Development of Control Strategies and Testing Procedures for Suspension Seats Used in High Speed Craft

by

Francesco Sorensen

A thesis submitted to
the Faculty of Graduate and Postdoctoral Affairs
in partial fulfilment of
the requirements for the degree of
Master of Applied Science
in
Mechanical Engineering

Ottawa-Carleton Institute for Mechanical and Aerospace Engineering
Department of Mechanical and Aerospace Engineering
Carleton University
Ottawa, Ontario, Canada
January 2020

Copyright ©
2020 - Francesco Sorensen

Abstract

The objective of this work was to develop control strategies and testing procedures for the Slam Impact Seat Test Rig (SISTR). The SISTR was developed to more accurately test suspension seats for use in high speed craft (HSC). In general, HSC are defined as vessels which can achieve speeds higher than 30 knots, and are commonly used for search and rescue, law enforcement, and military operations. HSC are subject to extreme repeated shock and vibration loading and therefore so are their occupants. Therefore it is vital that the testing machines used to evaluate these seats can accurately reproduce the motion that HSCs are subjected to at sea. Development of control strategies involved developing and evaluating different types of motion control in order to accurately reproduce the desired motions. Once this was done, the user interface of the SISTR was developed to efficiently test different motions. A test procedure was then developed, which consisted of several types of impacts and other motions to represent what HSC experience at sea, as well as several benchmarking motions to demonstrate the capabilities of the SISTR. Compared to a conventional drop tower, the SISTR was able to more accurately reproduce HSC motion because it could directly control the position of the seat. Four different seats were tested using the SISTR, and the test results were processed to extract the overall damped natural frequencies and damping ratios of the seats.

Table of Contents

Abstract	ii
Table of Contents	iii
List of Tables	vi
List of Figures	ix
1 Introduction	1
1.1 Motivation	1
1.2 Background and Literature Review	2
1.3 Thesis Overview	7
2 Drop Tower Seat Testing	9
2.1 Introduction	9
2.2 Test Setup	9
2.3 Test Plan	16
2.4 Results	19
2.4.1 Natural Frequencies and Damping Ratios	19
2.4.2 Peak Accelerations	25
2.4.3 Drop Testing with Variable Impacting Materials	33
2.5 Conclusion	35

3	Development of Control Strategies for the SISTR	36
3.1	Overview of SISTR Motion	36
3.2	Operational Control Methods	41
3.2.1	Jog Motion	41
3.2.2	Index Motion	42
3.2.3	Cam Motion	43
3.3	Challenges and Solutions	44
4	SISTR User Interface	50
4.1	PowerTools Pro (Vertical Motion)	51
4.1.1	Motor Setup	51
4.1.2	Input Configuration	54
4.1.3	Motion Profiles	55
4.1.4	Programs	59
4.2	LabVIEW (Horizontal Motion)	60
4.2.1	Data Acquisition	61
4.2.2	Damper Control	68
4.2.3	Horizontal Motion Control	68
4.3	Direct Inputs	69
4.4	Overall SISTR Operating Procedure	71
5	Standard Procedure for Testing Seats with the SISTR	72
5.1	Standard Profiles	72
5.1.1	Sample of Representative Boat Motion	72
5.1.2	Five Standard Impact Types	73
5.1.3	Repeated Constant Impacts	81
5.1.4	Repeated Increasing Impacts	82
5.2	Additional Motion Profiles for SISTR Benchmarking	83

5.2.1	Vertical Range of Motion and Acceleration	83
5.2.2	Horizontal Range of Motion and Acceleration	85
5.3	Procedure for Testing New Motion Profiles	86
6	Seat Testing Using the SISTR	87
6.1	Sample of Boat Motion	88
6.2	Five Impact Types	90
6.3	Repeated Constant Impacts	95
6.4	Repeated Increasing Impacts	97
6.5	Vertical Range of Motion and Acceleration	101
6.6	Horizontal Range of Motion and Acceleration	103
6.7	Discussion	104
7	Conclusions and Recommendations for Future Work	108
	References	110
	Appendix A Complete Drop Testing Results	112
	Appendix B Motor and Drive Configuration Parameters	128

List of Tables

2.1	Orientation of accelerometers used for seat drop testing.	15
2.2	Basic parameters of seats used for drop testing.	19
2.3	Natural frequency and damping ratio results for the Ullman Dynamics Compact seat.	20
2.4	Natural frequency and damping ratio results for the Shockwave Marine Suspension seat.	20
2.5	Natural frequency and damping ratio results for the SHOXS-6500 seat.	21
2.6	Natural frequency and damping ratio results for the SHOXS-4800 seat with passive suspension.	21
2.7	Natural frequency and damping ratio results for the SHOXS-4800 seat with semi-active suspension.	22
2.8	Peak measured vertical accelerations for the Ullman Dynamics seat. .	26
2.9	Peak measured vertical accelerations for the Shockwave Marine Sus- pension seat.	27
2.10	Peak measured vertical accelerations for the SHOXS-6500 seat.	28
2.11	Peak measured vertical accelerations for the SHOXS-4800 passive seat.	29
2.12	Peak measured vertical accelerations for the SHOXS-4800 semi-active seat.	30
3.1	Displacement and acceleration limits of the SISTR.	47
6.1	Peak measured vertical accelerations for the boat motion sample profile.	89

6.2	Natural frequency and damping ratio results for the boat motion sample profile.	90
6.3	Peak measured vertical accelerations for the five impact type profiles.	93
6.4	Natural frequency and damping ratios resulting from the five impact type profiles.	94
6.5	Peak measured vertical accelerations for the repeated constant impact profile.	96
6.6	Natural frequency and damping ratios resulting from the repeated constant impact profile.	97
6.7	Peak measured vertical accelerations for the 2 g impact of the repeated increasing impact profile.	99
6.8	Peak measured vertical accelerations for the 4 g impact of the repeated increasing impact profile.	99
6.9	Peak measured vertical accelerations for the 6 g impact of the repeated increasing impact profile.	100
6.10	Peak measured vertical accelerations for the 8 g impact of the repeated increasing impact profile.	100
6.11	Natural frequency and damping ratios resulting from the repeated increasing impact profile.	101
6.12	Overall averaged peak acceleration comparison.	105
6.13	Overall averaged impact duration comparison.	106
6.14	Overall averaged damped natural frequency and damping ratio results for all tests.	107
A.1	Damped natural frequency results for the Ullman Dynamics Compact seat.	112
A.2	Damped natural frequency results for the Shockwave Marine Suspension seat.	113

A.3	Damped natural frequency results for the SHOXS-6500 seat.	113
A.4	Damped natural frequency results for the SHOXS-4800 seat with pas- sive suspension.	114
A.5	Damped natural frequency results for the SHOXS-4800 seat with semi- active suspension.	115
A.6	Damping ratio results for the Ullman Dynamics Compact seat.	116
A.7	Damping ratio results for the Shockwave Marine Suspension seat.	116
A.8	Damping ratio results for the SHOXS-6500 seat.	116
A.9	Damping ratio results for the SHOXS-4800 seat with passive suspension.	117
A.10	Damping ratio results for the SHOXS-4800 seat with semi-active sus- pension.	118
A.11	Peak measured vertical accelerations for the Ullman Dynamics Com- pact seat.	119
A.12	Peak measured vertical accelerations for the Shockwave Marine Sus- pension seat.	120
A.13	Peak measured vertical accelerations for the SHOXS-6500 seat.	121
A.14	Peak measured vertical accelerations for the SHOXS-4800 seat with passive suspension.	122
A.15	Peak measured vertical accelerations for the SHOXS-4800 seat with semi-active suspension at setting 1.	123
A.16	Peak measured vertical accelerations for the SHOXS-4800 seat with semi-active suspension at setting 2.	124
A.17	Peak measured vertical accelerations for the SHOXS-4800 seat with semi-active suspension at setting 3.	125
A.18	Peak measured vertical accelerations for the SHOXS-4800 seat with semi-active suspension at setting 4.	126
B.1	Motor and drive configuration parameters.	128

List of Figures

1.1	Example of a High Speed Craft.	1
1.2	Test machine used by Coast Dynamics Group.	3
1.3	Drop Tower used by the UK Ministry of Defence.	3
1.4	Carleton University Drop Tower.	4
1.5	Seat Component Testing Machine.	5
1.6	Example of common impact profile dervied from sea trial data.	6
1.7	Dynamic model for HSC seat.	7
2.1	The Carleton University Drop Tower.	10
2.2	The Carleton University Drop Tower (side view).	11
2.3	Accelerometers mounted to a seat on the drop tower.	13
2.4	Mass strapped to a seat on the drop tower.	14
2.5	Ullman Dynamics Compact seat.	16
2.6	Shockwave Marine Suspension seat.	17
2.7	SHOXS-6500 seat.	18
2.8	SHOXS-4800 seat.	18
2.9	Natural frequency results for the Ullman, Shockwave, SHOXS-6500, and SHOXS-4800 seats.	23
2.10	Natural frequency results for the SHOXS-4800 Semi-Active seat.	24
2.11	Damping ratio results for the Ullman, Shockwave, SHOXS-6500, and SHOXS-4800 seats.	24

2.12	Damping ratio results for the SHOXS-4800 Semi-Active seat.	25
2.13	Peak measured vertical accelerations for the Ullman Dynamics seat. .	26
2.14	Peak measured vertical accelerations for the Shockwave Marine Sus- pension seat.	27
2.15	Peak measured vertical accelerations for the SHOXS-6500 seat.	28
2.16	Peak measured vertical accelerations for the SHOXS-4800 passive seat.	29
2.17	Peak measured vertical accelerations for the SHOXS-4800 semi-active seat on setting 1.	31
2.18	Peak measured vertical accelerations for the SHOXS-4800 semi-active seat on setting 2.	31
2.19	Peak measured vertical accelerations for the SHOXS-4800 semi-active seat on setting 3.	32
2.20	Peak measured vertical accelerations for the SHOXS-4800 semi-active seat on setting 4.	32
2.21	Drop tower base.	33
2.22	Carriage acceleration results from drop testing with variable impacting materials.	34
3.1	Photo of the SISTR.	37
3.2	SISTR diagram.	38
3.3	SISTR horizontal drive.	38
3.4	SISTR vertical drive (top view).	39
3.5	SISTR deck assembly.	40
3.6	Sample jog motion.	42
3.7	Sample index motion.	43
3.8	Sample cam motion.	44
3.9	Velocity-time graph showing following error.	45
3.10	Displacement-time graph showing following error.	46

3.11	Failure of top beams of the cart of the SISTR.	49
3.12	Top beams of the cart of the SISTR with pulleys before failure. . . .	49
4.1	SISTR block diagram.	51
4.2	Motor setup in PowerTools Pro - Part 1.	52
4.3	Motor setup in PowerTools Pro - Part 2.	53
4.4	Motor setup in PowerTools Pro - Part 3.	54
4.5	Inputs in PowerTools Pro.	55
4.6	Jog motion in PowerTools Pro.	56
4.7	Index motion in PowerTools Pro.	57
4.8	Cam motion in PowerTools Pro.	58
4.9	Sample input file for cam motion in PowerTools Pro.	59
4.10	Program in PowerTools Pro.	60
4.11	Sensor calibration in LabVIEW.	62
4.12	Channel list in LabVIEW.	63
4.13	Pinout for NI USB-6211 (left) and NI USB-6289 (right).	64
4.14	Block diagram in LabVIEW.	65
4.15	Live data display in LabVIEW.	66
4.16	Sample data collected by LabVIEW.	67
4.17	Sample data collected by LabVIEW.	68
4.18	SISTR control panel.	69
5.1	Acceleration profile of sample boat motion.	73
5.2	Displacement profile of sample boat motion.	73
5.3	Type 1 acceleration profile.	74
5.4	Type 2 acceleration profile.	75
5.5	Type 3 acceleration profile.	76
5.6	Type 4 acceleration profile.	77
5.7	Type 5 acceleration profile.	78

5.8	Type 1 displacement profile.	79
5.9	Type 2 displacement profile.	79
5.10	Type 3 displacement profile.	80
5.11	Type 4 displacement profile.	80
5.12	Type 5 displacement profile.	81
5.13	Repeated constant impacts displacement profile.	82
5.14	Repeated increasing impacts displacement profile.	83
5.15	Vertical range of motion displacement profile.	84
5.16	Maximum vertical acceleration profile.	84
5.17	Horizontal range of motion profile.	85
6.1	Deck acceleration profile of sample boat motion.	88
6.2	Acceleration profile of the highest impact portion of sample boat motion using the SHOXS-6500 with 80 kg mass.	89
6.3	Type 1 acceleration profile using SHOXS-4800 Passive with 80 kg mass.	91
6.4	Type 2 acceleration profile using SHOXS-6500 with 80 kg mass.	91
6.5	Type 3 acceleration profile using SHOXS-6500 with 110 kg mass.	92
6.6	Type 4 acceleration profile using Shockwave with 80 kg mass.	92
6.7	Type 5 acceleration profile using SHOXS-4800 Semi-Active Setting 4 with 110 kg mass.	93
6.8	Deck acceleration profile of repeated constant impacts.	95
6.9	Acceleration profile of one of the repeated constant impacts using the SHOXS-4800 Passive with 80 kg mass.	96
6.10	Deck acceleration profile of repeated increasing impacts.	98
6.11	Acceleration profile of the 8 g impact of the repeated increasing impacts using the SHOXS-4800 Semi-Active Setting 3 with 110 kg mass.	98
6.12	Displacement profile showing vertical range of motion.	102
6.13	Acceleration profile showing maximum vertical acceleration.	103

6.14	Profiles showing maximum horizontal range of motion and acceleration.	104
A.1	Absolute acceleration profiles measured during 6 inch drop of the Shockwave seat.	127

Chapter 1

Introduction

1.1 Motivation

High Speed Craft (HSC) are high-speed water vessels widely used in various applications including search and rescue, law enforcement, and military operations. Given the nature of these applications, these craft, and therefore their occupants, are subject to extreme dynamic loading conditions, including repeated shock. These impacts have been shown to have severe adverse effects on their occupants, notably spinal injuries. Both chronic and acute injuries can occur [1]. An example of an HSC is shown in Figure 1.1.

Figure 1.1: Example of a High Speed Craft [2].

To mitigate these impacts, many companies have developed special seating for HSC with built-in suspension systems. Given this, there is a need to test these seats to confirm their suitability and effectiveness for HSC applications. This research focuses on motion control strategies for replicating motion of HSC in testing various suspension seats using two testing machines.

1.2 Background and Literature Review

HSC are subject to various types of motion at sea, and different types of testing machines can be used to emulate their motion in different ways. In general, since impacts from wave motion are one of the more critical aspects of HSC motion, most testing machines specifically made for HSC seats focus on this aspect.

The simplest way to achieve an impact is usually through drop testing: lifting the seat to a specified height and dropping it onto an impacting surface below. Examples of this kind of drop testing machine include the drop tower shown in Figure 1.2 used by Coast Dynamics Group to test their SHOXs suspension seats [3], and the drop tower used by the UK Ministry of Defence [1] shown in Figure 1.3. Another example is the Carleton University Drop Tower developed by Zuneid Alam [4], about which more details and results are presented in Chapter 2. In all of these machines, the motion of interest - the impact - is not directly controlled by the testing machine, because the impact is preceded by a free fall.

Figure 1.2: Test machine used by Coast Dynamics Group [3].

Figure 1.3: Drop Tower used by the UK Ministry of Defence [1].

Figure 1.4: Carleton University Drop Tower [4].

In other types of testing machines, the fall can be controlled at all times, although very few are used for the testing of seats for HSC. Moreover, the testing machine developed by Yasser Fouad [5] shown in Figure 1.5 was used to test individual components of the seat as well as fully-assembled seats in a quasi-dynamic manner to characterise seat components.

Figure 1.5: Seat Component Testing Machine [5].

Given that impacts are one of the critical aspects of HSC motion, consideration must be given to the impacting interface in the testing machine and how it affects the acceleration profile of the impact. Existing seat testing machines make use of different impact interfaces and different methods of achieving the impact itself. As described previously, the drop tower operated by the UK Ministry of Defence uses sand as the impacting material with a wedge-shaped base on the falling seat platform. The machine used by the Coast Dynamics Group uses a tire with a flat metal seat base, as shown in Figure 1.2. The Carleton University Drop Tower can accommodate various different materials as the impacting interface, the results of which are discussed in

Chapter 2.

Many sea trials have been performed for the purpose of collecting motion data to identify the motions actually experienced by occupants of HSC. Mohamed El Tayeby [6] analyzed data from several sea trials in an effort to identify common types of impact profiles, which could then be reproduced in a testing environment. Five major types of profiles were identified in that work, which formed the basis for the profiles used for testing as described in Chapter 5. An example of such a profile is shown in Figure 1.6.

Figure 1.6: Example of common impact profile dervied from sea trial data [6].

In order to accurately reproduce profiles such as this, it is desirable to have complete control over the motion, as opposed to just a lift and drop. The Slam Impact

Seat Test Rig (SISTR) [7] was developed for this purpose, with complete control of its vertical and horizontal motions, including impact severity and profiling via electrorheological dampers.

Testing done on HSC seats can be used to extract seat parameters, such as stiffness and damping ratios, of the seat as a whole and of individual components. These values can then be used to build a dynamic model of the seat, which can in turn be used to improve future designs. An example of this is the work done by Anne Wice [8], using the dynamic model shown in Figure 1.7. In this model, A is the fixed seat frame, B is the moving seat saddle, and C is the seat occupant.

Figure 1.7: Dynamic model for HSC seat [8].

1.3 Thesis Overview

Chapter 2 outlines seat testing conducted using the Carleton University Drop Tower. This includes a description of the tower and the overall test setup, the test plan, and

results. Also discussed is the analysis method, as well as additional testing done using different impacting materials to shape the acceleration profile during the impact.

Chapter 3 discusses different motion control strategies for testing suspension seats using the SISTR. The SISTR and its operation are described, as well as the various methods of motion control available. The rationale behind the selected motion control is discussed, as are different aspects of the machine's operation to ensure accurate and reliable testing results. It is important to note that the control strategies did not involve directly tuning gains but rather using the control software effectively to achieve the desired motions.

The user interface for the SISTR is described in Chapter 4. This includes the interfaces for motion control and data acquisition. The PowerTools Pro [9] interface is described, including the different types of motion, motion programs, and user inputs. The LabVIEW [10] interface is also discussed, as well as the external control panel inputs.

In Chapter 5, the standard test procedure for seats using the SISTR is described. This includes details of the various profiles tested, as well as the instrumentation used in the test setup.

Chapter 6 details the results of the testing conducted using the SISTR. This includes motion profiles as well as tabulated results of peak accelerations, natural frequencies, and damping ratios.

In Chapter 7, conclusions are drawn from the results and recommendations for future work on the SISTR are made.

Chapter 2

Drop Tower Seat Testing

2.1 Introduction

This chapter describes the testing performed on five suspension seats for use in high speed craft. Drop testing was performed on the seats, which were instrumented to analyze their shock and vibration response. The data collected were then processed using an analysis code, based on the eigenrealization algorithm, developed by Zuneid Alam [4] to extract the damped natural frequency and damping ratio of the seats. This code also filtered the data with a fourth-order dual low pass Butterworth filter at 30 Hz. Peak acceleration values observed during testing were also extracted from the measured data and tabulated. This testing shows that it is possible to extract suspension seat parameters using simple drop testing. The SISTR is used for more complex testing, including motion profiles replicating sea trial data, as discussed in following chapters.

2.2 Test Setup

Drop testing of the suspension seats was performed using the Carleton University Drop Tower [4]. The drop tower consists of a carriage sliding on a linear guide rail

attached to an S200 X 27 steel I-beam; and has overall dimensions of 3 m high, 1.4 m wide, and 1.7 m long, as shown in Figures 2.1 and 2.2.

Figure 2.1: The Carleton University Drop Tower [4].

Figure 2.2: The Carleton University Drop Tower (side view) [4].

Seats were securely mounted to the seat plate on the carriage, and a 110 kg mass was mounted to the seats to simulate the mass of the occupant. An electric winch with a capacity of 540 kg located at the top of the I-beam lifts the carriage to the desired height using a cable with a quick-release hook on the end. A cord is pulled to

release the hook, allowing the carriage to fall onto the impacting base below. Drop heights of up to 60 cm are possible with impacts exceeding 20 g with a duration of 50-100 ms. Note that a second winch is visible in Figure 2.2 that is part of a safety system to render the system safe in the unlikely event that the quick-release hook does not unlatch completely when triggered.

Accelerometers (Measurement Specialties MEAS 4000A-100 [11]) with a measurement range of ± 40 g were mounted in three locations: on the carriage of the drop tower, on the seat, and on the payload mass. One single-axis accelerometer was mounted to the carriage in the vertical (z) direction, and three accelerometers were mounted on each of the seat and mass, to capture accelerations in all three orthogonal coordinate directions.

The accelerometers mounted to the seat were mounted to the rigid seat structure, such that they would sense the effects of the seat's suspension, as shown in Figure 2.3.

Figure 2.3: Accelerometers mounted to a seat on the drop tower.

Since the 110 kg mass was mounted on the seat pad, the accelerometers on the mass would capture the effects of the suspension and the seat pad. However, given that the mass needed to be strapped down securely to the seat for testing, this caused the seat cushion to be more compressed than if an occupant with the same mass were just sitting on it, as shown in Figure 2.4. Additionally, the mass does not have the same shape as a human occupant, so the pressure distribution would be different.

Figure 2.4: Mass strapped to a seat on the drop tower.

For all drop testing, the coordinate system used was:

$x+$ directed forward, normal to the front face of the guide rail (the occupant in the seat would be facing in this direction);

$y+$ directed towards the left when facing out the front of the drop test machine (the occupant's left side); and

$z+$ directed vertically upwards.

Table 2.1 indicates the specific orientation of accelerometers for measurements on each of the five seats tested (see Section 2.3). A “+” sign indicates that the accelerometer’s positive direction was oriented with the positive coordinate axis direction, and vice versa. The orientations were changed between seats for ease of installation.

Table 2.1: Orientation of accelerometers used for seat drop testing.

Specimen	Mass			Seat			Carriage
	x	y	z	x	y	z	
Ullman Dynamics Compact	-	+	+	+	+	-	-
Shockwave Marine Suspension	-	-	+	+	+	-	-
SHOXS-6500	-	+	+	-	+	+	-
SHOXS-4800 Passive	-	+	+	+	-	+	-
SHOXS-4800 Semi-active	-	+	+	+	+	-	-

2.3 Test Plan

The following five suspension seats were tested with the drop tower:

1. Ullman Dynamics Compact
2. Shockwave Marine Suspension
3. SHOXS-6500
4. SHOXS-4800 with Passive Suspension
5. SHOXS-4800 with SHOXSDUAL2 Semi-active Suspension

The seats are shown in Figures 2.5 through 2.8. Note that both SHOXS-4800 seats are the same apart from the suspension mechanism within.

Figure 2.5: Ullman Dynamics Compact seat.

Figure 2.6: Shockwave Marine Suspension seat.

Figure 2.7: SHOXS-6500 seat [12].

Figure 2.8: SHOXS-4800 seat [13].

All five seats tested have a built-in suspension system, as well as padding for the occupant. The main differences are that the Ullman and Shockwave seats are of a jockey-style, whereas the other seats are more substantial, with available arm rests and head rests. Some basic seat parameters are given in Table 2.2.

Table 2.2: Basic parameters of seats used for drop testing.

Seat	Suspension Type	Spring	Suspension Travel [mm]
Ullman	Passive	Air	150
Shockwave	Passive	Air	152
SHOXS-6500	Passive	Coil	254
SHOXS-4800 Passive	Passive	Coil	254
SHOXS-4800 Semi-Active	Semi-Active	Coil	254

For each seat, three drop tests were conducted from each of the following heights: 15, 30, 45, and 60 cm [4]. The SHOXS-4800 with semi-active suspension had four different settings for the semi-active suspension (numbered 1 through 4). Therefore, the drops were repeated for each of the four settings. Data from the accelerometers was acquired at 1 kHz with a National Instruments NI-USB 6289 18-bit Data Acquisition Device, connected to a PC running LabVIEW.

2.4 Results

2.4.1 Natural Frequencies and Damping Ratios

The results listed for each drop height represent the average of the three drops. Full results can be found in Appendix A. Damped natural frequency and damping ratio

results for each seat are provided in Tables 2.3 through 2.7.

Table 2.3: Natural frequency and damping ratio results for the Ullman Dynamics Compact seat.

Drop Height [cm]	Damped Nat. Freq. [Hz]	Damping Ratio
15	1.132	0.430
30	1.132	0.475
45	0.822	0.825
60	1.060	0.773

Table 2.4: Natural frequency and damping ratio results for the Shockwave Marine Suspension seat.

Drop Height [cm]	Damped Nat. Freq. [Hz]	Damping Ratio
15	1.164	0.242
30	1.229	0.347
45	1.104	0.445
60	1.128	0.424

Table 2.5: Natural frequency and damping ratio results for the SHOXS-6500 seat.

Drop Height [cm]	Damped Nat. Freq. [Hz]	Damping Ratio
15	1.539	0.425
30	1.329	0.365
45	1.576	0.375
60	1.377	0.425

Table 2.6: Natural frequency and damping ratio results for the SHOXS-4800 seat with passive suspension.

Drop Height [cm]	Damped Nat. Freq. [Hz]	Damping Ratio
15	1.699	0.282
30	1.552	0.428
45	1.529	0.383
60	1.362	0.257

Table 2.7: Natural frequency and damping ratio results for the SHOXS-4800 seat with semi-active suspension.

Drop Height [cm]	Setting	Damped Nat. Freq. [Hz]	Damping Ratio
15	1	0.999	0.359
15	2	0.895	0.341
15	3	0.811	0.485
15	4	0.928	0.390
30	1	1.225	0.507
30	2	1.233	0.422
30	3	1.215	0.423
30	4	1.140	0.442
45	1	1.305	0.477
45	2	1.215	0.499
45	3	0.820	0.818
45	4	0.834	0.714
60	1	1.260	0.492
60	2	1.180	0.558
60	3	1.175	0.481
60	4	1.322	0.587

The natural frequency and damping ratio results are summarized in Figures 2.9 through 2.12

Figure 2.9: Natural frequency results for the Ullman, Shockwave, SHOXS-6500, and SHOXS-4800 seats.

Figure 2.10: Natural frequency results for the SHOXS-4800 Semi-Active seat.

Figure 2.11: Damping ratio results for the Ullman, Shockwave, SHOXS-6500, and SHOXS-4800 seats.

Figure 2.12: Damping ratio results for the SHOXS-4800 Semi-Active seat.

From these results, it appears that the Ullman and Shockwave seats show higher damping ratios for larger drop heights, while the other seats do not. There does not appear to be any significant trend between the drop height and damped natural frequencies obtained. Higher semi-active settings on the SHOXS-4800 seat seem to produce slightly higher damping ratios although there is not a strong correlation.

2.4.2 Peak Accelerations

The measured peak vertical accelerations of the drop carriage, seat pan, and seat mass for each of the five seats are provided in Tables 2.8 through 2.12 and Figures 2.13 through 2.20. The results represent the average of the three drops. The full results can be found in Appendix A.

Table 2.8: Peak measured vertical accelerations for the Ullman Dynamics seat.

Drop Height [cm]	Carriage Accel. [g]	Seat Accel. [g]	Mass Accel. [g]
15	9.8	3.4	2.8
30	13.4	7.7	8.3
45	16.7	13.6	14.0
60	19.7	16.1	20.4

Figure 2.13: Peak measured vertical accelerations for the Ullman Dynamics seat.

Table 2.9: Peak measured vertical accelerations for the Shockwave Marine Suspension seat.

Drop Height [cm]	Carriage Accel. [g]	Seat Accel. [g]	Mass Accel. [g]
15	9.3	5.9	4.1
30	13.5	6.2	6.6
45	16.6	8.4	12.2
60	19.3	9.3	14.5

Figure 2.14: Peak measured vertical accelerations for the Shockwave Marine Suspension seat.

Table 2.10: Peak measured vertical accelerations for the SHOXS-6500 seat.

Drop Height [cm]	Carriage Accel. [g]	Seat Accel. [g]	Mass Accel. [g]
15	9.4	8.8	5.1
30	13.5	10.3	6.1
45	17.1	11.6	7.8
60	19.9	16.2	8.7

Figure 2.15: Peak measured vertical accelerations for the SHOXS-6500 seat.

Table 2.11: Peak measured vertical accelerations for the SHOXS-4800 passive seat.

Drop Height [cm]	Carriage Accel. [g]	Seat Accel. [g]	Mass Accel. [g]
15	9.0	6.2	4.2
30	13.7	9.6	7.6
45	16.7	12.5	9.9
60	19.6	14.2	12.4

Figure 2.16: Peak measured vertical accelerations for the SHOXS-4800 passive seat.

Table 2.12: Peak measured vertical accelerations for the SHOXS-4800 semi-active seat.

Drop Height [cm]	Setting	Carriage Accel. [g]	Seat Accel. [g]	Mass Accel. [g]
15	1	9.2	5.5	6.2
15	2	9.2	6.1	6.4
15	3	9.2	7.1	7.6
15	4	9.2	9.0	9.2
30	1	13.1	10.1	9.3
30	2	13.0	11.2	10.0
30	3	13.0	12.7	11.5
30	4	12.9	13.6	13.7
45	1	16.1	11.8	11.1
45	2	16.1	12.7	11.7
45	3	15.7	14.0	13.9
45	4	15.8	15.5	16.3
60	1	19.5	14.3	15.9
60	2	19.8	15.3	16.1
60	3	18.6	17.7	20.5
60	4	19.3	20.0	21.3

Figure 2.17: Peak measured vertical accelerations for the SHOXS-4800 semi-active seat on setting 1.

Figure 2.18: Peak measured vertical accelerations for the SHOXS-4800 semi-active seat on setting 2.

Figure 2.19: Peak measured vertical accelerations for the SHOXS-4800 semi-active seat on setting 3.

Figure 2.20: Peak measured vertical accelerations for the SHOXS-4800 semi-active seat on setting 4.

The peak acceleration results show that, in the case of the Ullman, Shockwave, and SHOX-4800 seat with semi-active suspension, the mass acceleration is about equal to or greater than the carriage acceleration for larger drop heights. It could be that in those cases, the seat suspension system cannot handle the large impact, and cannot reduce the peak accelerations that the occupant mass is subject to. Also, in some cases the mass acceleration increases relative to the seat acceleration for higher drop heights. This could be due to the fact that the seat cushioning cannot handle the higher impacts.

2.4.3 Drop Testing with Variable Impacting Materials

Drop testing was also performed with different impacting materials at the base, as shown in Figure 2.21.

Figure 2.21: Drop tower base.

As indicated in Figure 2.21, the additional impacting material would be crushed between the polyurethane bumper and the rubber base. The goal was to emulate the period and magnitude of the impact load to be closer to what is seen in the sea trial data. A number of different materials were tested, including white open-cell packing foam, closed-cell pink insulation foam, and aluminum honeycomb (Hexcel, nominal density 3.2 pcf). The goal was to reproduce the Type 1 Impact Profile as described in Section 5.1.2, therefore different impacting materials were needed to increase the impact duration, as the impact duration using the default materials (polyurethane bumper and rubber base) was too short. The results are shown in Figure 2.22.

Figure 2.22: Carriage acceleration results from drop testing with variable impacting materials.

The various materials used in addition to the standard rubber base clearly can be used to shape the impact profile, but their effectiveness is limited. Additionally, Type 1 is the most simple of the five impact types, and more direct motion control is therefore needed to accurately reproduce all the profiles. The Slam Impact Seat Test

Rig, discussed in the following chapters, will be used to achieve this goal.

2.5 Conclusion

A series of drop tests was performed on five representative high speed craft suspension seats and acceleration data were recorded and processed for each of the seats. The damped natural frequencies and damping ratios for each of the seats were computed and tabulated. Peak accelerations from which the level of shock isolation provided by each of the seats can be assessed were also tabulated. Assessing the performance of individual seats for their intended purpose in an operational context (reducing risk of injury) was not within the scope of this research.

Chapter 3

Development of Control Strategies for the SISTR

3.1 Overview of SISTR Motion

In order to improve testing of suspension seats, the SISTR [7] was developed. The primary goal was to be capable of reproducing high speed craft deck motions in different sea state conditions. In order to achieve this goal, the SISTR is capable of both vertical and horizontal motion. Both motions are controlled by electric motors which drive the machine through a pulley and cable system. This allows the SISTR to have several advantages over a conventional drop tower, including the ability to reproduce low-frequency motion due to waves seen by HSC, occasional and repeated shock loading (since repeated motion may affect seat performance, e.g. suspension components heating up, or suspension not returning to static position before the next impact), and shock loading occurring for different levels of seat compression. Additionally, the horizontal motion which the SISTR is capable of is useful because the motion of HSC is not always vertical, and the seat suspension system may be affected by friction due to side loading.

A picture of the SISTR is shown in Figure 3.1. The SISTR consists of two electric

motors, one for horizontal motion and one for vertical motion. The motor for horizontal motion drives a cart assembly along rails. The motor for vertical motion is located in the cart assembly, and drives a deck assembly within the cart assembly. The deck assembly consists of two sub-structures connected to each other via a load cell. The first structure is what moves along the rails, and the second structure is what the seat mounts to. The SISTR has an overall range of motion of 1.3 m vertically and 2.5 m horizontally, as well as acceleration limits of 2 g upwards using the cable drive system, 8 g upwards through impact with the dampers, 0.9 g downwards, and 0.5 g in either direction horizontally [7].

Figure 3.1: Photo of the SISTR.

Figure 3.2: SISTR diagram [7].

As can be seen in Figure 3.2, the horizontal drive assembly drives the cart along the horizontal rails. The motor acts through a 20:1 speed reduction gearbox, which is connected to a pulley that drives the cables connected to the cart as shown in Figure 3.3.

Figure 3.3: SISTR horizontal drive [7].

The vertical drive motor is located at the bottom of the cart assembly, and acts through a 7:1 speed reduction planetary gearbox as shown in Figure 3.4. The gearbox drives a spool pulley assembly through a belt, which in turn drives the cables connected to the deck. The deck assembly is shown in Figure 3.5.

Figure 3.4: SISTR vertical drive (top view) [7].

Figure 3.5: SISTR deck assembly [7].

The motor driving the vertical motion is an Emerson Unimotor 190E 10.4 kW servomotor controlled by an Emerson Unidrive SP3202 controller. The motor driving the horizontal motion is a Baldor ZDNM3669T 1.5 kW induction motor controlled by a Baldor ZD18H controller.

To create slam impacts in the vertical motion, two electrorheological dampers are installed at the bottom of the cart assembly. The dampers are Fludicon RheDamp 63, each controlled by a DampCon 40 amplifier. The dynamically-adjustable damping ratio of these dampers is intended to allow for the impact profile to be shaped to appropriately reproduce HSC motion.

For more details on the SISTR design and build process, please refer to [7].

3.2 Operational Control Methods

Various software is used to control the SISTR. As mentioned previously, the overall goal of the SISTR is to more accurately reproduce HSC motion compared to conventional drop testing. To control the vertical motion, the PowerTools Pro software made by Emerson was used, as it is designed specifically to work with the motor and controller. To control the horizontal motion, both X-CTU and LabVIEW were used. For more information on the software and user interface, please refer to Chapter 4.

Different control strategies were tested during the commissioning of the SISTR in order to obtain the desired motion for testing the suspension seats accurately and reliably.

The following three main types of motions, available within the PowerTools Pro software, were tested to control the vertical motion.

3.2.1 Jog Motion

With this motion profile, the machine moves at a constant prescribed velocity. The acceleration and deceleration rates are also defined. Figure 3.6 shows a sample jog motion.

Figure 3.6: Sample jog motion.

Jog motion is useful for moving the cart at a low velocity into different positions to facilitate seat installation/removal or other work on the machine, because the total time is dependent on the user input of holding down the appropriate jog button. This will be explained further in the next section.

3.2.2 Index Motion

With this motion profile, the machine moves a prescribed distance. The maximum velocity, as well as the acceleration and deceleration rates to and from that velocity, are also defined. Depending on the parameters specified, the maximum velocity may not actually be attained if the acceleration rates are not high enough relative to the specified distance. If this is the case, the machine will still move by the prescribed distance, but during the motion it will begin decelerating before reaching the maximum specified velocity. Figure 3.7 shows a sample index motion.

Figure 3.7: Sample index motion.

Index motion is also useful for moving the machine to different positions to facilitate work on the machine.

3.2.3 Cam Motion

With this motion profile, position versus time points are input directly into the program to control motion. Once these points are specified, the control software generates a preview of the velocity and acceleration profiles. An example of cam motion is shown in Figure 3.8.

Figure 3.8: Sample cam motion.

The cam motion was selected as it proved to be the most robust method for control, given that exact position versus time points are specified. When used properly, it ensures that no machine limits will be exceeded, so that the intended motion can be safely and accurately reproduced.

3.3 Challenges and Solutions

As described previously, the cam motion was chosen as it is the most robust form of motion control given that it most directly specifies the motion. Once the cam type motion was selected for use as the primary motion control strategy, a number of issues needed to be addressed to ensure that the SISTR could operate accurately, reliably, and safely.

The first issue is to ensure that the machine stays within its displacement limits.

This can be ensured firstly by reviewing the displacement-time profile before starting the motion to make sure there are no commanded points outside of the displacement limits.

Next, the acceleration profile must be checked to ensure that there is never an acceleration greater than 1 g in the downward direction commanded. This is because the vertical motion of the cart is accomplished through cables which can only pull upwards, therefore acceleration downward is only due to gravity. If greater than 1 g acceleration downward is commanded, there will be a following error between the cables and the cart. Additionally, due to friction in the machine, it is recommended to stay below 0.9 g in the downwards direction to avoid following error.

Figures 3.9 and 3.10 show an example of following error. In this case, a downwards acceleration of 1.5 g has been commanded. As a result, the velocity takes longer than expected to reach zero. Also, the displacement peaks at a higher value than expected, and it again occurs after a longer period of time.

Figure 3.9: Velocity-time graph showing following error.

Figure 3.10: Displacement-time graph showing following error.

This kind of following error should be avoided for three reasons. Firstly, this following error will cause the cables to become slack, which could cause them to become entangled in the machine. Secondly, if the cables become slack, then when the cart catches up to the cables there will be potentially damaging impact loading when the cables become taught. Thirdly, if the following error occurs when the cart is moving upwards, this could mean that the cart does not come to a stop before reaching the vertical limit of travel of the machine. In addition to the main safety reasons, this following error should also be avoided because it would cause the machine to not accurately reproduce the commanded motion profile.

The second issue is to ensure that at the end of any motion profile, the velocity of the cart is zero. This is because the cam-type motion in PowerTools Pro is positional control. Therefore, after executing the motion profile, the last commanded position will be held. If the velocity of the machine is not zero, the motor will try to stop immediately, which could cause following errors between the cables and the cart as described above. Therefore, if a desired motion profile does not end with zero velocity,

additional motion must be added to the profile to bring the cart to rest safely.

The third issue is to ensure the commanded acceleration is not higher than the machine's capabilities, which are a maximum of 2 g in the upwards direction, and 0.9 g in the downwards direction.

The final consideration is whether the displacement commanded from the motor is specified as an absolute or a relative value. When specified as an absolute value, the machine will move to the specified location within its range of motion. When specified as a relative value, the machine will move by the commanded displacement relative to its current position.

For example, if the deck is located at a position of 0.3 m and is commanded to move 1.0 m in absolute displacement, then the deck will move to the 1.0 m position. If it is commanded to move 1.0 m in relative displacement, then it will move to the 1.3 m position. Table 3.1 shows the maximum displacements and accelerations of the SISTR, which are tested in Chapter 5.

Table 3.1: Displacement and acceleration limits of the SISTR.

Limit	Acceleration [g]	Displacement [m]
Vertical	+2/-0.9	1.3
Horizontal	+/-0.5	2.5

Both types of positional control have their advantages and disadvantages. In absolute control, in most cases it will be easier to ensure that the specified motion does not exceed the machine's displacement limits, since the exact position is specified. Conversely, in relative control, care must be taken to ensure the commanded motion profile does not exceed the machine's range of motion when added onto its current position, therefore potentially more verification is necessary.

However, when using absolute control, the position of the machine must be known and specifically controlled such that when a motion profile is initiated, its first commanded position lines up with the initial position of the machine. For example, if the machine is at a position of 0.2 m, and then a motion profile is run in absolute positional control with the first commanded point being 0.7 m, the machine will immediately jump by 0.5 m, which could cause damage. Relative control is used in all of the tests described in Chapter 5.

In any case, it is essential to thoroughly check all motion profiles before initiation of any motion to ensure safe and accurate operation. This is especially important due to the machine's cable drive system which pulls upwards, with only gravity available to slow the seat cart down when it is moving upwards.

Following these guidelines will help avoid failures, such as one that occurred during the commissioning phase of the SISTR, which resulted in minor damage to the machine. The failure was caused by a combination of two issues: the type of motion control used and the discrepancy between the deck position and the position given by the motor encoder.

The type of motion control used when the failure occurred was the Index motion. Once the position, acceleration, deceleration, and maximum velocity parameters were specified, the software generated a velocity-time graph of the expected motion. However, due to an impact from a previous motion profile run, the deck was starting the motion profile from below the zero position as read by the encoder. Since the generated velocity-time graph assumes the machine starts at the zero position, it seems that starting from a position other than zero could result in unpredictable motion. In this case, the unpredictable motion meant that the deck exceeded the maximum specified speed and deceleration rates. This led to the deck overshooting the commanded position, which created slack in the cables. When the deck fell back down, the resulting impact load on the cables damaged the machine as shown in Figure 3.11.

Figure 3.12 shows the assembly before the failure.

Figure 3.11: Failure of top beams of the cart of the SISTR.

Figure 3.12: Top beams of the cart of the SISTR with pulleys before failure [7].

Chapter 4

SISTR User Interface

This chapter describes the different software and other inputs used to control the SISTR. The user interface for the SISTR consists of three main software components, as well as direct inputs to the machine via push buttons.

The vertical drive motor is controlled by PowerTools Pro, made by Emerson, the same company which manufactures the motor. The horizontal drive motor is controlled by both X-CTU and LabVIEW. X-CTU is a program which can issue serial commands to control the motor, but its functionality is limited; therefore, LabVIEW is the main program used to control the horizontal drive motor. LabVIEW is also used to acquire data from the various sensors which the SISTR is instrumented with.

In addition to the software used to control the horizontal and vertical drive motors, several push buttons are also used to control the SISTR. The overall control and data acquisition system is shown in the simplified block diagram in Figure 4.1.

Figure 4.1: SISTR block diagram.

4.1 PowerTools Pro (Vertical Motion)

In this software, the main parameters used to control the vertical drive motor are defined, as well as all the motion profiles and software programs. This software is used to connect the PC to the vertical drive, and to download programs to the drive.

PowerTools Pro has four main sections: motor setup, input configuration, motion profiles, and programs.

4.1.1 Motor Setup

In this section the main parameters for the motion of the motor are defined, as shown in Figures 4.2 through 4.4. These include the type and model of motor, and most importantly, the linear travel of the deck assembly per revolution of the motor. This is important because it allows all inputs to the machine to be given in the proper linear distance. Full parameters can be found in Appendix B.

Figure 4.2: Motor setup in PowerTools Pro - Part 1.

Figure 4.3: Motor setup in PowerTools Pro - Part 2.

Figure 4.4: Motor setup in PowerTools Pro - Part 3.

4.1.2 Input Configuration

In this section, various inputs into the controller are defined, including direct inputs via buttons on the control panel (see Section 4.3). As shown in Figure 4.5, Boolean variables denoted “EzInputs” are assigned to physical inputs on the drive “Bits”. The EzInput variables can then be called by programs written within PowerTools Pro (see Section 4.1.4). Additionally, the polarity of the inputs can be specified as either “Active On”, where the sign of the variable matches that of the input; or “Active Off”, where the sign of the variable is opposite to the sign of the input.

Figure 4.5: Inputs in PowerTools Pro.

4.1.3 Motion Profiles

In this section, different types of user-created motion profiles are found. As described in Section 3.2, there are three different types of motion: jog motion, index motion, and cam motion.

Jog motion moves the deck at a constant jog velocity. The user specifies a constant jog velocity, as well as the acceleration value to reach that velocity, and the deceleration back to zero velocity. Figure 4.6 shows the jog motion within the PowerTools Pro software.

Figure 4.6: Jog motion in PowerTools Pro.

The deck within the SISTR moves vertically at the specified jog velocity as long as the profile is active. Positive velocity moves the deck upwards, while negative velocity moves the deck downwards.

Index motion moves the deck by a specified distance. The maximum velocity, as well as the acceleration rate to and deceleration rate from that velocity are also specified. Once the parameters are specified, the software generates a preview of the motion, as shown in Figure 4.7.

Figure 4.7: Index motion in PowerTools Pro.

Care must be taken to ensure that there are no motion parameters specified outside of the machine's capabilities (as discussed in Section 3.3). Additionally, either absolute or relative displacement can be specified (see Section 3.2 for further details).

Cam motion consists of specific position versus time points, as described in Section 3.2.3. Points can be entered manually, or imported from an external csv format file. Figure 4.8 shows the interface for entering cam motion.

Figure 4.8: Cam motion in PowerTools Pro.

When importing from an external csv format file, the data must be in the specific format shown in Figure 4.9. This includes the [MF] header, the first column containing time values in seconds, and the second column containing displacement values in metres.

	A	B
1	[MF]	
2	0	0
3	0.00132	1.74E-07
4	0.00264	1.05E-06
5	0.00396	3.35E-06
6	0.00528	7.8E-06
7	0.0066	1.52E-05
8	0.00792	2.62E-05
9	0.00924	4.18E-05
10	0.01056	6.26E-05
11	0.01188	8.95E-05
12	0.0132	0.000123
13	0.01452	0.000165
14	0.01584	0.000215
15	0.01716	0.000275

Figure 4.9: Sample input file for cam motion in PowerTools Pro.

Additionally, a cam profile can be defined to repeat, or to chain directly to another cam profile.

4.1.4 Programs

In this section, user-created programs, which make use of user-defined motion profiles, are outlined. Using programs offers greater control over the SISTR's motion than simply executing motion profiles directly from their respective menus. Programs can be used to call different motion profiles in a specified order, as well as accept direct inputs as described in Section 4.3.

Figure 4.10: Program in PowerTools Pro.

The program shown in Figure 4.10 allows the user to activate jog motion by pressing buttons on the control panel (see Section 4.3). In this case, the white button, assigned to EzInput 2, activates the vertical jog upwards, while the black button, assigned to EzInput 3, activates the vertical jog downwards. The program accomplishes this by using a loop and “if” statements to use the button presses. The red button is used to end the program.

4.2 LabVIEW (Horizontal Motion)

LabVIEW software serves three purposes:

1. acquiring data from all of the various sensors installed on the SISTR;
2. controlling the damping ratio of the electro-rheological dampers installed on the SISTR; and
3. controlling the horizontal motion of the SISTR.

4.2.1 Data Acquisition

All sensors installed on the SISTR are connected to National Instruments data acquisition (DAQ) devices, and LabVIEW is used to configure and acquire data from these sensors. These sensors comprise:

- A 3-axis accelerometer on the deck (Memsic CXL25GP3);
- 3 orthogonally-arranged single-axis accelerometers on the seat (Measurement Specialties MEAS 4000A-100);
- 3 orthogonally-arranged single-axis accelerometers on the mass (Measurement Specialties MEAS 4000A-100);
- A load cell between the main motion deck and seat deck to which the seat is mounted (Omega 250);
- A string potentiometer mounted in the cart which measures the absolute vertical displacement of the deck (UniMeasure HX-PA 80); and
- A string potentiometer mounted in the rail supports which measures the absolute horizontal displacement of the cart (UniMeasure HX-PA 250).

Given that the sensors output voltage to the analog inputs on the data acquisition devices, they must be calibrated in LabVIEW as shown in Figure 4.11.

Figure 4.11: Sensor calibration in LabVIEW.

This calibration involves specifying a linear gain and offset to convert the voltage output from the sensor to the appropriate units of the quantity being measured. Figure 4.11 shows the calibration for a MEMSIC CXL25GP3 accelerometer, which has a range of ± 25 g with an output range of 0 to 5 volts.

The SISTR uses three different DAQ devices to acquire all the data from all the sensors installed. A NI-USB 6211 DAQ device is mounted at the bottom of the cart assembly. This DAQ device acquires data from all the accelerometers. A separate NI-USB 6289 DAQ device is located on the control desk with the PC and control panel, and acquires data from the two string potentiometers. Finally, a separate NI UMI DAQ card installed in the PC acquires data from the load cell.

The sensors must also be wired to the appropriate input on each of the DAQ devices. Figure 4.12 specifies how the inputs are configured in LabVIEW.

Figure 4.12: Channel list in LabVIEW.

The inputs correspond to specific pins on the devices - the sensors were all connected to analog inputs (AI). The pinout is given in Figure 4.13.

During testing, data being acquired is displayed in real time in LabVIEW. The LabVIEW block diagram shown in Figure 4.14 is used to display the data in real time.

Figure 4.13: Pinout for NI USB-6211 (left) [14] and NI USB-6289 (right) [15].

Figure 4.14: Block diagram in LabVIEW.

The live display of the data being collected is shown in the Figure 4.15.

Figure 4.15: Live data display in LabVIEW.

Running the data collection program in LabVIEW creates a Technical Data Management Streaming (TDMS) format file, which can be opened as a spreadsheet in Microsoft Excel with the appropriate TDMS plugin. If the data collection program is run multiple times with the same file path specified, then each time the program is run, a new sheet will be created within the Excel file. The first sheet of the file contains a summary of the following sheets, as shown in Figures 4.16 and 4.17.

	A	B	C	D	E	F	G	H	I	
1	Root Name	Title	Author	Date/Time	Groups	Description				
2	Test_2017-08-09_Accel				6					
3										
4	Group	Channels	Description							
5	Group Name	9								
6	Group Name #1	9								
7	Group Name #2	9								
8	Group Name #3	9								
9	Group Name #4	9								
10	Group Name #5	9								
11										
12	Group Name									
13	Channel	Datatype	Unit	Length	Minimum	Maximum	Description	NI_ChannelName	NI_Number_Of_Scales	NI_St
14	Z_DECK_ACC	DT_DOUBLE	g	100				Z_DECK_ACC	2	
15	Y_DECK_ACC	DT_DOUBLE	g	100				Y_DECK_ACC	2	
16	X_DECK_ACC	DT_DOUBLE	g	100				X_DECK_ACC	2	
17	Z_SEAT_ACC	DT_DOUBLE	g	100				Z_SEAT_ACC	2	
18	Y_SEAT_ACC	DT_DOUBLE	g	100				Y_SEAT_ACC	2	
19	X_SEAT_ACC	DT_DOUBLE	g	100				X_SEAT_ACC	2	
20	Z_MASS_ACC	DT_DOUBLE	g	100				Z_MASS_ACC	2	
21	Y_MASS_ACC	DT_DOUBLE	g	100				Y_MASS_ACC	2	
22	X_MASS_ACC	DT_DOUBLE	g	100				X_MASS_ACC	2	
23										
24	Group Name #1									
25	Channel	Datatype	Unit	Length	Minimum	Maximum	Description	NI_ChannelName	NI_Number_Of_Scales	NI_St
26	Z_DECK_ACC	DT_DOUBLE	g	35500				Z_DECK_ACC	2	
27	Y_DECK_ACC	DT_DOUBLE	g	35500				Y_DECK_ACC	2	
28	X_DECK_ACC	DT_DOUBLE	g	35500				X_DECK_ACC	2	
29	Z_SEAT_ACC	DT_DOUBLE	g	35500				Z_SEAT_ACC	2	
30	Y_SEAT_ACC	DT_DOUBLE	g	35500				Y_SEAT_ACC	2	
31	X_SEAT_ACC	DT_DOUBLE	g	35500				X_SEAT_ACC	2	
32	Z_MASS_ACC	DT_DOUBLE	g	35500				Z_MASS_ACC	2	
33	Y_MASS_ACC	DT_DOUBLE	g	35500				Y_MASS_ACC	2	
34	X_MASS_ACC	DT_DOUBLE	g	35500				X_MASS_ACC	2	
35										
36	Group Name #2									
37	Channel	Datatype	Unit	Length	Minimum	Maximum	Description	NI_ChannelName	NI_Number_Of_Scales	NI_St
38	Z_DECK_ACC	DT_DOUBLE	g	56800				Z_DECK_ACC	2	
39	Y_DECK_ACC	DT_DOUBLE	g	56800				Y_DECK_ACC	2	
	Test_2017-08-09_Accel (root)									
	Test1 Test2 1_BoatMotion 2_5_Impact_Types 3_RepeatImpacts 4_AscendingImpacts									

Figure 4.16: Sample data collected by LabVIEW.

	A	B	C	D	E	F	G	H	I
1	Z_DECK_ACC	Y_DECK_ACC	X_DECK_ACC	Z_SEAT_ACC	Y_SEAT_ACC	X_SEAT_ACC	Z_MASS_ACC	Y_MASS_ACC	X_MASS_ACC
2	-0.994821237	0.155314019	-0.147075087	-3.730830498	-0.319548097	-0.525047042	1.68612165	1.998480061	-1.371702688
3	-0.978173064	0.155314019	-0.169966339	-3.689730711	-0.319548097	-0.566146831	1.68612165	1.95738027	-1.289503112
4	-0.996902258	0.174043228	-0.151237133	-3.714390583	-0.360647886	-0.549706915	1.710781525	2.006700019	-1.322382942
5	-0.99898328	0.163638112	-0.151237133	-3.796590157	-0.188028771	-0.451067422	1.653241818	1.883400646	-1.314162985
6	-1.017712474	0.180286297	-0.147075087	-3.75549037	-0.303108181	-0.549706915	1.669681734	1.949160312	-1.322382942
7	-0.99898328	0.180286297	-0.14915611	-3.656850881	-0.171588856	-0.599026662	1.743661357	2.072459685	-1.338822858
8	-0.992740215	0.167800158	-0.19910066	-3.656850881	-0.262008392	-0.483947253	1.68612165	1.973820186	-1.289503112
9	-0.969848978	0.167800158	-0.207424752	-3.697950668	-0.294888223	-0.590806704	1.677901692	1.932720395	-1.338822858
10	-0.969848978	0.138665834	-0.1845335	-3.689730711	-0.286668265	-0.631906493	1.653241818	1.932720395	-1.314162985
11	-0.974011021	0.144908904	-0.176209408	-3.75549037	-0.27022835	-0.516827084	1.694341609	2.031359894	-1.297723069
12	-0.97193	0.14907095	-0.180371454	-3.706170625	-0.401747675	-0.385307759	1.669681734	1.908060521	-1.305943027
13	-0.974011021	0.165719135	-0.174128385	-3.706170625	-0.122269109	-0.525047042	1.694341609	1.932720395	-1.363482731
14	-0.97193	0.159476066	-0.194938614	-3.780150242	-0.393527717	-0.409967633	1.719001483	2.006700019	-1.338822858
15	-0.986497151	0.157395042	-0.176209408	-3.632191009	-0.434627506	-0.467507337	1.677901692	1.982040144	-1.297723069
16	-0.988578172	0.184448343	-0.138750995	-3.763710327	-0.311328139	-0.385307759	1.719001483	1.95738027	-1.297723069
17	-1.005226345	0.180286297	-0.147075087	-3.72261054	-0.311328139	-0.516827084	1.735441399	1.998480061	-1.363482731
18	-1.013550431	0.178205274	-0.155399179	-3.730830498	-0.253788434	-0.525047042	1.702561567	1.899840563	-1.190863619
19	-0.988578172	0.167800158	-0.180371454	-3.730830498	-0.319548097	-0.541486957	1.68612165	1.95738027	-1.273063196
20	-0.99898328	0.192772436	-0.197019637	-3.673290796	-0.327768055	-0.516827084	1.669681734	1.982040144	-1.322382942
21	-0.978173064	0.196934482	-0.176209408	-3.640410966	-0.262008392	-0.467507337	1.702561567	1.834080897	-1.363482731
22	-0.976092043	0.169881181	-0.172047362	-3.706170625	-0.303108181	-0.566146831	1.603922069	1.899840563	-1.347042815
23	-0.967767956	0.18236732	-0.167885316	-3.632191009	-0.04006953	-0.623686535	1.68612165	1.850520814	-1.396362561
24	-0.974011021	0.161557089	-0.178290431	-3.739050455	-0.262008392	-0.467507337	1.702561567	1.77654119	-1.355262773
25	-0.980254086	0.157395042	-0.16372327	-3.804810114	-0.097609235	-0.648346409	1.702561567	1.834080897	-1.347042815
26	-1.001064302	0.174043228	-0.165804293	-3.681510753	-0.492167211	-0.492167211	1.77654119	1.916280479	-1.264843239

Figure 4.17: Sample data collected by LabVIEW.

4.2.2 Damper Control

Within the same graphical user interface that displays the live data from the various sensors on the SISTR, the excitation voltage to the two electrorheological dampers can be set. This allows for the desired damping ratio to be set depending on the type of impact profile required from the machine.

4.2.3 Horizontal Motion Control

Similar to the vertical motion control scheme used in PowerTools Pro, the LabVIEW interface also accepts the same csv-format file for horizontal motion position versus time inputs. As with the vertical motion, the limitations of the machine must be taken into account when entering a motion profile. For horizontal motion, the displacement

limit is 2.5 m and the acceleration limit is 0.5 g. However, unlike the vertical motion, where the cable drive system can only pull upwards, the horizontal cable drive system can pull in both directions.

4.3 Direct Inputs

Used in conjunction with the software controls are the direct inputs into the SISTR, which are several buttons on the main control panel, shown in Figure 4.18. The control panel is located next to the computer which controls the SISTR.

Figure 4.18: SISTR control panel.

The two green buttons, labelled “Vertical Activate” and “Horizontal Activate”, are used to enable the vertical and horizontal drive motors. These are the main inputs which allow the motors to move. These buttons are directly wired to the enable function of the drives themselves, so they act above any software programs or other inputs which control the motors. Therefore, it is not possible for the software

or programs to bypass these buttons.

The red button labelled “Truncate Program” is used to stop execution of a program for the vertical motion. It is used as a digital input to the vertical drive motor controller, and its input is coded into all programs that are uploaded to the drive. This is done using a loop within the programs which constantly monitors the status of the “Truncate Program” button input, and if activated, halts the execution of the program and moves the vertical cart down to its default home position. It is important to note that since this button is a digital input to the drive, in order to abort the execution of a program, its input must be coded into any new program. Limit switches installed at the limits of the machine’s motion have the same function as this button.

The white and black buttons serve different functions depending on the program being executed (see Section 4.1.4 for more details on the different programs). For example, in the jog program, the white button moves the cart up at a constant velocity when held down, and the black button moves the cart down (hence the labels “Jog Vertical Up” and “Jog Vertical Down”). In the program which executes the Five Impact Profiles (see Section 5.1.2), the white button is used to advance to the next profile (hence the label “Advance Program”). In most other programs, once the program is initiated from within the software, the white button is used to start motion.

The red button with white arrows labelled “Parking Brake” is used to activate the brake on the vertical drive motor. This brake is separate from the motor controller, and has its own power source. Therefore, the brake can be active even when there is no direct power to the motor through the controller. It is important to note that the default state of the brake is on, therefore a signal is required to deactivate the brake. This is an important safety feature given that the brake will activate in the event of a total loss of power, so the deck assembly will remain in place instead of

falling suddenly to the bottom of its range of motion.

The switch labelled “Solenoid” is used to retract the solenoid at the top of the cart. When the solenoid is retracted, the light labelled “Solenoid Retracted” will be illuminated. The solenoid is used to hold the ballast cart in place when a seat is installed or removed. In addition to the solenoid, a redundant manual lock is installed to hold the ballast cart in place. The solenoid and lock must be retracted when the machine is running.

4.4 Overall SISTR Operating Procedure

Firstly, the appropriate general safety procedures must be followed. The lab in which the SISTR is located is limited access to authorized personnel. The safety screen must be in place, and personnel should remain behind the yellow safety line.

Starting up the SISTR first involves energizing the horizontal and vertical drives. The horizontal drive must be energized first, since the encoder for the vertical drive looks for a signal from the encoder for the horizontal drive (for the purpose of synchronized motion). After both drives are energized, PowerTools Pro can connect to the vertical drive.

Once a connection is established, the desired program must be downloaded to the vertical drive. This allows for greater reliability and accuracy as the program is stored and run directly from the memory built into the drive.

Next, data acquisition in LabVIEW can be started. Before the desired motion profile can be run (by using PowerTools Pro for vertical motion or LabVIEW for horizontal motion), the drive must be enabled from the control panel, and the parking brake must be disabled. Once the motion profile has been completed, the data acquisition can be stopped, the parking brake should be enabled, and the drive disabled.

Chapter 5

Standard Procedure for Testing Seats with the SISTR

5.1 Standard Profiles

To test suspension seats with the SISTR, a standard test procedure has been developed. The purpose of establishing a standard test procedure is so that any suspension seat can be tested and the results could be assessed to determine its suitability for use in a HSC. Four different types of motion profiles form the standard test procedure, and they are described in the following sections. These four tests were performed with two different masses on each seat: 80 kg and 110 kg.

5.1.1 Sample of Representative Boat Motion

This test consists of a 20-second sample of boat motion. This motion is based on at-sea tests performed on 14 June 2007 with an HSC. A portion of the accelerometer data from those tests was filtered using a fourth-order dual-low-pass Butterworth filter with a cut-off frequency of 30 Hz to produce the profile shown in Figure 5.1.

Figure 5.1: Acceleration profile of sample boat motion.

The acceleration data were integrated twice using trapezoidal numerical integration to obtain the displacement profile shown in Figure 5.2, which was uploaded to the PowerTools Pro software as a cam motion. The measured accelerations from the sea trial were used to create this profile since no absolute velocity or displacement measurements exist during such a trial.

Figure 5.2: Displacement profile of sample boat motion.

5.1.2 Five Standard Impact Types

Five impact profiles were identified by Mohamed El Tayeb [6]. Data from sea trials of Rigid-Hull Inflatable Boats (RHIBs) were examined. The impacts in the data were categorized into five main types. Each impact was identified by an equation that was obtained by using a combination of modified Gaussian curves. The profiles represent

different types of impacts that HSC may experience due to various conditions such as sea state, types of waves, orientation of the HSC on impact, etc. The profiles are as follows:

Type 1: Half-Sine

The function used to describe the half-sine profile is:

$$F(x) = \frac{x(x-1)e^{-\left(\frac{x-m_1}{\sigma_1}\right)^2}}{x_1(x_1-1)e^{-\left(\frac{x_1-m_1}{\sigma_1}\right)^2}} \quad (5.1)$$

where

$$m_1 = \frac{-(2x_1-1)\sigma_1^2}{2x_1(x_1-1)} + x_1 \quad (5.2)$$

and $x_1 = 0.42, \sigma_1 = 0.50$.

This gives a normalized acceleration profile, with a normalized acceleration of 1 and normalized time of 1. Using a period of $T = 132$ ms and peak acceleration $a = 1.5$ g, the profile is shown in Figure 5.3.

Figure 5.3: Type 1 acceleration profile.

Type 2: Half-Sine with Single Shoulder

The function used to describe the half-sine with single shoulder profile is:

$$F(x) = \frac{x(x-1)a_1 e^{-\left(\frac{x-m_1}{\sigma_1}\right)^2}}{x_1(x_1-1)e^{-\left(\frac{x_1-m_1}{\sigma_1}\right)^2}} + \frac{x(x-1)a_2 e^{-\left(\frac{x-m_2}{\sigma_2}\right)^2}}{x_2(x_2-1)e^{-\left(\frac{x_2-m_2}{\sigma_2}\right)^2}} \quad (5.3)$$

where

$$m_1 = \frac{-(2x_1-1)\sigma_1^2}{2x_1(x_1-1)} + x_1, m_2 = \frac{-(2x_2-1)\sigma_2^2}{2x_2(x_2-1)} + x_2 \quad (5.4)$$

and $x_1 = 0.29, a_1 = 1, \sigma_1 = 0.30, x_2 = 0.70, a_2 = 0.19, \sigma_2 = 0.26$, the period $T = 231$ ms, and the peak acceleration $a = 1.5$ g. The profile is shown in Figure 5.4.

Figure 5.4: Type 2 acceleration profile.

Type 3: Half-Sine with Multiple Shoulders

The function used to describe the half-sine with multiple shoulders profile is:

$$F(x) = \sum_{j=1}^3 a_j \frac{x(x-1)e^{-\left(\frac{x-m_j}{\sigma_j}\right)^2}}{x_j(x_j-1)e^{-\left(\frac{x_j-m_j}{\sigma_j}\right)^2}} \quad (5.5)$$

where

$$m_j = \frac{-(2x_j - 1)\sigma_j^2}{2x_j(x_j - 1)} + x_j \quad (5.6)$$

and $x_1 = 0.17, a_1 = 1, \sigma_1 = 0.17, x_2 = 0.41, a_2 = 0.27, \sigma_2 = 0.13, x_3 = 0.66, a_3 = 0.15, \sigma_3 = 0.30$, the period $T = 413$ ms, and the peak acceleration $a = 1.5$ g. The profile is shown in Figure 5.5.

Figure 5.5: Type 3 acceleration profile.

Type 4: Delayed Peak

The function used to describe the delayed peak profile is:

$$F(x) = \sum_{j=1}^3 a_j \frac{x(x-1)e^{-\left(\frac{x-m_j}{\sigma_j}\right)^2}}{x_j(x_j-1)e^{-\left(\frac{x_j-m_j}{\sigma_j}\right)^2}} \quad (5.7)$$

where

$$m_j = \frac{-(2x_j - 1)\sigma_j^2}{2x_j(x_j - 1)} + x_j \quad (5.8)$$

and $x_1 = 0.41, a_1 = 1, \sigma_1 = 0.23, x_2 = 0.13, a_2 = 0.27, \sigma_2 = 0.15, x_3 = 0.75, a_3 = 0.21, \sigma_3 = 0.18$, the period $T = 347$ ms, and the peak acceleration $a = 1.5$ g.

The profile is shown in Figure 5.6.

Figure 5.6: Type 4 acceleration profile.

Type 5: Double Peak

The function used to describe the double peak profile is:

$$F(x) = \sum_{j=1}^3 a_j \frac{x(x-1)e^{-\left(\frac{x-m_j}{\sigma_j}\right)^2}}{x_j(x_j-1)e^{-\left(\frac{x_j-m_j}{\sigma_j}\right)^2}} \quad (5.9)$$

where

$$m_j = \frac{-(2x_j-1)\sigma_j^2}{2x_j(x_j-1)} + x_j \quad (5.10)$$

and $x_1 = 0.12, a_1 = 1, \sigma_1 = 0.13, x_2 = 0.44, a_2 = 0.56, \sigma_2 = 0.15, x_3 = 0.67, a_3 = 0.27, \sigma_3 = 0.39$, the period $T = 459$ ms, and the peak acceleration $a = 1.5$ g.

The profile is shown in Figure 5.7.

Figure 5.7: Type 5 acceleration profile.

These five acceleration profiles were numerically integrated to obtain velocity profiles. Once this was done, additional motion needed to be added after the end of each profile to bring the final velocity back down to zero. As described previously, this was necessary to ensure smooth and safe operation of the machine. To do this, a constant deceleration of 0.5 g was added to the end of the profile for as much time as needed to reduce the velocity to zero. Once this was done, the velocity profile was integrated to obtain the displacement profile, which could be uploaded to the machine. The resulting displacement profiles are as indicated in Figures 5.8 through 5.12.

Unlike the other profiles part of the standard test procedure, the accelerations in these profiles were achieved using the cable drive system only, and did not make use of the dampers. The impacts in the other profiles were achieved using the dampers set in the middle of their adjustable range (2.5 V input).

Figure 5.8: Type 1 displacement profile.

Figure 5.9: Type 2 displacement profile.

Figure 5.10: Type 3 displacement profile.

Figure 5.11: Type 4 displacement profile.

Figure 5.12: Type 5 displacement profile.

5.1.3 Repeated Constant Impacts

This motion profile consists of 4 repeated 6-7 g impacts. The amplitude was chosen based on the reasearch done in [4]. The overall motion is modelled as a sinusoidal input with an amplitude of 50 cm and a period of 2 seconds. The motion profile is shown in Figure 5.13.

Figure 5.13: Repeated constant impacts displacement profile.

Note that the 6-7 g impact is not shown because the motion is defined such that the deck of the SISTR would hit the dampers at the lowest point, producing the desired impact.

5.1.4 Repeated Increasing Impacts

This motion profile consists of four increasing impacts: 2 g, 4 g, 6 g, and 8 g. The amplitude was chosen based on the reasearch done in [4]. Similarly to the repeated constant impacts, the motion is modelled as a sinusoidal input with a period of 2 seconds, as shown in Figure 5.14.

Figure 5.14: Repeated increasing impacts displacement profile.

In this motion, the increasing impact is achieved through the increasing displacement amplitudes. As with the previous motion, the impact occurs at the lowest point.

5.2 Additional Motion Profiles for SISTR Benchmarking

5.2.1 Vertical Range of Motion and Acceleration

These motion profiles are used to show the full vertical range of motion of the SISTR of 1.3 metres, as shown in Figure 5.15; as well as the maximum design vertical acceleration of the SISTR of 2 g upwards and 0.9 g downwards, shown in Figure 5.16.

Figure 5.15: Vertical range of motion displacement profile.

Figure 5.16: Maximum vertical acceleration profile.

Note that this is the maximum vertical acceleration available from the actuated

cables pulling on the deck, driven by the Emerson vertical drive motor. Greater accelerations are possible from impacts between the deck and the dampers.

5.2.2 Horizontal Range of Motion and Acceleration

This motion profile is used to show the horizontal range of motion of 2.5 m and maximum horizontal acceleration of 0.5 g of the SISTR. The commanded displacement profile to achieve this is shown in Figure 5.17.

Figure 5.17: Horizontal range of motion profile.

5.3 Procedure for Testing New Motion Profiles

In order to test a new motion profile with the SISTR, the profile should first be generated in acceleration, velocity, and displacement versus time formats. Although the displacement-time profile is what is actually uploaded to the SISTR, the acceleration and velocity profiles are necessary to check if the motion is feasible to run. Once the profiles are generated, they can be checked according to the criteria described in Section 3.3. Once it is determined that the profiles are feasible to run, the displacement profile can be saved in the csv file format and imported into the PowerTools Pro software, as described in Section 4.1.3.

Chapter 6

Seat Testing Using the SISTR

Using the standard test procedure as described in the previous section, four different suspension seats were tested:

1. SHOXS-6500
2. SHOXS-4800 with Passive Suspension
3. SHOXS-4800 with SHOXSDUAL2 Semi-active Suspension
4. Shockwave Marine Suspension

After drop tower testing, the Ullman seat was deemed unsuitable for laboratory testing because its shock isolation relies on supplementation by a human occupant and was as such excluded from testing with the SISTR. The results of the testing are presented in the following sections. These results were obtained from the accelerometers mounted on the SISTR, and the damped natural frequency and damping ratio results were obtained by processing the data with the code developed by Zuneid Alam [4]. One of the main goals of the tests conducted was to show that the SISTR could accurately reproduce commanded motion and meet motion benchmarks set out in the tests.

6.1 Sample of Boat Motion

This section presents measured motions produced by the SISTR based on the sample boat motion profile in Figures 6.1 and 6.2 and Tables 6.1 and 6.2, as described in Section 5.1.1. In Figure 6.1, only a one second sample is given to more clearly show how the SISTR is able to reproduce boat motion. In Figure 6.2, the impact occurring at 13 seconds is shown. This impact was added to the boat motion profile as the sample boat motion did not have any impacts much higher than 1 g.

Figure 6.1: Deck acceleration profile of sample boat motion.

Figure 6.2: Acceleration profile of the highest impact portion of sample boat motion using the SHOXS-6500 with 80 kg mass.

Table 6.1: Peak measured vertical accelerations for the boat motion sample profile.

Seat	Setting	Deck Accel. [g]	Seat Accel. [g]	Mass Accel. [g]
SHOXS-6500	-	3.7	2.8	2.3
SHOXS-4800 Passive	-	3.5	2.8	2.4
SHOXS-4800 Semi-Active	1	3.6	2.7	2.2
SHOXS-4800 Semi-Active	2	3.8	2.5	2.1
SHOXS-4800 Semi-Active	3	3.7	2.4	1.9
SHOXS-4800 Semi-Active	4	3.8	2.1	1.5
Shockwave	-	3.5	2.9	2.5

Table 6.2: Natural frequency and damping ratio results for the boat motion sample profile.

Seat	Setting	Damped Nat. Freq. [Hz]	Damping Ratio
SHOXS-6500	-	1.360	0.438
SHOXS-4800 Passive	-	1.627	0.379
SHOXS-4800 Semi-Active	1	1.273	0.367
SHOXS-4800 Semi-Active	2	1.068	0.431
SHOXS-4800 Semi-Active	3	0.917	0.518
SHOXS-4800 Semi-Active	4	0.772	0.560
Shockwave	-	1.149	0.261

Table 6.1 shows that all seats provide a reduction in acceleration between the deck and occupant mass. Table 6.2 shows that the damping ratio increases with increasing setting in the SHOXS-4800 semi-active seat, and that the Shockwave seat has the lowest damping ratio.

6.2 Five Impact Types

This section presents the results from the five impact type profiles, as described in Section 5.1.2, in Figures 6.3 through 6.7 and Tables 6.3 and 6.4.

Figure 6.3: Type 1 acceleration profile using SHOXS-4800 Passive with 80 kg mass.

Figure 6.4: Type 2 acceleration profile using SHOXS-6500 with 80 kg mass.

Figure 6.5: Type 3 acceleration profile using SHOXS-6500 with 110 kg mass.

Figure 6.6: Type 4 acceleration profile using Shockwave with 80 kg mass.

Figure 6.7: Type 5 acceleration profile using SHOXS-4800 Semi-Active Setting 4 with 110 kg mass.

Table 6.3: Peak measured vertical accelerations for the five impact type profiles.

Seat	Setting	Deck Accel. [g]	Seat Accel. [g]	Mass Accel. [g]
SHOXS-6500	-	1.5	1.1	0.9
SHOXS-4800 Passive	-	1.5	1.2	1.1
SHOXS-4800 Semi-Active	1	1.5	1.2	1.0
SHOXS-4800 Semi-Active	2	1.5	1.1	1.0
SHOXS-4800 Semi-Active	3	1.5	1.0	0.9
SHOXS-4800 Semi-Active	4	1.5	0.9	0.8
Shockwave	-	1.5	1.2	1.0

Table 6.4: Natural frequency and damping ratios resulting from the five impact type profiles.

Seat	Setting	Damped Nat. Freq. [Hz]	Damping Ratio
SHOXS-6500	-	1.305	0.429
SHOXS-4800 Passive	-	1.536	0.374
SHOXS-4800 Semi-Active	1	1.105	0.447
SHOXS-4800 Semi-Active	2	1.027	0.483
SHOXS-4800 Semi-Active	3	0.915	0.550
SHOXS-4800 Semi-Active	4	0.872	0.628
Shockwave	-	1.194	0.370

The results in Figures 6.3 through 6.7 show that the SISTR is able to reproduce the commanded motion reasonably accurately, as the measured deck accelerations are close to the commanded accelerations. In future work (see Chapter 7), the electrorheological dampers would have the potential to further improve the accuracy of these results, especially in the profiles with multiple peaks, where in the current results show the acceleration profile dipping into negative values between peaks, potentially due to elasticity in the cables.

As can be seen in Table 6.3, all seats tested provide a certain amount of reduction in acceleration seen at the occupant mass relative to the deck acceleration. Table 6.4 shows the damping ratio increasing with a higher setting on the SHOXS-4800 semi-active seat.

6.3 Repeated Constant Impacts

This section presents the results from the repeated constant impact profile in Figures 6.8 and 6.9 and Tables 6.5 and 6.6, as described in Section 5.1.3.

Figure 6.8: Deck acceleration profile of repeated constant impacts.

Figure 6.9: Acceleration profile of one of the repeated constant impacts using the SHOXS-4800 Passive with 80 kg mass.

Table 6.5: Peak measured vertical accelerations for the repeated constant impact profile.

Seat	Setting	Deck Accel. [g]	Seat Accel. [g]	Mass Accel. [g]
SHOXS-6500	-	6.4	4.1	3.2
SHOXS-4800 Passive	-	6.4	4.5	3.5
SHOXS-4800 Semi-Active	1	6.3	4.4	3.6
SHOXS-4800 Semi-Active	2	6.5	4.2	3.5
SHOXS-4800 Semi-Active	3	6.4	4.1	3.3
SHOXS-4800 Semi-Active	4	6.3	4.0	3.2
Shockwave	-	6.6	4.8	3.9

Table 6.6: Natural frequency and damping ratios resulting from the repeated constant impact profile.

Seat	Setting	Damped Nat. Freq. [Hz]	Damping Ratio
SHOXS-6500	-	1.356	0.382
SHOXS-4800 Passive	-	1.517	0.391
SHOXS-4800 Semi-Active	1	1.294	0.402
SHOXS-4800 Semi-Active	2	1.146	0.465
SHOXS-4800 Semi-Active	3	0.983	0.523
SHOXS-4800 Semi-Active	4	0.896	0.598
Shockwave	-	1.106	0.314

As with the previous tests, Table 6.5 shows that all seats provide a reduction in acceleration between the deck and occupant mass; and Table 6.6 shows that the damping ratio increases with increasing setting in the SHOXS-4800 semi-active seat, and that the Shockwave seat has the lowest damping ratio.

6.4 Repeated Increasing Impacts

This section presents the results from the repeated increasing impacts profile in Figures 6.10 and 6.11 and Tables 6.7 through 6.11, as described in Section 5.1.4.

Figure 6.10: Deck acceleration profile of repeated increasing impacts.

Figure 6.11: Acceleration profile of the 8 g impact of the repeated increasing impacts using the SHOXS-4800 Semi-Active Setting 3 with 110 kg mass.

Table 6.7: Peak measured vertical accelerations for the 2 g impact of the repeated increasing impact profile.

Seat	Setting	Deck Accel. [g]	Seat Accel. [g]	Mass Accel. [g]
SHOXS-6500	-	2.1	1.5	1.2
SHOXS-4800 Passive	-	2.0	1.6	1.3
SHOXS-4800 Semi-Active	1	1.9	1.6	1.4
SHOXS-4800 Semi-Active	2	2.0	1.5	1.2
SHOXS-4800 Semi-Active	3	2.1	1.3	1.2
SHOXS-4800 Semi-Active	4	1.9	1.2	1.0
Shockwave	-	2.2	1.7	1.5

Table 6.8: Peak measured vertical accelerations for the 4 g impact of the repeated increasing impact profile.

Seat	Setting	Deck Accel. [g]	Seat Accel. [g]	Mass Accel. [g]
SHOXS-6500	-	4.2	3.1	2.5
SHOXS-4800 Passive	-	3.8	3.2	2.7
SHOXS-4800 Semi-Active	1	4.0	3.3	2.9
SHOXS-4800 Semi-Active	2	4.1	3.1	2.6
SHOXS-4800 Semi-Active	3	3.9	2.8	2.5
SHOXS-4800 Semi-Active	4	4.2	2.7	2.3
Shockwave	-	4.1	3.4	3.0

Table 6.9: Peak measured vertical accelerations for the 6 g impact of the repeated increasing impact profile.

Seat	Setting	Deck Accel. [g]	Seat Accel. [g]	Mass Accel. [g]
SHOXS-6500	-	6.0	3.9	3.2
SHOXS-4800 Passive	-	5.8	4.3	3.4
SHOXS-4800 Semi-Active	1	6.1	4.4	3.6
SHOXS-4800 Semi-Active	2	5.9	4.2	3.5
SHOXS-4800 Semi-Active	3	6.0	3.9	3.1
SHOXS-4800 Semi-Active	4	6.2	3.7	3.0
Shockwave	-	5.9	4.5	3.8

Table 6.10: Peak measured vertical accelerations for the 8 g impact of the repeated increasing impact profile.

Seat	Setting	Deck Accel. [g]	Seat Accel. [g]	Mass Accel. [g]
SHOXS-6500	-	8.3	5.9	4.3
SHOXS-4800 Passive	-	8.0	6.2	4.9
SHOXS-4800 Semi-Active	1	7.8	6.3	5.1
SHOXS-4800 Semi-Active	2	7.9	5.9	4.8
SHOXS-4800 Semi-Active	3	8.2	5.7	4.5
SHOXS-4800 Semi-Active	4	8.1	5.3	4.2
Shockwave	-	8.2	6.4	5.3

Table 6.11: Natural frequency and damping ratios resulting from the repeated increasing impact profile.

Seat	Setting	Damped Nat. Freq. [Hz]	Damping Ratio
SHOXS-6500	-	1.405	0.406
SHOXS-4800 Passive	-	1.549	0.352
SHOXS-4800 Semi-Active	1	1.197	0.423
SHOXS-4800 Semi-Active	2	1.081	0.479
SHOXS-4800 Semi-Active	3	0.879	0.508
SHOXS-4800 Semi-Active	4	0.803	0.623
Shockwave	-	1.173	0.297

Tables 6.7 through 6.10 show that all seats are able to provide a reduction in acceleration between the deck and the occupant mass, even for the highest impact of 8 g. As seen in the previous tests, Table 6.11 shows that the damping ratio increases with increasing setting in the SHOXS-4800 semi-active seat, and that the Shockwave seat has the lowest damping ratio.

6.5 Vertical Range of Motion and Acceleration

This section presents the results from the Vertical Range of Motion and Vertical Acceleration profiles, as described in Section 5.2.1. As these were profiles for benchmarking the SISTR machine, the main result to present are the data from the relevant sensors showing that the SISTR achieved the target motions. The displacement data from the string potentiometer connected to the seat deck, showing the total range of

1.3 m, is shown in Figure 6.12.

Figure 6.12: Displacement profile showing vertical range of motion.

The data from the accelerometer mounted to the seat deck showing the vertical acceleration is shown in Figure 6.13.

Figure 6.13: Acceleration profile showing maximum vertical acceleration.

6.6 Horizontal Range of Motion and Acceleration

This section presents the results from the horizontal range of motion and acceleration profile in Figure 6.14, as described in Section 5.2.2. As this was a profile for benchmarking the SISTR machine, the main result to present are the data from the string potentiometer connected to the rail supports showing the total horizontal range, as well as from the accelerometer mounted on the deck showing the horizontal acceleration.

Figure 6.14: Profiles showing maximum horizontal range of motion and acceleration.

6.7 Discussion

One of the primary goals of the tests conducted was to show that the SISTR could accurately reproduce commanded motion and meet certain motion benchmarks set out. In this regard, the SISTR was relatively successful. The sample of boat motion was accurately reproduced, as were the five different impact profiles with relatively good accuracy. Additionally, the SISTR successfully demonstrated peak vertical accelerations of 2 g upwards using the cable drive system, 8 g upwards through impacting the dampers, 0.9 g downwards, as well as peak horizontal accelerations of 0.5 g, a vertical range of motion of 1.3 m, and a horizontal range of motion of 2.5 m. One measure of

the accuracy of the SISTR of reproducing the desired motions is comparing the peak accelerations and impact durations. A summary of the results is given in Tables 6.12 and 6.13.

Table 6.12: Overall averaged peak acceleration comparison.

Test	Target Accel. [g]	SISTR Accel. [g]
Boat Motion Impact	3.8	3.7
Impact Type 1	1.5	1.5
Impact Type 2	1.5	1.5
Impact Type 3	1.5	1.5
Impact Type 4	1.5	1.5
Impact Type 5	1.5	1.5
Repeat Constant	6.5	6.4
Repeat Increasing 2g	2.0	2.0
Repeat Increasing 4g	4.0	4.0
Repeat Increasing 6g	6.0	6.0
Repeat Increasing 8g	8.0	8.1

Table 6.13: Overall averaged impact duration comparison.

Test	Target Duration [ms]	SISTR Duration [ms]
Boat Motion Impact	120	125
Impact Type 1	132	124
Impact Type 2	231	206
Impact Type 3	431	395
Impact Type 4	347	350
Impact Type 5	459	425

From this comparison, the SISTR can achieve the peak accelerations accurately but has some trouble achieving the target impact duration with more complex impact types.

Considering the damped natural frequencies and damping ratios obtained from the tests performed, some relatively consistent trends emerge for the seats. Firstly, across all results, the damping ratio obtained from the SHOXS-4800 Semi-Active seat increased with a higher semi-active setting. Referring to Tables 6.2, 6.4, 6.6, and 6.11, the damped natural frequencies and damping ratios were relatively consistent for each seat across all the tests performed.

The overall averages of the damped natural frequencies and damping ratios obtained in Sections 6.1 through 6.4 are presented in Table 6.14.

Table 6.14: Overall averaged damped natural frequency and damping ratio results for all tests.

Seat	Setting	Damped Nat. Freq. [Hz]	Damping Ratio
SHOXS-6500	-	1.357	0.414
SHOXS-4800 Passive	-	1.557	0.374
SHOXS-4800 Semi-Active	1	1.217	0.410
SHOXS-4800 Semi-Active	2	1.081	0.465
SHOXS-4800 Semi-Active	3	0.924	0.525
SHOXS-4800 Semi-Active	4	0.836	0.602
Shockwave	-	1.156	0.311

It can be seen that from these averaged results, the Shockwave seat has the lowest damping ratio and the SHOXS-4800 Semi-Active at setting 4 has the highest damping ratio.

Chapter 7

Conclusions and Recommendations for Future Work

In order to improve analysis and test capability for high-speed craft (HSC) suspension seats, the Slam Impact Seat Test Rig (SISTR) was developed to more accurately reproduce the motions seen by HSCs at sea.

A variety of different testing was conducted using both the Carleton University Drop Tower and the Slam Impact Seat Test Rig (SISTR). Five different seats were tested using the Drop Tower, and the results of the drop tests were used to extract the natural frequencies and damping ratios of the seats. Drop testing was conducted at different heights, and also with different impacting materials to emulate the impact acceleration profile obtained from sea data. The different impacting materials were able to replicate the impact profile such that it more closely represented actual impact profiles from sea trial data, but more accuracy was desired, hence the development of the SISTR.

The SISTR was developed to improve testing capabilities for the seats. This first involved developing the appropriate motion control capabilities for the SISTR, so that it could reproduce motion more representative of what is actually experienced by HSCs. During this process, the overall user interface of the SISTR was also

developed to facilitate testing and data collection.

Once the SISTR motion control strategies were developed, a test procedure was developed, which included profiles for testing with all seats, as well as several profiles for benchmarking the SISTR machine.

Four different seats were tested using the SISTR: the SHOXS-6500, SHOXS-4800 with passive suspension, SHOXS-4800 with semi-active suspension, and Shockwave Marine Suspension seat. The tests showed that the SISTR was able to reproduce the desired motions accurately and consistently. The SISTR was also able to meet its motion benchmark targets.

Overall, the damped natural frequencies and damping ratios obtained from the tests were relatively consistent for each seat, and it was found that the Shockwave Marine Suspension seat had the lowest damping ratio, while the SHOXS-4800 with semi-active suspension on setting 4 had the highest damping ratio.

In the future, work can be done to tune the electrorheological dampers to further improve the capabilities of the SISTR to reproduce impact profiles. Additionally, future work should include improving the interface between the mass and the seat. The testing conducted used a stack of weights strapped down securely on top of the seat cushion. The straps would potentially compress the seat cushion more than an actual occupant, which could change its effectiveness.

References

- [1] M. Riley and T. Coats. *How to Measure Mitigation Characteristics of Passive Shock Isolation Seats*. IBEX, 2014.
- [2] RIBnet. Stock HSC image. <http://www.rib.net/forum/f16/wave-jumping-15923.html>, 2006.
- [3] J. Canova. *Analytic Deck Loading*. Coast Dynamics Group Limited, Saanichton, British Columbia, Canada, 2013.
- [4] Z. Alam. *Implementation of a Drop Test Impact Rig for Dynamic Testing of High Speed Craft Shock Mitigation Seats and Extraction of Modal Parameters*. Carleton University, Ottawa, Ontario, Canada, 2013.
- [5] Y. Fouad. *An Experimental Methodology for Characterizing High Speed Craft Seat Suspension Components*. Carleton University, Ottawa, Ontario, Canada, 2014.
- [6] M. El Tayeby. *Modelling and Synthesis of High Speed Craft Acceleration Profiles*. Carleton University, Ottawa, Ontario, Canada, 2015.
- [7] O. C. Roberts. *Development of the High Speed Craft Slam Impact Seat Test Rig*. Carleton University, Ottawa, Ontario, Canada, 2015.
- [8] A. Wice. *Spatial Dynamic Modelling of High Speed Craft Suspension Seating*. Carleton University, Ottawa, Ontario, Canada, 2015.
- [9] Control Techniques. PowerTools Pro. <https://acim.nidec.com/en-us/drives/control-techniques/products/software/programming/powertools-pro>, 2019.
- [10] National Instruments. LabVIEW. <https://www.ni.com/en-ca/shop/labview/labview-details.html>, 2019.

- [11] Measurement Specialties. *Model 4000A and 4001A Accelerometer*. Measurement Specialties, Aliso Viejo, California, USA, 2010.
- [12] SHOXs. SHOXs-6500. <https://shoxs.com/products/seats/shoxs-6500>, 2018.
- [13] SHOXs. SHOXs-4800. <https://shoxs.com/products/seats/shoxs-4800>, 2018.
- [14] National Instruments. USB-6211 Pinout. <http://www.ni.com/documentation/en/multifunction-io-device/latest/usb-6211/pinout/>, 2017.
- [15] National Instruments. USB-6289 Pinout. <http://www.ni.com/documentation/en/multifunction-io-device/latest/usb-6289/pinout-screwterm/>, 2017.

Appendix A

Complete Drop Testing Results

Table A.1: Damped natural frequency results for the Ullman Dynamics Compact seat.

Drop Height [cm]	Drop 1 [Hz]	Drop 2 [Hz]	Drop 3 [Hz]	Average [Hz]
15	1.186	1.092	1.118	1.132
30	1.149	1.113	1.134	1.132
45	0.876	0.805	0.785	0.822
60	1.105	1.035	1.040	1.060

Table A.2: Damped natural frequency results for the Shockwave Marine Suspension seat.

Drop Height [cm]	Drop 1 [Hz]	Drop 2 [Hz]	Drop 3 [Hz]	Average [Hz]
15	1.195	1.172	1.125	1.164
30	1.205	1.267	1.215	1.229
45	1.089	1.118	1.105	1.104
60	1.135	1.152	1.097	1.128

Table A.3: Damped natural frequency results for the SHOXs-6500 seat.

Drop Height [cm]	Drop 1 [Hz]	Drop 2 [Hz]	Drop 3 [Hz]	Average [Hz]
15	1.595	1.506	1.516	1.539
30	1.315	1.346	1.326	1.329
45	1.552	1.603	1.573	1.576
60	1.371	1.402	1.358	1.377

Table A.4: Damped natural frequency results for the SHOXS-4800 seat with passive suspension.

Drop Height [cm]	Drop 1 [Hz]	Drop 2 [Hz]	Drop 3 [Hz]	Average [Hz]
15	1.721	1.705	1.671	1.699
30	1.543	1.526	1.587	1.552
45	1.541	1.515	1.531	1.529
60	1.306	1.335	1.445	1.362

Table A.5: Damped natural frequency results for the SHOXS-4800 seat with semi-active suspension.

Drop Height [cm]	Setting	Drop 1 [Hz]	Drop 2 [Hz]	Drop 3 [Hz]	Average [Hz]
15	1	1.023	0.985	0.989	0.999
15	2	0.872	0.856	0.957	0.895
15	3	0.834	0.807	0.792	0.811
15	4	0.934	0.905	0.945	0.928
30	1	1.246	1.213	1.216	1.225
30	2	1.239	1.264	1.196	1.233
30	3	1.228	1.201	1.216	1.215
30	4	1.184	1.157	1.079	1.140
45	1	1.329	1.286	1.300	1.305
45	2	1.238	1.195	1.212	1.215
45	3	0.792	0.807	0.861	0.820
45	4	0.856	0.863	0.783	0.834
60	1	1.288	1.251	1.241	1.260
60	2	1.220	1.192	1.128	1.180
60	3	1.137	1.183	1.205	1.175
60	4	1.374	1.309	1.283	1.322

Table A.6: Damping ratio results for the Ullman Dynamics Compact seat.

Drop Height [cm]	Drop 1	Drop 2	Drop 3	Average
15	0.485	0.446	0.359	0.430
30	0.452	0.497	0.476	0.475
45	0.874	0.798	0.803	0.825
60	0.755	0.792	0.772	0.773

Table A.7: Damping ratio results for the Shockwave Marine Suspension seat.

Drop Height [cm]	Drop 1	Drop 2	Drop 3	Average
15	0.267	0.228	0.231	0.242
30	0.365	0.371	0.305	0.347
45	0.423	0.457	0.455	0.445
60	0.406	0.437	0.429	0.424

Table A.8: Damping ratio results for the SHOXS-6500 seat.

Drop Height [cm]	Drop 1	Drop 2	Drop 3	Average
15	0.442	0.413	0.420	0.425
30	0.379	0.347	0.369	0.365
45	0.392	0.384	0.349	0.375
60	0.399	0.418	0.458	0.425

Table A.9: Damping ratio results for the SHOXS-4800 seat with passive suspension.

Drop Height [cm]	Drop 1	Drop 2	Drop 3	Average
15	0.251	0.298	0.297	0.282
30	0.445	0.409	0.430	0.428
45	0.361	0.387	0.401	0.383
60	0.229	0.248	0.294	0.257

Table A.10: Damping ratio results for the SHOXS-4800 seat with semi-active suspension.

Drop Height [cm]	Setting	Drop 1	Drop 2	Drop 3	Average
15	1	0.372	0.383	0.322	0.359
15	2	0.332	0.371	0.320	0.341
15	3	0.498	0.469	0.488	0.485
15	4	0.407	0.377	0.386	0.390
30	1	0.523	0.514	0.484	0.507
30	2	0.435	0.411	0.420	0.422
30	3	0.438	0.443	0.388	0.423
30	4	0.464	0.437	0.425	0.442
45	1	0.496	0.454	0.481	0.477
45	2	0.511	0.478	0.508	0.499
45	3	0.831	0.799	0.824	0.818
45	4	0.728	0.702	0.712	0.714
60	1	0.510	0.480	0.486	0.492
60	2	0.571	0.549	0.554	0.558
60	3	0.488	0.502	0.453	0.481
60	4	0.602	0.593	0.566	0.587

Table A.11: Peak measured vertical accelerations for the Ullman Dynamics Compact seat.

Drop Height [cm]	Location	Drop 1 [g]	Drop 2 [g]	Drop 3 [g]	Average [g]
15	Carriage	10.1	9.2	10.1	9.8
15	Seat	3.7	3.3	3.2	3.4
15	Mass	3.0	2.9	2.5	2.8
30	Carriage	13.7	13.2	13.3	13.4
30	Seat	8.0	7.6	7.5	7.7
30	Mass	8.6	8.5	7.8	8.3
45	Carriage	17.2	16.9	16.0	16.7
45	Seat	13.2	13.7	13.9	13.6
45	Mass	14.3	13.9	13.8	14.0
60	Carriage	20.2	19.9	19.0	19.7
60	Seat	16.5	15.8	16.0	16.1
60	Mass	19.9	20.3	21.0	20.4

Table A.12: Peak measured vertical accelerations for the Shockwave Marine Suspension seat.

Drop Height [cm]	Location	Drop 1 [g]	Drop 2 [g]	Drop 3 [g]	Average [g]
15	Carriage	9.5	9.2	9.2	9.3
15	Seat	6.1	6.1	5.5	5.9
15	Mass	4.0	4.4	3.9	4.1
30	Carriage	13.9	13.8	12.8	13.5
30	Seat	6.4	6.2	6.0	6.2
30	Mass	6.7	6.3	6.8	6.6
45	Carriage	17.0	16.4	16.4	16.6
45	Seat	8.5	8.1	8.6	8.4
45	Mass	12.5	12.0	12.1	12.2
60	Carriage	19.5	19.4	19.0	19.3
60	Seat	9.5	9.0	9.4	9.3
60	Mass	14.8	14.1	14.6	14.5

Table A.13: Peak measured vertical accelerations for the SHOXS-6500 seat.

Drop Height [cm]	Location	Drop 1 [g]	Drop 2 [g]	Drop 3 [g]	Average [g]
15	Carriage	9.5	9.6	9.1	9.4
15	Seat	8.5	9.0	8.9	8.8
15	Mass	5.2	5.3	4.8	5.1
30	Carriage	13.7	13.6	13.2	13.5
30	Seat	10.2	10.5	10.2	10.3
30	Mass	6.5	5.9	5.9	6.1
45	Carriage	17.3	16.8	17.2	17.1
45	Seat	11.9	11.7	11.2	11.6
45	Mass	7.7	7.5	8.2	7.8
60	Carriage	20.3	19.8	19.6	19.9
60	Seat	16.4	15.9	16.3	16.2
60	Mass	8.8	8.9	8.4	8.7

Table A.14: Peak measured vertical accelerations for the SHOXS-4800 seat with passive suspension.

Drop Height [cm]	Location	Drop 1 [g]	Drop 2 [g]	Drop 3 [g]	Average [g]
15	Carriage	9.1	9.2	8.7	9.0
15	Seat	6.0	6.1	6.5	6.2
15	Mass	4.4	4.1	4.1	4.2
30	Carriage	13.8	13.4	13.9	13.7
30	Seat	9.7	9.2	9.9	9.6
30	Mass	7.5	8.0	7.3	7.6
45	Carriage	16.9	17.0	16.2	16.7
45	Seat	12.1	12.4	13.0	12.5
45	Mass	10.1	9.5	10.1	9.9
60	Carriage	19.8	19.7	19.3	19.6
60	Seat	14.4	13.9	14.3	14.2
60	Mass	12.3	12.2	12.7	12.4

Table A.15: Peak measured vertical accelerations for the SHOXS-4800 seat with semi-active suspension at setting 1.

Drop Height [cm]	Location	Drop 1 [g]	Drop 2 [g]	Drop 3 [g]	Average [g]
15	Carriage	9.5	9.0	9.1	9.2
15	Seat	5.4	5.2	5.9	5.5
15	Mass	6.6	6.1	5.9	6.2
30	Carriage	13.3	12.8	13.2	13.1
30	Seat	10.3	9.7	10.3	10.1
30	Mass	9.5	9.4	9.0	9.3
45	Carriage	16.5	15.8	16.0	16.1
45	Seat	11.9	11.5	12.0	11.8
45	Mass	11.4	11.0	10.9	11.1
60	Carriage	19.9	19.4	19.2	19.5
60	Seat	14.4	14.5	14.0	14.3
60	Mass	16.2	16.0	15.5	15.9

Table A.16: Peak measured vertical accelerations for the SHOXS-4800 seat with semi-active suspension at setting 2.

Drop Height [cm]	Location	Drop 1 [g]	Drop 2 [g]	Drop 3 [g]	Average [g]
15	Carriage	9.5	9.0	9.1	9.2
15	Seat	6.0	5.9	6.4	6.1
15	Mass	6.5	6.6	6.1	6.4
30	Carriage	12.5	12.9	13.6	13.0
30	Seat	11.4	11.1	11.1	11.2
30	Mass	9.7	10.1	10.2	10.0
45	Carriage	16.4	16.0	15.9	16.1
45	Seat	12.9	12.8	12.4	12.7
45	Mass	11.6	11.5	12.0	11.7
60	Carriage	20.1	19.7	19.6	19.8
60	Seat	15.2	15.6	15.1	15.3
60	Mass	16.3	15.8	16.2	16.1

Table A.17: Peak measured vertical accelerations for the SHOXS-4800 seat with semi-active suspension at setting 3.

Drop Height [cm]	Location	Drop 1 [g]	Drop 2 [g]	Drop 3 [g]	Average [g]
15	Carriage	9.5	9.1	9.0	9.2
15	Seat	7.3	7.0	7.0	7.1
15	Mass	7.7	7.8	7.3	7.6
30	Carriage	12.9	13.4	12.7	13.0
30	Seat	12.4	12.9	12.8	12.7
30	Mass	11.1	11.6	11.8	11.5
45	Carriage	15.9	16.0	15.2	15.7
45	Seat	14.2	14.0	13.8	14.0
45	Mass	13.6	13.5	14.6	13.9
60	Carriage	18.9	18.5	18.4	18.6
60	Seat	17.8	17.3	18.0	17.7
60	Mass	20.3	20.6	20.6	20.5

Table A.18: Peak measured vertical accelerations for the SHOXS-4800 seat with semi-active suspension at setting 4.

Drop Height [cm]	Location	Drop 1 [g]	Drop 2 [g]	Drop 3 [g]	Average [g]
15	Carriage	9.4	9.3	8.9	9.2
15	Seat	8.7	9.5	8.8	9.0
15	Mass	9.1	9.6	8.9	9.2
30	Carriage	13.1	12.5	13.1	12.9
30	Seat	13.5	13.2	14.1	13.6
30	Mass	13.9	13.6	13.6	13.7
45	Carriage	16.2	15.9	15.3	15.8
45	Seat	15.4	15.8	15.3	15.5
45	Mass	16.0	16.2	16.7	16.3
60	Carriage	19.5	19.0	19.4	19.3
60	Seat	20.4	20.1	19.5	20.0
60	Mass	21.7	21.2	21.0	21.3

Figure A.1: Absolute acceleration profiles measured during 6 inch drop of the Shock-wave seat [4].

Appendix B

Motor and Drive Configuration Parameters

Table B.1: Motor and drive configuration parameters.

Parameter	Value
Drive Type	SP 3202
Drive Mode	Servo
Motor Type	190E2F201
Encoder Type	Quadrature Incremental w Commutation Outputs
Encoder Supply Voltage	5 Volts
Lines Per Rev	4096
Distance Scaling	0.6384 m per 7 revs