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TWO POINT CORRELATIONS OF TEMPERATURE IN A HOT SUBSONIC JET

by

Hao Q. Duong

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

**OTTAWA CARLETON INSTITUTE OF MECHANICAL
AND AERONAUTICAL ENGINEERING**

DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING
CARLETON UNIVERSITY
OTTAWA, CANADA

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The undersigned hereby recommend to the Faculty of Graduate Studies and Research acceptance of the thesis: Two point Correlations of Temperature in a Hot Subsonic Jet submitted by Hao. Q. Duong in partial fulfillment of the requirements for the degree of Master of Engineering.

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ABSTACT

A low speed hot flow apparatus was built to provide a diagnostic facility for heated jets. The features of the facility are described and the results of preliminary testing are presented. The measurements reported here are mainly two-point space-time correlations of the unsteady temperature field. These are analyzed to provide estimates of length and time scales as well as eddy convection speeds.

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CHAPT.1 INTRODUCTION

The research reported herein was carried out at Carleton University. The aim was to design and construct a 3/4 inch hot jet flow facility and to perform preliminary tests, thereby providing information on the mean temperature profiles as well as the length and time scales of the unsteady temperature field.

The study of heated jets is of importance to a variety of engineering fields: convection of hot exhaust gases from smoke stacks, heating and drying applications, and gas-turbines are but a few examples. Ruden[1] and Corrsin[2] have examined hot jets with axial symmetry. Ruden measured velocity and temperature distributions out to an axial distance of about 15 diameters in a heated jet; while Corrsin extended these measurements to axial distances of 40 diameters from nozzle exit. Corrsin later went on to work on the effect of mean densities differences upon the rate of spread of the jet, which can be examined through the average velocity and density fields and the relative rates of transfer of heat and momentum in a heated jet, which involves a

study of fluctuation in velocity and temperature as well as average fields. Measurements performed at Carleton suggest that the hot flow facility exhibits the key features of hot subsonic jets: the potential cone, in which the velocity is equal to that at the nozzle exit, has its apex at about 4 nozzle diameters from the exit; the final non-dimensional velocity and temperature profiles are well established at an axial distance of 10 nozzle diameters [3,4,5].

This thesis work is concerned with the structure and behavior of the temperature turbulent eddies within the heated, subsonic jet shear layer. It provides measurements of the length and time scales of the unsteady temperature field. Interest in these features arose from a need to describe certain source terms which govern the generation of noise from hot turbulent jets [6]. There is little detailed information available in the literature [7,8], and this work is a first step in measuring source terms relevant to the sound of heated jets.

CHAPTER 2. EXPERIMENTAL FACILITY

I OVERVIEW OF HOT JET FACILITY

The hot jet unit is shown schematically in Fig 2.1. A mass flow rate of about 0.035 kg/s is supplied by a converted industrial vacuum cleaner. Heat is added to the air flow by means of 3 "heat gun type" electric heaters. The heated air then passes through a section of honeycomb. The flow exits through the 1.91 cm (3/4 inch) diameter convergent nozzle into stationary air at room temperature and atmospheric pressure.

During measurements, nozzle exit velocity ranged from 105 to 112 m/s and the exit air reached a temperature of approximately 165 to 175 degrees Celsius. The approximate nozzle Mach number was 0.3 and the nozzle Reynolds number was of the order of 60,000.

The outside of the hot jet unit, including the aluminum nozzle was insulated with fibreglass blankets. The entire unit was mounted to a heavy metal frame and held vertically by means of four hose clamps. Rubber damping pads were placed under the

metal frame in order to isolate the unit from vibration.

I.1 BLOWER

A modified Dustbane industrial vacuum cleaner (120 VAC, 6-25 Amp.) is used to deliver air flow at rates up to .035 kg/sec to the jet unit. The unit features a large cylindrical collection chamber with the blower installed in the lid. The unit has a reverse airflow capability, permitting the user to either suck (conventional vacuum) or blow.

Several holes were punched through the cylindrical wall near the base of the blower drum and a bell mouth was added to the (blower) intake. These modifications should reduce pressure losses. Acoustic foam placed inside the blower drum provides some noise control. The voltage applied to the electric motor was controlled by a variable auto-transformer (Variac), thus the nozzle velocity could be set to different values. During the experiment, the blower unit was operated close to its maximum rated power.

I.2 HEATING SECTION

A cross sectional view of the 3 electric, heat gun type

heaters is shown in Fig 2.2. Two long, thin threaded rods hold each heater parallel to the flow. The heaters are carefully positioned in effort to obtain the best possible uniform temperature distribution across the pipe. A perforated metal shield is placed between the pipe wall and heaters to minimize the heat radiation to the pipe surface.

The heaters are each rated at 14 Amp. and are supplied with 120 VAC controlled by Solid State Relays (SSR). For this purpose, an electronic circuit was built (Fig. 2.3). Two LM 555 timers, operating in astable and monostable modes, generate an adjustable duty cycle pulse to trigger 3 solid state relays which act as heater ON/OFF switches. These solid state relays are retriggable and each can control currents up to 25 Amp. The heater ON/OFF time depends on the duty cycle of timer system. This can be set at different values by means of a variable resistor (see APPENDIX I).

The metal support frame serves as a heat sink for the Solid State Relays. Since each heater operates at 120 VA and draws up to 14 Amp current, a total electric power of up to 5,000 watts can be supplied to the heating section.

Holes were drilled around the pipe circumference to fit three 12 gauge solid wires, which can carry up to 25 Amp current, connecting the heaters to the the Solid State Relays. Plexiglass covers all circuit connections and the galvanized pipe containing the heaters is grounded to guard against electrical shock. The hot jet unit is sealed with high temperature resistant Silicon compound.

The air flows over the heaters, at an estimated speed of about 14 m/s. This corresponds to the 10 - 12 m/s found in heat guns. Thus the heater configuration should be operating close to its design point.

Care was taken to avoid regions of hot, stagnant air which might be trapped due to blockage. In an earlier design this problem led to high temperatures resulting in damage to one of the heating coils. In order to control the inevitable high turbulence levels generated by the presence of the heating coils and their supports, a section of honeycomb was installed to serve as a 'flow-straightener'.

1.3 NOZZLE SECTION

The heater air is exhausted to atmosphere via a circular aluminum nozzle, used in previous jet flow studies. The convergent nozzle has a contraction ratio of 7:1 and provides a symmetrical, uniform velocity and temperature distribution at nozzle exit.

A T type thermocouple was inserted on the centre line of the flow, just upstream of the nozzle and a static pressure tap was mounted in the pipe wall in order to obtain estimates of mean flow temperature and static pressure.

II INSTRUMENTATION

One of the objectives of the research programme was the measurement of the length and time scales of the unsteady temperature field of the hot jet flow. To this end two point space-time correlations of the temperature field must be measured. The instrumentation used to perform these and related measurements is described below. The key components of the system are shown in figure 2.4: two hot wire anemometers, signal conditioners, and a signal correlator.

II.1 HOT WIRE ANEMOMETRY

Two TSI 1050 series anemometer units were configured to measure the temperature fluctuations of the hot jet flow. Each channel featured a power supply, a full bridge and amplifier circuit, a signal conditioner and a DC panel meter. The anemometers were operated in the constant current mode. The drive current was kept sufficiently small to provide negligible 'overheat' to the hot wire probe. Thus the bridge circuit detected only changes in wire temperature which tracked the local temperature of the air surrounding the probe. A set of DISA hot wires and probe supports was used in conjunction with the TSI anemometry.

The constant current method is used to measure the temperature fluctuations of the hot subsonic free jet. Fluctuating temperatures are indicated by using the hot wire as a resistant thermometer. The relation between temperature change and voltage is as follows:

$$V - V_o = R_o * G * i * (T - T_o)$$

where	T	wire temperature
	T _o	reference temperature (ambient)
	R _o	hot wire resistance at ambient temperature
	G	amplifier gain (1000)
	i	current through hot wire (1.67 mA)
		temperature coefficient of resistance
		(.0036 / Celsius for tungsten)

The probes were standard DISA P11 probes. The sensor is constructed from a thin tungsten wire held in place by a pair of pin-like supports. The relevant probe dimensions are: sensing wire diameter of 5 μ m, sensor length of 1.2 mm. The frequency response of the sensing system is set by the response of the hot wire probe. The nominal bandwidth is estimated to be of the order of 700 Hz (see Appendix II).

The probes were supported by a traversing gear which controlled the position of the reference probe as well as the separation between the two probes. The former was accomplished by means of a simple slider arrangement on a vertical support beam which was clamped to the steel base. The probe separation was adjustable in the axial (streamwise) direction. The position was controlled by a DISA 52B01 sweep drive unit and a DISA 52C01 stepper motor. The built-in counter was calibrated to permit measurement of the probe separation.

Proximity of the high power electric heaters induces a 60 Hz (and higher harmonics) noise signal. Some shielding was provided by a 2m long copper pipe which contained the cables connecting the probes to the anemometer system.

For the most part temperature fluctuations rather than absolute temperature were measured. The large DC (mean temperature) component is removed from the bridge output by the built-in signal conditioner. The adjustable bandwidth was set to span 2 Hz to 2,000 Hz.

CHAPTER 3. SIGNAL PROCESSING

I ANEMOMETER SIGNALS

The sensing element of a typical anemometer is a thin, conducting wire, carrying a controlled current. Under normal operation the current is sufficiently large to heat the wire to a temperature which exceeds that of its surroundings. The heat loss can be related to the fluid flow over the wire and the fluid temperature via King's law or extensions thereof. Two distinct modes of hot wire operation are widely used: constant temperature and constant current operation. In both, it is the potential difference V which is measured to find the fluctuations in fluid properties. For simplicity, this potential difference can be expressed as follows:

$$V + v = S_u(U + u) + S_t(T + t) \quad (3.1)$$

S_u and S_t are hot wire velocity and temperature sensitivities, and depend on sensor characteristics, sensor operating temperature and ambient conditions. V , U , T are the steady components and v, u, t the unsteady components of the potential difference, mean flow velocity and temperature. The DC portions possess no dynamic information; they were

suppressed and the components of interest are: as:

$$v = S_u u + S_t t \quad (3.2)$$

I.1 CONSTANT CURRENT METHOD FOR TEMPERATURE MEASUREMENT

For temperature measurements, the constant current method is used. The circuitry maintains a low, constant current i . The wire temperature T_w and resistance R_w fluctuate in response to changes in velocity and temperature. Relation between voltage fluctuation and wire resistance fluctuation is obtained from:

$$V + v = i(R_w + r_w)$$

$$\text{or} \quad v = i r_w \quad (3.3)$$

from equation 3.2

$$v = i r_w = S_u u + S_t t$$

At low overheat ratio, and very low constant current, the hot wire mean temperature is close to the mean fluid temperature, making the hot wire much less sensitive to velocity fluctuations than temperature fluctuations. This effectively eliminates the velocity signal and the temperature fluctuation signal is seen to be:

$$v = i r_w = S_t t \quad (3.4)$$

For subsonic flow with a temperature less than 300 celsius degrees, the wire temperature sensitivity is constant and the hot wire works as a pure resistance thermometer with a very small heat capacity (see APPENDIX II).

I.2 ANEMOMETER OUTPUT SIGNALS

Figure 2.5 shows the basic electrical connection of the hot wire anemometer when operating in temperature mode. Because of the low current involved, a high gain operational amplifier is used to amplify the low output voltage to a level that is suitable with most indicating and recording equipment. The amplified signal is conditioned to improve the signal to noise ratio and to facilitate further signal processing. The signal conditioner of the anemometer system serves as a low pass filter to eliminate high frequency noise above 2 KHz.

Two hot wire anemometer systems are used in the experiment to obtain two instantaneous signals corresponding to temperature fluctuations at different positions in hot jet shear layer (see figure 3.1). The temperature at each probe position is defined as:

At position 1 $S_1 = S_1 + s_1$

At position 2 $S_2 = S_2 + s_2$

Or in terms of output voltages

$$V_1 = K_1(S_1 + s_1)$$

$$V_2 = K_2(S_2 + s_2)$$

K_1 and K_2 are different fixed voltage gains of the systems, including factors such as: hot wire sensitivity, internal amplifier, magnitude of the small constant current through the wire. In general, K_1 and K_2 differ from each other. Since there is no need for the mean temperature, the Signal Conditioner is used to suppress the DC voltage signal. At the same time the AC voltage signal is amplified. Thus, at two anemometer system outputs, two amplified unsteady AC signals, corresponding to temperature fluctuations s_1 , s_2 at different positions in the jet shear layer (see Figure 3.1) are available. Note that temperature fluctuation is now denoted as s in lieu of t which could be mistaken for time.

$$v_1 = K_1 s_1 \quad (3.5)$$

$$v_2 = K_2 s_2$$

1.3 SIGNAL NORMALIZER AND SIGNAL CORRELATOR

The signal correlator computes the cross-correlation of s_1 and s_2 according to the following formula

$$\overline{s_1 s_2}(\tau) = \lim_{T \rightarrow \infty} \frac{1}{2T} \int_{-T}^T s_1(t) s_2(t-\tau) dt \quad (3.6)$$

The cross-correlation coefficient of two temperature fluctuations is defined as

$$R_{s_1 s_2}(\tau) = \frac{\overline{s_1 s_2}(\tau)}{s_1' s_2'}$$

where $s_1' = \sqrt{\overline{s_1^2}}$ and $s_2' = \sqrt{\overline{s_2^2}}$. In other words, s_1' and s_2' are the R.M.S values of s_1 and s_2 .

Now the correlator measures a cross correlation of two AC voltages (equations 3.2). By connecting a Signal Normalizer to the Anemometer outputs, the temperature fluctuation signals are then normalized :

$$v_1 = \frac{K_1 s_1}{K_1 s_1'} = \frac{s_1}{s_1'}$$

$$v_2 = \frac{K_2 s_2}{K_2 s_2'} = \frac{s_2}{s_2'}$$

Again s_1' , s_2' are the RMS values of s_1 and s_2 . The two AC signals v_1 and v_2 thus automatically have RMS values of 1.

A SAI-43 Signal correlator performs the cross-correlation of two normalized AC signal which yields the cross correlation of two signals with respect to time:

$$R_{s_1s_2}(\tau) = \frac{1}{2T} \int_{-T}^T s_1(t) s_2(t-\tau) dt \quad (3.7)$$

The signal correlation analysis provides a quantitative measure of the degree of similarity between the two temperature signals or waveforms as they are shifted relative to one another in time. If the signal is being compared with itself, the resulting waveform is an Auto-Correlation. Any two different waveforms may be compared via Cross-Correlation. The SAI-43A Signal Correlator provides auto and cross correlation functions with incremental lag or time delay values ranging from .2 micro-seconds to 1 second resulting in a total time delays from 80 micro-seconds to 400 seconds. An auto or cross correlation function is determined simultaneously at 400 incremental lag points so that a complete correlation function is available for display. Precomputational delay permits the 400 point correlation function to be shifted with respect to the zero lag point ($\tau = 0$). The auto-correlation R reaches its maximum value at zero time delay: $R(0) \rightarrow 1$ as $\tau \rightarrow 0$.

Because the output of each signal normalizer channel has an RMS value of 1V, the maximum value of the cross correlation is

1V. This value corresponds to the auto-correlation at zero delay which provides a convenient amplitude reference when the computed correlations are recorded on an XY plotter.

II MEASUREMENT PROCEDURES

II.1 TEMPERATURE PROFILES

The mean temperature of the hot jet is measured directly by using a single normal wire as a pure resistance thermometer. The data is normalized by the difference between the jet exit and the ambient temperature. The mean temperature data was compared to that found in the literature and served as a check that the apparatus was functioning properly.

II.2 CORRELATION OF TEMPERATURE FLUCTUATION

At each "fixed" probe position relative to nozzle exit, a systematic series of temperature cross-correlations are performed for 7 to 8 probe separations, as well as the auto correlation of the fixed probe signal which served as a reference (Fig. 3.1). For each probe separation, the cross-correlation is recorded with respect to time. The correlation was viewed on the oscilloscope

from which, with help of a correlator counter, the time delay of the cross correlation is recorded. The cross correlation is then plotted by a H.P 7044A X-Y recorder which shows the 400 point display of the correlation with a selected time increment of 10 micro-seconds between points.

II.3 JET OPERATING CONDITIONS

The jet velocity is estimated from data provided by a static pressure gauge, mounted to the inside pipe wall, just in front of nozzle entry. The static gauge is calibrated with a pitot tube, travelling across the hot jet flow at 1 to 2 diameter distance from the nozzle exit. The jet temperature is monitored by means of a T type thermocouple, and kept at between 165 to 170 celsius degrees during the experiment.

II.4 FREQUENCY ANALYSIS OF TEMPERATURE

Frequency spectra of the jet temperature turbulence were measured with a B&K 2515 spectrum Analyzer. A single hot wire was placed in the jet. The tests served as a diagnostic for the signal bandwidth.

CHAPTER 4. RESULTS

IV.1 TEMPERATURE DISTRIBUTIONS

Figure 4.1 illustrates the mean temperature field of the jet. The non-dimensional temperature is the ratio $(T - T_o)/(T_e - T_o)$, here T_o denotes the ambient temperature and T_e the jet exit temperature. The profiles are remarkably similar to those of the velocities of a subsonic jet: the field diffuses laterally while the centre-line temperature decays in the downstream direction. The rate of diffusion is apparent in figure 4.2. It was found that self-similar profiles could be constructed when T_e was replaced with the local centre-line temperature and the radial dimension was normalized by the radius at which the normalized temperature has dropped to a value of 0.5 of that at the centre-line. Agreement is quite good (Fig. 4.3), especially for values of x/D greater than 7. This indicates that the flow is becoming self-similar.

The distribution of the normalized RMS unsteady temperature is shown in figure 4.4. Here the pattern evolves from a double-peaked distribution to a smooth, single peaked one.

IV.2 POWER SPECTRA OF TEMPERATURE

The power spectra were also measured. This served as a diagnostic tool for a check on signal bandwidth and spurious pure tone noise (60 Hz hum). Figure 4.5 shows that the spectrum is well behaved, exhibiting a low frequency peak and a more typical 'flat' portion extending to about 400 Hz, followed by a roll-off. Thus, the signal conditioner has no significant influence on the measured temperature signal.

The low frequency peak is not apparent when the heaters are off and the fluctuating temperature in a cold jet are measured (Fig. 4.6). The spectrum levels are comparable since both signals have passed through the signal normalizer which has a 1 V RMS output. The spectra are identical for hot and cold flows when the probes are outside the flow (Fig. 4.7).

These diagnostic checks suggest that the signal bandwidth of 2 Hz to 2,000 Hz provides an excellent 'window'. Furthermore, the signals behave in manner consistent with features of turbulent flow.

IV.3 CROSS-CORRELATIONS

Two point space-time correlations were measured at $x/D = 4$ and 8 both on the centre-line and along the extension of the nozzle lip. Fig. 4.8 and 4.9 show the cross-correlations at $x/D = 4$, just at the end of the so-called potential core. The expected shift towards the positive time delay is apparent as well as a dual feature: a wide, gentle rise with a 'narrow' peak. The former is associated with the low frequency peak observed in the spectra, the latter is due to the 'wide-band' portion of the spectrum. The cross-correlations all have similar shapes.

At eight diameters downstream the low frequency component has virtually vanished (Fig. 4.10 and 4.11). The time scale is larger as evidenced by the broader peak.

This data can be examined in various ways. For one, it is possible to construct lines of constant correlation coefficients. As is shown in Appendix III these contours can be used to estimate the eddy convection velocities. Figures 4.12 to 4.15 illustrate the contours. They exhibit the shape characteristic of convected turbulence. The sharp corners are an artifact of the computer program used to generate the curves.

The convection velocities deduced from this data are shown in figure 4.16. The convection velocity measured along the extended lip -line is marginally less than that on the centre-line. The shape is similar to that of a typical jet centre-line velocity, albeit smaller by a numerical value of about 0.65.

It remains to deduce the time and length scales of the eddies. To this end the envelope of the cross-correlations as well as the function $R_{xx}(\xi, 0)$ are examined. The definition of the length and time scales are somewhat arbitrary. Here the data is fitted with a decaying exponential (Fig. 4.17 to 4.24). The argument of the best fit curve is taken to be proportional to the reciprocal of the appropriate scale.

One would expect that both the length and time scales increase as the observer moves downstream: the dimensions of the flow become larger and the flow velocities decrease. The table below shows a different trend:

Position		(Length Scale)/D	Time Scale (msec)
x/D	r/D		
4	0	1.85	0.89
4	0.5	1.49	1.04
8	0	1.28	1.13
8	0.5	1.00	1.23

The time scale does indeed increase; the length scale decreases. One possible explanation is the shift from large-scale motion near the jet nozzle to the more characteristic small-scale turbulent mixing pattern which exists downstream.

The large scale motion is characteristic of the columnar jet instability of low Reynolds number jets [9]. Such flows feature large 'eddies' in the shape of vortex rings. These vortices grow rapidly in the initial shear layer, promoting vigorous mixing. The patterns decay violently 3 to 5 jet diameters downstream. The low frequency peak of the power spectra as well as the shape of the autocorrelation at $x/D = 4$ are consistent with the large scale motion. Optical diagnostics such as shadowgraphs or Schlieren images would have proved helpful, but were not available.

CHAPTER FIVE: CONCLUDING REMARKS

A low speed heated jet facility suitable for temperature and velocity surveys has been designed and constructed. Both the temperature and the velocity of the jet can be adjusted independently. The measured temperature profiles were found to be similar to those observed by previous researchers.

Two point space-time correlations provided were measured and provide information on the length and time scale of the unsteady temperature field. There is evidence that the jet exhibits a low frequency instability which establishes relatively large eddies near the end of the potential core.

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FIGURE 2.2: HEATER CROSS-SECTIONAL VIEW

FIGURE 2.3 HEATING CONTROL CIRCUIT

FIGURE 2. 4 : CONNECTION FOR TEMPERATURE MEASUREMENT

MEASUREMENT OF TWO-POINT SPACE-TIME CORRELATIONS

FIGURE 2.5 : HOT WIRE ELECTRICAL CONNECTION FOR TEMPERATURE MEASUREMENT

FIGURE 3.1: SUBSONIC JET

FIGURE 3.2: INSTRUMENTAL SET UP FOR REFERENCE CROSS CORRELATION

FIGURE 4.1: TEMPERATURE PROFILE AWAY FROM NOZZLE

FIGURE 4.2: MEAN TEMPERATURE DISTRIBUTION

FIGURE 4.3: TEMPERATURE PROFILE SIMILARITIES

FIGURE 4.4: TEMPERATURE TURBULENCE INTENSITIES

FIGURES 4.5A&B: TEMP. FREQ. SPECTRA ANALYSIS (hot jet)

A. Frequency Range: 0 - 2 KHz , Full scale: 90dB
 Bredt & Kijar

QP 0110

B. Frequency Range: 0 - 500 Hz, Full scale: 90dB
 Bredt & Kijar

QP 0110

FIGURES 4.6ASB: TEMP. FREQ. SPECTRA ANALYSIS

A. Frequency Range: 0 - 2 KHz. F.S: 90dB, Cold jet (heaters off)

Bred & Kjer

QP 0110

B. Frequency Range: 0 - 2 KHz. F.S: 90dB, Hot jet

Bred & Kjer

QP 0110

FIGURES 4.7A&B: TEMP. FREQ. SPECTRA ANALYSIS

A. Freq. Range: 0-500 Hz. F.S: 90dB. Hot wire out of cold jet flow

Briel & Kjaer

QP 0110

B. Freq. Range: 0-500 Hz. F.S: 90dB. Hot wire out of hot jet flow

Briel & Kjaer

QP 0110

FIGURES 4.8&4.9: NORMALIZED CORRELATION CURVES AT $X/D=4$
FIG. 4.8: $R/D = 0.0$

FIG. 4.9: $R/D = .5$

FIGURES 4.10&4.11: NORMALIZED CORRELATION CURVES AT $X/D=8$
FIG. 4.10: $R/D = 0.0$

FIG. 4.11: $R/D = .5$

CONTour KEY	
1	0.1
2	0.2
3	0.3
4	0.4
5	0.5
6	0.6
7	0.7
8	0.8
9	0.9
10	1.0

CONTINUOUS KEY	
1	0.1
2	0.2
3	0.3
4	0.4
5	0.5
6	0.6
7	0.7
8	0.8
9	0.9
10	1.0

CONTOUR KEY	
1	0.1
2	0.2
3	0.3
4	0.4
5	0.5
6	0.6
7	0.7
8	0.8
9	0.9
10	1.0

CONTour KEY	
1	0.1
2	0.2
3	0.3
4	0.4
5	0.5
6	0.6
7	0.7
8	0.8
9	0.9
10	1.0

FIGURE 4.16: TEMPERATURE EDDY CONVECTION VELOCITY

FIGURE 4.17: TIME SCALE CHARACTERISTICS AT $X/D=4$, $R/D=.0$

FIGURE 4.18: TIME SCALE CHARACTERISTICS AT $X/D=4$, $R/D=.5$

FIGURE 4.19: TIME SCALE CHARACTERISTICS AT $X/D=8$, $R/D=0$

FIGURE 4.20: TIME SCALE CHARACTERISTICS AT $X/D=8$, $R/D=.5$

FIGURE 4.21: LENGTH SCALE CHARACTERISTICS AT $X/D=4$, $R/D=0$

FIGURE 4.22: LENGTH SCALE CHARACTERISTICS AT $X/D=4$, $R/D=.5$

FIGURE 4.23: LENGTH SCALE CHARACTERISTICS AT $X/D=8$, $R/D=0$

FIGURE 4.24: LENGTH SCALE CHARACTERISTICS AT $X/D=8$, $R/D=.5$

APPENDIX 1: LM 555 TIMER

The LM 555 is an electronic device for generating accurate timing pulses. It can be configured to perform a variety of different functions. To construct an oscillator, two timers are connected in series: one in the astable mode the other in the monostable mode. The advantage of this two element system over a single timer in the astable mode is that the both the frequency of oscillation and the duty cycle accurately controlled and adjusted.

1 ASTABLE OPERATION

If the circuit is connected as shown below, it will trigger itself and free run as a multivibrator.

FIGURE 1 ASTABLE

The capacitor charges and discharges between $1/3 V_{cc}$ and $2/3 V_{cc}$. The charging time (output high) is given by :

$$T_1 = 0.693(R_a + R_b)C$$

The discharge time (output low) is $T_2 = 0.693(R_b)C$; thus, the total period is: $T = T_1 + T_2 = 0.693(R_a + 2R_b)C$. The duty cycle is: $D = R_b / (R_a + 2R_b)$

2 MONOSTABLE OPERATION

In this mode of operation, the timer function as a one-shot. The external capacitor is initially held discharged. Upon application of a negative trigger pulse (from astable mode timer in our case) of less than $1/3 V_{cc}$ to pin 2 (Figure 2 shown below), the flip-flop is set and drives the output high. The voltage across the capacitor then increases exponentially for a period of $t = 1.1 R_a C$, at the end of which time the voltage equals $2/3 V_{cc}$. The comparator then resets the flip-flop which in turns discharges the capacitor and drives the output to its low state. During the timing cycle when the output is high, the further application of a trigger pulse will not effect the

circuit. The output will remain in the low state until a trigger pulse (from astable mode timer) is again applied.

FIGURE 2 MONOSTABLE

SEE FIGURE 2.3 HEATING CONTROL CIRCUIT

APPENDIX II: HOT WIRE FREQUENCY RESPONSE

Fluctuating temperatures may be measured by using a hot wire anemometer sensor as a resistance thermometer: the unit is operated like a constant current anemometer at a very low overheat ratio. The frequency response of the measurement system is limited by the response of the hot wire, since there is no feedback system. A simplified analysis estimating the frequency response of the wire follows.

a) King's Law semi-empirical formula approach:

The heat balance of a hot wire filament is taken to be:

$$H_g = H_t + H_a \quad (1)$$

where H_g : heat generated per unit time by heating ($i^2 R$)

H_t : heat loss due to convection per unit time

H_a : heat accumulation per unit time (dH/dt)

$$dH_w/dt = i^2 R - (A' + B' U) (T_w - T_g) \quad (2)$$

Following Perry [1] equation 2 is rewritten as:

$$cdR_w/dt = i^2 R - (A + B U) (R_w - R_g) \quad (3)$$

where $A = .42 \frac{1 K_f (Pr_f)^{.2}}{R_c}$

$$B = .57 \frac{1}{R_o} K_f (Pr_f)^{.33} (Re)^{.5}$$

$$c = \frac{(v) c_w}{R_o} : \text{heat capacity of hot wire}$$

Rw = wire resistance

Rg = wire resistance at fluid temperature

Ro = wire resistance at reference temperature

c_w = wire specific heat at constant pressure (c_p)

v_w = wire (filament) volume

= temperature coefficient of resistance

Here the term i²R is small compared to (A + B U), this leaves equation 3 as a first order differential equation with a time constant M

$$\frac{1}{M} = \frac{1}{c_w r_w^2} (.42 K_f (Pr_f)^{.2} + .57 K_f (Pr)^{.33} Re^{.5})$$

setting 1/M = 2 fo

fo is estimated to be 750 Hz at U = 60 m/sec, for the type of sensor used in the measurements.

b) Single lumped heat capacity approach

The heat convection from fluid to hot wire filament is described below:

$$Q = hA(T_f - T_w) = -C_p V(dT_w/dt)$$

or the time constant of the system:

$$M = \frac{C_p V}{hA_s} = \frac{1}{2 f_o}$$

Since A and v are the surface area and volume of the wire, then f_o can be simplified as follows

$$f_o = \frac{h}{C_p r_w}$$

The cut-off frequency is estimated at about 800 Hz at

$U = 60$ m/sec

In both approaches, thermal radiation from hot wire filament can be safely neglected since the flow and wire temperature never exceed 300 C. The cut-off frequency f_o is a function of h , the heat convection coefficient, we may, therefore, expect a higher value of f_o in the highly turbulent shear layer of the heated subsonic jet.

- [1] **PERRY, A.E.**; Hot Wire Anemometry, Oxford University Press, New York, 1982.

APPENDIX III: TWO-POINT SPACE-TIME CORRELATIONS

It is well known that two point space-time correlations can be used to deduce characteristic features of turbulence. In particular, they permit one to estimate the size, life-time, and convection velocity of 'eddies'. Consider a non-periodic function $s(\mathbf{x}, t)$ of zero mean. The two point space time correlation is defined by

$$R_{ss}(\mathbf{x}, \mathbf{y}, \tau) = \lim_{T \rightarrow \infty} \frac{1}{2T} \int_{-T}^T s\left(\mathbf{x} + \frac{1}{2}\mathbf{y}, t\right) s\left(\mathbf{x} - \frac{1}{2}\mathbf{y}, t - \tau\right) dt$$

In general this function has one global maximum (usually at $\mathbf{y}=0$ and $\tau=0$) and decays smoothly to 0 for large $|\mathbf{y}|$ and t . In some instances the function s may possess some spatial bias. An example would be the intensity of a wave which spreads spherically without change in shape, but with a decrease in amplitude. To avoid such a bias, it is customary to normalize the correlation by the respective local RMS values:

$$R_{ss}(\mathbf{y}, \tau) = \frac{R_{s,s}(\mathbf{x}_1, \mathbf{y}, \tau)}{\sqrt{\bar{s}_1^2(\mathbf{x} + \frac{1}{2}\mathbf{y}) \bar{s}_2^2(\mathbf{x} - \frac{1}{2}\mathbf{y})}}$$

In order to help with the interpretation of actual data, let us

examine a simple model function:

$$R_{ss}(y, \tau) = e^{-a^2 |y|^2 - b^2 \tau^2}$$

The model exhibits a maximum at $|y| = 0$ and $\tau = 0$. The correlation decays as the arguments become sufficiently large: when $\tau = 4/b$ and $|y|=0$ or $\tau=0$ and $|y| = 4/a$ the function has a value of $\exp(-4)$. The interpretation which may be made is that the signals are virtually independent of each other.

In most turbulent flows the eddies are convected by the mean flow. This is modelled by:

$$R_{ss}(y, \tau) = e^{-a^2 |y - u_c \tau|^2 - b^2 \tau^2}$$

The measurement system employed in this study permits one to measure only the temporal correlation. The entire function $R_{ss}(x, y, \tau)$ must be assembled by performing measurements at various values of y . Here only one component (the axial one) is measured. Thus the model reduces to

$$R_{ss}(y, \tau) = e^{-a^2 (y - u_c \tau)^2 - b^2 \tau^2}$$

Figure 1 illustrates this function for various values of y over a range of τ . The peaks are seen to shift towards positive values

of time delay, their magnitudes diminishing. The apparent time scale is set by $1/(b + aU)$; whereas an observer moving at a velocity U would measure a time-scale of $1/b$. A little thought shows that the movement of the eddies past a stationary observer will produce this effect.

Note that the equation

$$a^2 (y - aU\tau)^2 + b^2 \tau^2 = c^2$$

defines an ellipse in the y, τ plane with one axis along $x = U\tau$. This then provides a means of deducing the convection speed: lines of constant correlation values are plotted and the locus of the maximum separation from the origin (in the y, τ plane) defines the path of the eddy (Fig. 2).

The constant a (or the corresponding length scale $1/a$) is found from

$$R_{ss}(y, 0) \approx e^{-a|y|}$$

The time scale is found by fitting an envelope to the space time correlations.

Fig. 1 Model two-point space-time correlations

Fig. 2 Contours of constant correlation coefficient

END

1 9|0 2|9 1

FIN