	0	0.001	0	#DIV/0!	0	10	0	a	sim1d1 y3
0.0001	0	0.01	0	#DIV/0!	0	100	0	d	sim1d1 y4
0.0001	0	0.1	0	#DIV/0!	0	1000	0	d	sim1d1 y5
0.0001	0	1	0	#DIV/0!	0	10000	0	d	sim1d1 y6
0.0001	0	3	0	#DIV/0!	0	30000	0	d	sim1d1 y7
0.0001	0	5	0	#DIV/0!	0	50000	0	d	sim1d1 y8
0.0001	0.0001	0	3.4641016	0	1	0	#DIV/0!	a	sim1d2 y1
0.0001	0.0001	0.0001	3.4641016	1.73205	1	1	1	a	sim1d2 y2
0.0001	0.0001	0.001	3.4641016	17.3205	1	10	0.1	a	sim1d2 y3
0.0001	0.0001	0.01	3.4641016	173.205	1	100	0.01	d	sim1d2 y4
0.0001	0.0001	0.1	3.4641016	1732.05	1	1000	0.001	d	sim1d2 y5
0.0001	0.0001	1	3.4641016	17320.5	1	10000	0.0001	d	sim1d2 y6
0.0001	0.0001	3	3.4641016	51961.5	1	30000	3.33333	d	sim1d2 y7
0.0001	0.0001	5	3.4641016	86602.5	1	50000	0.00002	d	sim1d2 y8
0.0001	0.001	0	10.954451	0	10	0	#DIV/0!	a	sim1d3 y1
0.0001	0.001	0.0001	10.954451	0.54772	10	1	10	a	sim1d3 y2
0.0001	0.001	0.001	10.954451	5.47722	10	10	1	a	sim1d3 y3
0.0001	0.001	0.01	10.954451	54.7722	10	100	0.1	d	sim1d3 y4
0.0001	0.001	0.1	10.954451	547.722	10	1000	0.01	d	sim1d3 y5
0.0001	0.001	1	10.954451	5477.22	10	10000	0.001	d	sim1d3 y6
0.0001	0.001	3	10.954451	16431.6	10	30000	0.00033	d	sim1d3 y7
0.0001	0.001	5	10.954451	27386.1	10	50000	0.0002	d	sim1d3 y8
0.0001	0.01	0	34.641016	0	100	0	#DIV/0!	a	sim1d4 y1
0.0001	0.01	0.0001	34.641016	0.17320	100	1	100	a	sim1d4 y2
0.0001	0.01	0.001	34.641016	1.73205	100	10	10	a	sim1d4 y3
0.0001	0.01	0.01	34.641016	17.3205	100	100	1	d	sim1d4 y4
0.0001	0.01	0.1	34.641016	173.205	100	1000	0.1	d	sim1d4 y5
0.0001	0.01	1	34.641016	1732.05	100	10000	0.01	d	sim1d4 y6
0.0001	0.01	3	34.641016	5196.15	100	30000	0.00333	d	sim1d4 y7
0.0001	0.01	5	34.641016	8660.25	100	50000	0.002	d	sim1d4 y8
0.0001	0.1	0	109.54451	0	1000	0	#DIV/0!	a	sim1d5 y1
0.0001	0.1	0.0001	109.54451	0.05477	1000	1	1000	a	sim1d5 y2
0.0001	0.1	0.001	109.54451	0.54772	1000	10	100	a	sim1d5 y3

TABLE 3.10: SIMULATION RESULTS - POSITION SENSOR NOISE

mass (slug)	k (lb/in)	Cv (lb/in/s)	ω_n (rad/s)	ζ	k/m	Cv/m	k/Cv	code	designation
0.0001	0.1	0.01	109.54451	5.47722	1000	100	10	d	sim1d5 y4
0.0001	0.1	0.1	109.54451	5.47722	1000	1000	1	d	sim1d5 y5
0.0001	0.1	1	109.54451	5.47722	1000	10000	0.1	d	sim1d5 y6
0.0001	0.1	3	109.54451	1643.16	1000	30000	0.03333	d	sim1d5 y7
0.0001	0.1	5	109.54451	2738.61	1000	50000	0.02	d	sim1d5 y8
0.0001	1	0	346.41016	0	10000	0	#DIV 0!	d	sim1d6 y1
0.0001	1	0.0001	346.41016	0.01732	10000	1	10000	d	sim1d6 y2
0.0001	1	0.001	346.41016	0.17320	10000	10	1000	d	sim1d6 y3
0.0001	1	0.01	346.41016	1.73205	10000	100	100	d	sim1d6 y4
0.0001	1	0.1	346.41016	17.3205	10000	1000	10	d	sim1d6 y5
0.0001	1	1	346.41016	173.205	10000	10000	1	d	sim1d6 y6
0.0001	1	3	346.41016	519.615	10000	30000	0.33333	d	sim1d6 y7
0.0001	1	5	346.41016	866.025	10000	50000	0.2	d	sim1d6 y8
0.0001	5	0	774.59666	0	50000	0	#DIV 0!	d	sim1d7 y1
0.0001	5	0.0001	774.59666	0.00774	50000	1	50000	d	sim1d7 y2
0.0001	5	0.001	774.59666	0.07745	50000	10	5000	d	sim1d7 y3
0.0001	5	0.01	774.59666	0.77459	50000	100	500	d	sim1d7 y4
0.0001	5	0.1	774.59666	7.74596	50000	1000	50	d	sim1d7 y5
0.0001	5	1	774.59666	77.4596	50000	10000	5	d	sim1d7 y6
0.0001	5	3	774.59666	232.379	50000	30000	1.66666	d	sim1d7 y7
0.0001	5	5	774.59666	387.298	50000	50000	1	d	sim1d7 y8
0.0001	10	0	1095.4451	0	100000	0	#DIV 0!	d	sim1d8 y1
0.0001	10	0.0001	1095.4451	0.00547	100000	1	100000	d	sim1d8 y2
0.0001	10	0.001	1095.4451	0.05477	100000	10	10000	d	sim1d8 y3
0.0001	10	0.01	1095.4451	0.54772	100000	100	1000	d	sim1d8 y4
0.0001	10	0.1	1095.4451	5.47722	100000	1000	100	d	sim1d8 y5
0.0001	10	1	1095.4451	54.7722	100000	10000	10	d	sim1d8 y6
0.0001	10	3	1095.4451	164.316	100000	30000	3.33333	d	sim1d8 y7
0.0001	10	5	1095.4451	273.861	100000	50000	2	d	sim1d8 y8

TABLE 3.11: RANGE OF PARAMETERS FOR EACH RESPONSE TYPE

RESPONSE TYPE	ω_n	ζ	k/m	C_v/m	k/C_v
Acceptable	0-45	0-707 median=1	0-2000 median=0.2	0-600 median=1	0-1000 median=1
Divergent	0-316 median=4.5	1.58-25000 median=158	0-100000 median=20	1000-50000 median=3000	0-100 median=0.01
Limit Cycle	1.4-316 median=14	0-1 median=0.0015	2-100000 median=700	0-632 median=0.02	10-100000 median=10000
Highly Damped	0-10 median=0.14	2.2-2500 median=111	0-100 median=0.02	3-600 median=50	0-0.333 median=0.0003
Oscillation Overshoot	1-223 median=4.47	0-1 median=0.5	1-50000 median=20	0-447 median=3	1-10000 median=10

TABLE 5.1: STEADY STATE RESPONSE TEST RESULTS

Spring gradient (lb/in)	Applied Force (lbf)	Theoretical Distance (in)	Measured Longitudinal (in)		Measured Lateral (in)		Measured Pedal (in)	
			+ve	-ve	+ve	-ve	+ve	-ve
1.0	1.0	1.0	1.00	1.05	0.95	1.05	1.00	1.05
1.0	3.0	3.0	3.05	2.95	3.00	2.95	3.00	3.05
1.0	5.0	5.0	4.95	5.00	4.95	5.05	5.05	5.05
3.0	3.0	1.0	1.00	1.00	1.05	1.00	1.00	1.00
3.0	6.0	2.0	2.05	1.95	1.95	2.00	2.00	2.00
3.0	12.0	4.0	4.05	4.05	4.00	3.95	4.00	4.00
5.0	5.0	1.0	1.00	1.05	1.05	1.05	0.95	0.95
5.0	10.0	2.0	2.05	2.00	2.05	2.00	2.00	1.95
5.0	20.0	4.0	3.95	4.00	3.95	3.95	4.00	4.05

TABLE 5.2: FREQUENCY DOMAIN TEST MATRIX

mass (slug)	k (lb/in)	Cv (lb/in/s)	ω_n (rad/s)	ζ	Test Channel & #	Analysis Tool
0.1	0.408333	0.08248	7	0.707	1 - Lateral	Bode
0.1	0.408333	0.02333	7	0.20	2 - Longitudinal	Bode
0.1	0.408333	0.01	7	0.08	3 - Pedal	PSD
0.05	0.816667	0.105	14	0.90	4 - Pedal	Bode
0.05	0.816667	0.04667	14	0.40	5 - Lateral	Bode
0.05	0.816667	0.01	14	0.08	6 - Longitudinal	PSD
0.15	1.25	0.25	10	1.00	7 - Longitudinal	Bode
0.15	1.25	0.1375	10	0.55	8 - Pedal	Bode
0.15	1.25	0.02	10	0.08	9 - Lateral	PSD

TABLE 5.3: TIME DOMAIN TEST MATRIX

Parameter	Model 1	Model 2	Model 3	Model 4
viscous friction (lbf in sec)	0.15	0.3	0.70	0.05
spring gradient (lbf/in)	0.70	2.0	10.0	3.00
mass (slug)	0.20	0.15	0.30	0.20
static friction (lbf)	1.00	1.50	5.00	0.50
ratio of kinetic-static friction	0.80	0.90	0.40	0.80
breakout force (lbf)	1.00	3.00	1.00	1.00
throw limits (in)	4.00	4.00	4.00	4.00
notch size (in)	1.00	1.00	0.25	0.25
notch viscous friction (lbf in sec)	0.10	0.08	0.10	0.10
notch mass (slug)	0.02	0.03	0.10	0.10
notch static friction (lbf)	0.50	0.20	0.50	0.10
notch friction ratio	0.80	0.90	0.40	0.80
Test Channel	Longitudinal	Lateral	Pedal	Lateral

FIGURE 1.1: BELL 205 AIRBORNE SIMULATOR

FIGURE 1.2: ASRA BELL 412 HELICOPTER TEST PLATFORM

FIGURE 1.3: BELL 412 CYCLIC CONTROL ASSEMBLY

FIGURE 1.4: BELL 412 SPRING GRADIENT ASSEMBLY **FIGURE 1.5: COOPER-HARPER RATING SCALE**

FIGURE 2.1: SCHEMATIC OF EXISTING FORCE FEEL SYSTEM

FIGURE 2.2: STICK ASSEMBLY

FIGURE 2.3: STICK ASSEMBLY MOUNTING BRACKET

FIGURE 2.4: STICK ASSEMBLY MOUNTING BRACKET **FIGURE 2.5: LATERAL ACTUATOR**

FIGURE 2.6: PEDAL ACTUATION SYSTEM **FIGURE 2.7: PEDALS - FRONT VIEW**

FIGURE 2.8: MECHANICAL ASSEMBLY AND ACTUATOR LAYOUT

FIGURE 2.9: FEEL SYSTEM MOCK-UP

FIGURE 2.10: INSTALLATION PHOTO - REAR VIEW

FIGURE 2.11: INSTALLATION PHOTO - SIDE VIEW

FIGURE 2.12: INSTALLATION PHOTO - FRONT VIEW

FIGURE 2.13: GRIP

FIGURE 2.14: INNER GRIP STRUCTURE

FIGURE 2.15: STRAIN GAUGE AMPLIFIER CIRCUIT

FIGURE 2.16: RUDDER PEDAL ASSEMBLY **FIGURE 2.17: PEDAL STALK**

FIGURE 2.18: DISASSEMBLED PEDAL

FIGURE 2.19: HYDRAULIC ACTUATOR DRAWINGS

FIGURE 2.20: HYDRAULIC ACTUATOR PHOTOGRAPH

FIGURE 2.21: DISASSEMBLED HYDRAULIC ACTUATOR

FIGURE 2.22: HYDRAULIC MOOG (SERVO) VALVE **FIGURE 2.23: MOOG VALVE: CURRENT / FLOW RELATION**

Scales:

Flow: 5.0 cubic inches / block

Current: 2.0 milliamp / block

Leakage: 0.25 cubic inches / block

FIGURE 2.24: MOOG VALVE CURRENT DRIVER CIRCUITRY

FIGURE 2.25: STICK AND FEEL SYSTEM DYNAMICS

FIGURE 3.1: LINEAR INNER MODEL **FIGURE 3.2: INNER MODEL RESPONSE: INITIAL PARAMETERS**

FIGURE 3.3: INNER MODEL RESPONSE: MASS = 2 SLUGS **FIGURE 3.4: INNER MODEL RESPONSE: $C_v = 2$ lbf/in/sec**

FIGURE 3.5: INNER MODEL RESPONSE: $k = 3 \text{ lbf/in}$ **FIGURE 3.6: ADDITION OF THROW LIMITS**

FIGURE 3.7: THROW LIMITS: 9 lbf INPUT **FIGURE 3.8: THROW LIMITS: 7.5 lbf INPUT**

FIGURE 3.13: ZERO BREAKOUT FORCE **FIGURE 3.14: 1 lbf BREAKOUT FORCE**

FIGURE 3.15: ADDITION OF MODEL SWITCHING **FIGURE 3.16: FORCE INPUT**

FIGURE 3.17: MODEL SWITCHING, NOTCH SIZE 4-in **FIGURE 3.18: ADDITION OF SENSOR AND SERVO MODELS**

FIGURE 3.19: FORCE INPUT **FIGURE 3.20: COMPLETED MODEL RESPONSE TO INITIAL VALUES**

FIGURE 3.21: LOCATION OF SENSOR NOISE IN MODEL.

FIGURE 3.22: ACCEPTABLE RESPONSE, $k=0$, SMALL DAMPING

FIGURE 3.23: ACCEPTABLE RESPONSE, $k = 1$, DAMPING RATIO = 1 **FIGURE 3.24: HIGHLY DAMPED RESPONSE**

FIGURE 3.25: DIVERGENT RESPONSE **FIGURE 3.26: OVERSHOOT AND OSCILLATION**

FIGURE 3.27: LIMIT CYCLE

FIGURE 3.28: TYPICAL RESPONSE TO SINE INPUT, 0.04 HZ

FIGURE 3.29: TYPICAL RESPONSE TO SINE INPUT, 2 HZ **FIGURE 3.30: RESPONSE WITH 1 LBF BREAKOUT FORCE**

FIGURE 3.31: RESPONSE WITH 3 LBF BREAKOUT FORCE **FIGURE 3.32: RESPONSE WITH 1 LBF STATIC FRICTION**

FIGURE 3.33: RESPONSE WITH 3 LBF STATIC FRICTION **FIGURE 3.34: TYPICAL RESPONSE WITH STRAIN GAUGE NOISE**

FIGURE 3.35: TYPICAL RESPONSE WITH POSITION SENSOR NOISE

FIGURE 4.1: PROGRAM MENU STRUCTURE

FIGURE 4.2: SOFTWARE DECISION STRUCTURE

FIGURE 4.3: INNER MODEL COMPARISON: INITIAL PARAMETERS **FIGURE 4.4: INNER MODEL COMPARISON: MASS = 2 SLUGS**

FIGURE 4.5: INNER MODEL COMPARISON: $C_v = 2 \text{ lbf/in/sec}$ **FIGURE 4.6: INNER MODEL COMPARISON: $k = 3 \text{ lbf/in}$**

FIGURE 4.7: MODEL COMPARISON: THROW LIMITS - 9 lbf INPUT **FIGURE 4.8: MODEL COMPARISON: THROW LIMITS - 7.5 lbf INPUT**

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PRECISIONSM RESOLUTION TARGETS

FIGURE 4.9: MODEL COMPARISON: MODEL SWITCHING, $n_s = 4$ -in **FIGURE 4.10: MODEL COMPARISON: 1 lbf BREAKOUT FORCE**

FIGURE 4.11: MODEL COMPARISON: 3 lbf BREAKOUT FORCE **FIGURE 4.12: MODEL COMPARISON: 1 lbf STATIC FRICTION**

FIGURE 4.13: MODEL COMPARISON: 3 lbf STATIC FRICTION **FIGURE 4.14: MODEL COMPARISON: LIMP NOODLE CASE**

FIGURE 4.15: MODEL COMPARISON: ACCEPTABLE RESPONSE **FIGURE 4.16: MODEL COMPARISON: HIGHLY DAMPED RESPONSE**

FIGURE 4.17: MODEL COMPARISON: DIVERGENT RESPONSE **FIGURE 4.18: MODEL COMPARISON: OSCILLATORY RESPONSE**

FIGURE 5.1: HARDWARE INSTALLATION **FIGURE 5.2: REDESIGNED FEEL SYSTEM CONTROL PANEL**

FIGURE 5.13: FREQUENCY DOMAIN TEST 5: BODE PLOT **FIGURE 5.14: FREQUENCY DOMAIN TEST 6: PSD**

FIGURE 5.5: BODE PLOT: HIGH SYSTEM BANDWIDTH **FIGURE 5.6: BODE PLOT: LONGITUDINAL CHANNEL**

FIGURE 5.7: BODE PLOT: LATERAL CHANNEL **FIGURE 5.8: BODE PLOT: PEDAL CHANNEL**

FIGURE 5.9: FREQUENCY DOMAIN TEST 1: BODE PLOT **FIGURE 5.10: FREQUENCY DOMAIN TEST 2: BODE PLOT**

FIGURE 5.11: FREQUENCY DOMAIN TEST 3: PSD **FIGURE 5.12: FREQUENCY DOMAIN TEST 4: BODE PLOT**

FIGURE 5.13: FREQUENCY DOMAIN TEST 5: BODE PLOT **FIGURE 5.14: FREQUENCY DOMAIN TEST 6: PSD**

FIGURE 5.15: FREQUENCY DOMAIN TEST 7: BODE PLOT **FIGURE 5.16: FREQUENCY DOMAIN TEST 8: BODE PLOT**

FIGURE 5.17: FREQUENCY DOMAIN TEST 9: PSD **FIGURE 5.18: TIME DOMAIN COMPARISON: MODEL 1**

FIGURE 5.19: TIME DOMAIN COMPARISON: MODEL 2 **FIGURE 5.20: TIME DOMAIN COMPARISON: MODEL 3**

FIGURE 5.21: TIME DOMAIN COMPARISON: MODEL 4

APPENDIX A: SAMPLE CONFIGURATION AND CALIBRATION FILES**CONFIGURATION FILE:**

```
#-----  
#  
# Bell 205 Airborne Simulator.  
#  
# FEEL System configuration.  
#  
#-----  
  
module: sb9325f  
module: ad0_21  
  
module: sb9210  
module: da0_2  
  
event: anlg_ev  
  
process: analog /ad0_21 feel.cal anlg_buf anlg_ev:0  
process: feel anlg_ev anlg_buf /da0_2 feel_buf
```

CALIBRATION FILE:

```

#-----
#
# Bell 205 Airborne Simulator.
#
# FEEL System Analog to digital converter calibrations.
#
#-----

Fpx   = 0.0 + 0.0258113 * ad0
Fpy   = 0.0 + 0.0427347 * ad1
Fpr   = 0.0 + 0.1314527 * ad2
Xin   = 0.0 + 0.000752278 * ad3
Yin   = 0.0 + 0.001446411 * ad4
Rin   = 0.0 + 0.000561238 * ad5
RTrim = 0.0 + 0.0048828125 * ad6
#
# For discrete inputs,
#   a voltage less than 2.5 V for 50 milliseconds yields 0
#   a voltage above 2.5 V for 50 milliseconds yields 1
#
ModSw0 = discrete ( ad7 )
ModSw1 = discrete ( ad8 )
ModSw2 = discrete ( ad9 )
ModSw3 = discrete ( ad10 )
ModSw4 = discrete ( ad11 )
ModSw5 = discrete ( ad12 )
ModSw6 = discrete ( ad13 )
ModSw7 = discrete ( ad14 )
ch_x_r = discrete ( ad16 )
ch_x_l = discrete ( ad15 )
ch_y_f = discrete ( ad17 )
ch_y_b = discrete ( ad18 )
for_rel = discrete ( ad19 )
trim_op = discrete ( ad20 )
engage  = discrete ( ad21 )

```

END

1 8 0 6 9 7

FIN