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Cold flow simulation of vortex shedding in a segmented solid rocket motor

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COLD FLOW SIMULATION OF VORTEX SHEDDING IN A SEGMENTED SOLID ROCKET MOTOR

by

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ABSTRACT

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Title Cold Flow Simulation of Vortex Shedding in a Segmented Solid Rocket Motor

Combustion instabilities are a major problem in large solid rocket boosters. They are responsible for exciting undesirable oscillations in the propellant burn rate. It is believed that vortex shedding from upstream inhibitors is one of the phenomena responsible for the onset of these instabilities. Vortex shedding frequencies are time dependent due to the unsteady nature of the flow inside the rocket motor. When one of these frequencies coincides with a structural frequency, the oscillations can increase substantially. The protruding inhibitors are caused by their slow burn rate compared to that of the fuel. In the current research, cold flow simulations were carried out to understand the problem of vortex shedding. Results were generated for a fixed baffle diameter and distance between inhibitors while varying the flow velocity. Six different flow conditions were used starting from 70 gallons per minute to 120 gallons per minute, while vortex shedding distances corresponding to each flow configuration were measured in order to determine the Strouhal number. The Strouhal number for the various runs was found to be in the range of 0.19 to 0.28, which is slightly higher than that of previously published experiments of 0.185 to 0.20.

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LIST OF SYMBOLS

v	Velocity
V	volume
m	Meter
S	Second
Hz	Hertz
S_t	Strouhal number
t	Time
R_e	Reynolds umber
Gpm	gallons per minute
f	Frequency
D	Diameter
d	Distance
A	Area

CHAPTER I

INTRODUCTION AND BACKGROUND

1.1 Introduction

In large solid rocket motors, propellant surfaces at the intersegment joints are often covered with annular inhibitors which prevent burning at that face in order to get the desired thrust versus time characteristics.

Initially, the inhibitors are almost flush with the propellant inner bore circumference. As the motor is fired, the inhibitors protrude into the exiting gas flow path because they do not burn as fast as the propellant. This eventually leads to the creation of vortices within the chamber cavity at different frequencies which could coincide with the acoustic frequency of the motor cavity leading to undesirable conditions in large solid rocket motors. These large solid rocket motors, in most cases, carry very sensitive payloads when used as launch vehicles or war heads when used as missiles, which could be destroyed as a result of these oscillations due to vortex interactions within the motor cavity.

“Water analogue are often used to simulate the flow of air and other gases around or through propulsion devices. Water is an easily obtainable, nontoxic fluid which lends itself readily to the introduction of dye and particles for flow visualization. Scaling laws are such that a relatively slow flow in water can accurately simulate a much more rapid gas flow allowing easy observation of time dependent phenomena’’ [9].

The Reynolds number is a primary scaling parameter used to ensure similarities between water flow models and their real gas counterparts. It expresses the ratio of inertia to viscous forces and determines the likelihood of a fluid existing in turbulent or laminar states in terms of microscopic-scale molecular motion [9].

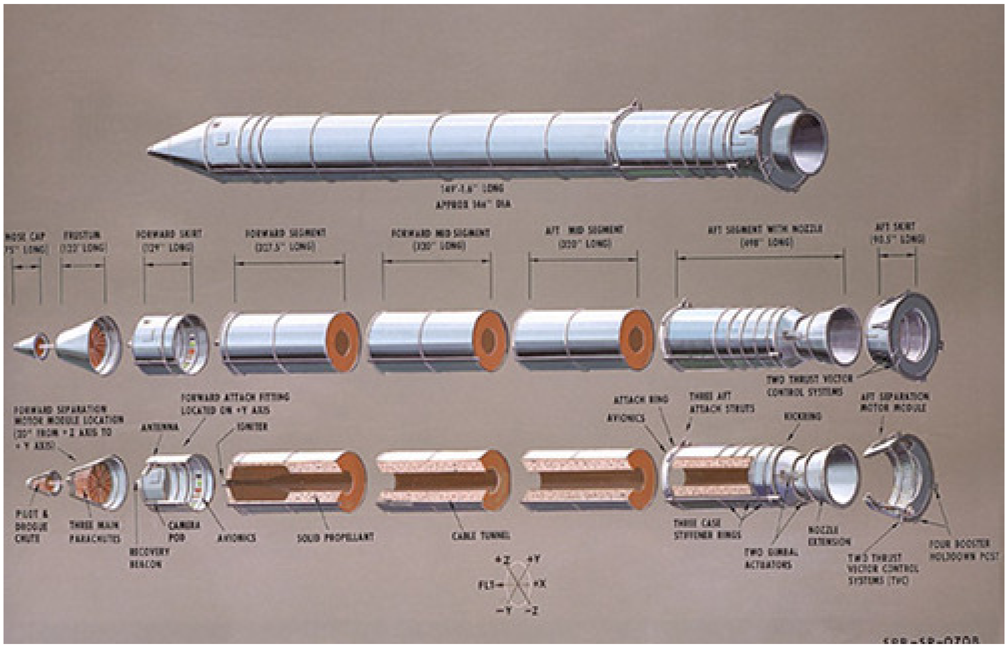

Figure 1.1 Internal Cavity of a Large Solid Rocket Booster [7].

1.2 Background

A number of large solid propellant rocket motors, including the space shuttle, Titan and Arian 5 solid boosters, exhibit instabilities due to vortex shedding driven acoustic pressure oscillations [1]. This research work is to determine the effects of vortex shedding on the thrust oscillation of large solid rocket motors using cold flow simulation experiment techniques. The cold flow water tunnel facilities at the Johnson's propulsion research center was used to simulate the internal cavity of a large solid propellant rocket motor in order to generate data for the flow simulation experiment.

Vortex shedding induced acoustic responses are observed from a variety of geometric and flow configuration combinations. Solid propellant rocket flow past two inhibitors is modeled in a cold flow cylindrical water tunnel test section with thin annular baffles used to simulate the inhibitors.

The objective of this research work is to determine the effects of vortex shedding on thrust oscillations of large solid rocket motors as a function of the vehicle internal geometry and velocity using a water tunnel facility to simulate the internal conditions of a large solid rocket booster.

The following variations can be made in the test configuration in order to generate data for different vortex shedding frequencies and velocity profiles in the test section.

(1) The spacing between baffles can be varied to excite different vortex shedding frequencies.

(2) Flow velocities past the baffles were varied to excite different vortex shedding frequencies.

(3) The location of baffle pairs in the test section can also be varied to excite different acoustic responses of the test cavity.

(4) The Baffle diameter can be varied to excite different vortex shedding frequencies.

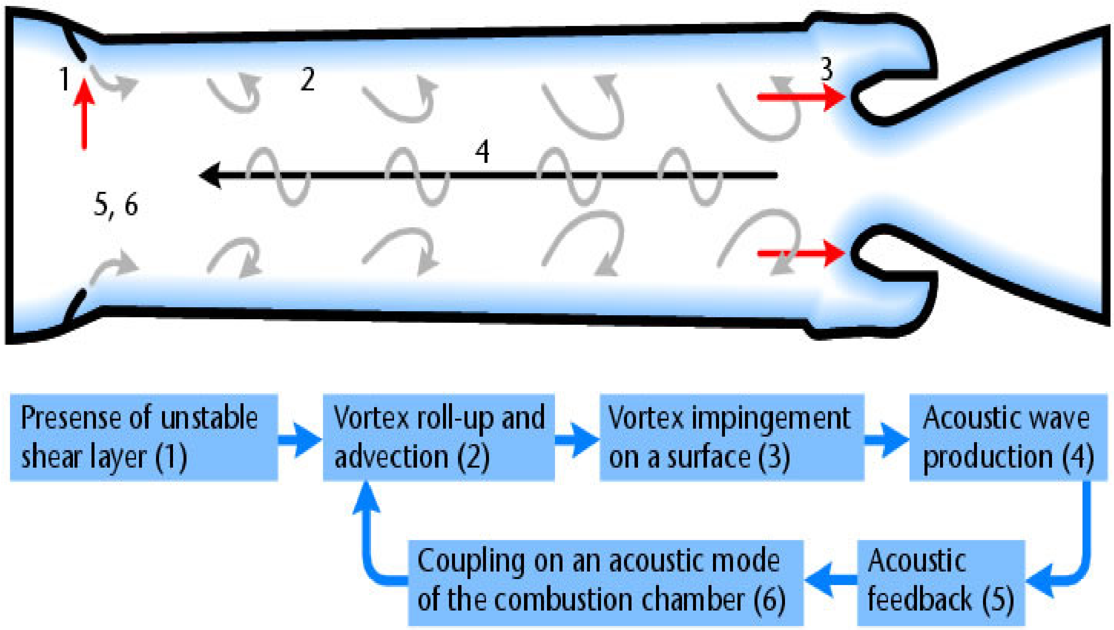

Figure 1.2 Vortex Interactions in Rocket Motor

Water Tunnels have been utilized in one form or another to explore fluid mechanics and aerodynamic phenomena for a very long time. Only in recent years, however, have Water Tunnels been recognized as highly useful facilities for critical evaluation of complex flow fields on many modern vehicles such as high performance aircraft [8].

In particular, Water Tunnels have filled a unique role as research facilities for understanding the complex flows dominated by vortices and vortex interactions. Flow visualization in Water Tunnels provides an excellent means for detailed observation of the flow around a wide variety of configurations. The free stream flow and the flow field dynamics are low-speed, allowing real time visual assessment of the flow patterns using a number of techniques, including dye flow through ports in the model, hydrogen bubble generation from strategic locations on the model, or laser light sheet illumination [8].

Comparison of flow visualization in water and wind tunnel experiments on a common model shows nearly identical vortex flow patterns, clearly illustrating that Water Tunnel observations have direct application to aerodynamics [8].

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CHAPTER II

TEST FACILITY DESCRIPTION

2.1 Test Facility Description

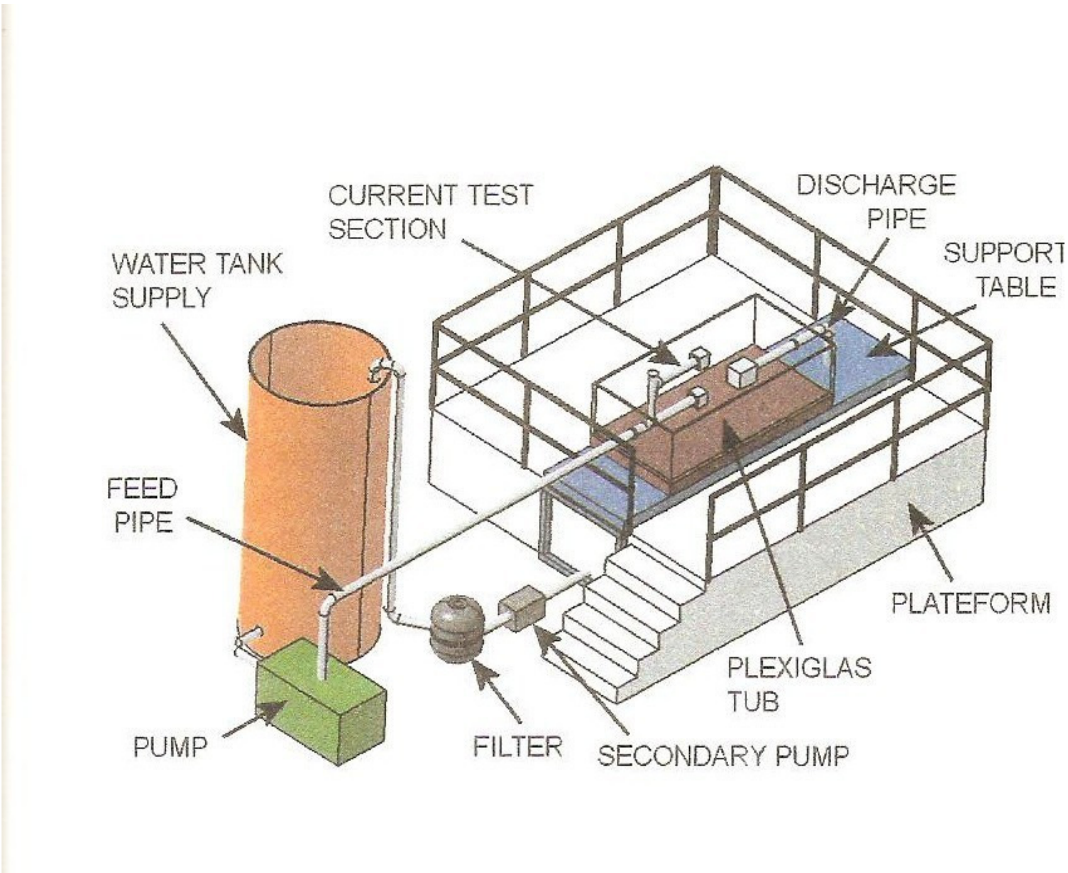

Figure 2.1 Water Tunnel Facility Schematic [6].

Water tunnel facilities of various sizes and capacities have been used to simulate the internal conditions of large solid rocket motors with a view to obtaining relevant data that could be used to validate CFD codes.

The water tunnel facility for the cold flow experiment comprises the following equipment and components.

The run tank is a 300 gallons capacity tank that holds water which runs through the test section. It is equipped with a stop switch which cuts off the return pump when it is full, in order to avoid overflow. A 25 hp capacity pump, Figure 2.2 (main pump), pumps water from the run tank through the test section. The flow rate of water flowing through the test section is measured using a magneto-hydrodynamic (MHD) flow meter in gallons per minute, Figure 2.4. The water then flows past the inhibitors in the test section, Figure 2.7. The water exiting the test section goes directly into the catch tank which is a 600 gallon capacity tank below the test stand. A 1.5 Hp return pump, Figure 2.6, is used to pump water from the catch tank back into the run tank, making the system a closed cycle system. The filter, Figure 2.5, is used to remove unwanted particles and dirt from the entire system so as to ensure running the test with clean water. The video camera was also interfaced with the computer, and it was used to capture images and record flow conditions while carrying out an experiment. The computer was used for computation and data analysis, and also an interface between equipment within the test facility.

Figure 2.2 Test Facility

Figure 2.3 Outlet Valve

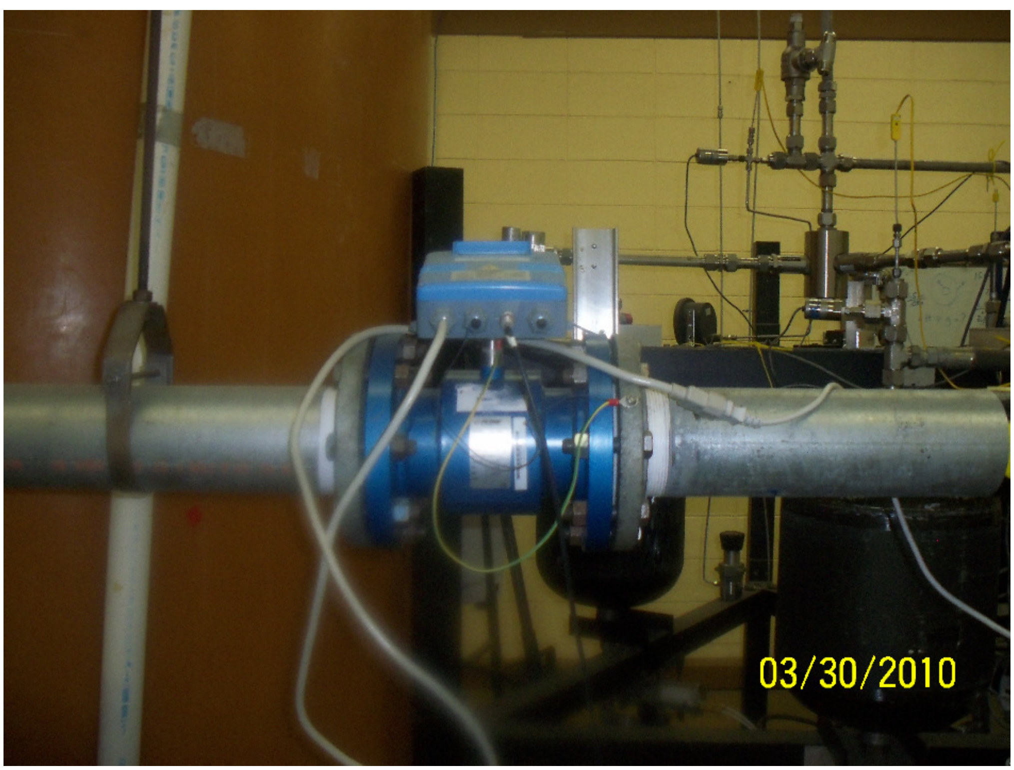

Figure 2.4 MHD Flow Meter

Figure 2.5 Filter

Figure 2.6 Return Pump

Figure 2.7 Test Section

Figure 2.8 Discharge Valve

Figure 2.9 Pump Control Switch

2.2 Physical Observation

Before an attempt was made to carry out the experiment, it was ensured that a physical observation and inspection of facilities for any abnormalities within the facilities and surroundings was carried out, e.g., water leakage, improper placement of tools, oil spillage etc.

2.3 Tank filling (transfer from catch tank to run tank)

Open the catch tank outlet valve and then set the filter selector to the filter position. Start the pump to fill the tank; stop the pump when the tank level reaches the desired level (pump stops automatically) when the main tank is full or when catch the tank is empty.

Filling directly with fresh water is done by opening the valve above the main tank to fill with fresh water; close valve when the main tank is full.

2.4 Backwashing

This is done occasionally for the purpose of cleaning the filters. Adjust the valve to the backwashing position and ensure that the catch tank outlet valve is in the open position, while the hose is directed to the drain. Start the pump and partially close the catch tank outlet valve so that the drain does not overflow. Wait until clear water starts coming out from the outlet valve to the drain, then stop the pump.

2.5 Rinse

Set the selector to the rinse position, and then start the pump and let it run for several minutes; stop the pump and adjust the valve back to the filtering position.

2.6 Main Operation

Open the outlet valve from the flow line which leads directly to the catch tank under the test stand. Open the main valve from the pump and then connect the power

cable. Turn on the main power and then set the selector to the desired speed starting at slow. Lift the safety cover to turn on the pump.

The current UAH water tunnel facility schematic is shown in Figure 2.11. Water is pumped from a main tank with a capacity of 300 gallons by a 25 hp variable speed pump through a feed pipe into the test section. The water then exits through a discharge pipe that leads to a secondary tank known as the catch tank with a capacity of 600 gallons placed under the platform. A 1.5 hp pump (return pump) pushes the water through a sand filter and then back into the main tank. The test section is mounted into a Plexiglas tube with inner dimensions of 239x117x64 cm and both the feed and discharge pipe have 10.2 cm (4inches) inner diameters.

2.7 Laser Set Up

Ensure there is an adequate barricade around the experiment area; connect the laser to a power source and then turn on the laser. Check on the stray beam and adjust the rays to focus on the flow line (test area).

2.8 Shutdown Sequence

Decrease the speed from the speed control switch, turn off the pump and then turn off the main power from the wall. Turn off the return pump, close both outlet and discharge valves, and finally turn off the laser.

CHAPTER III

EXPERIMENT

3.1 Experiment

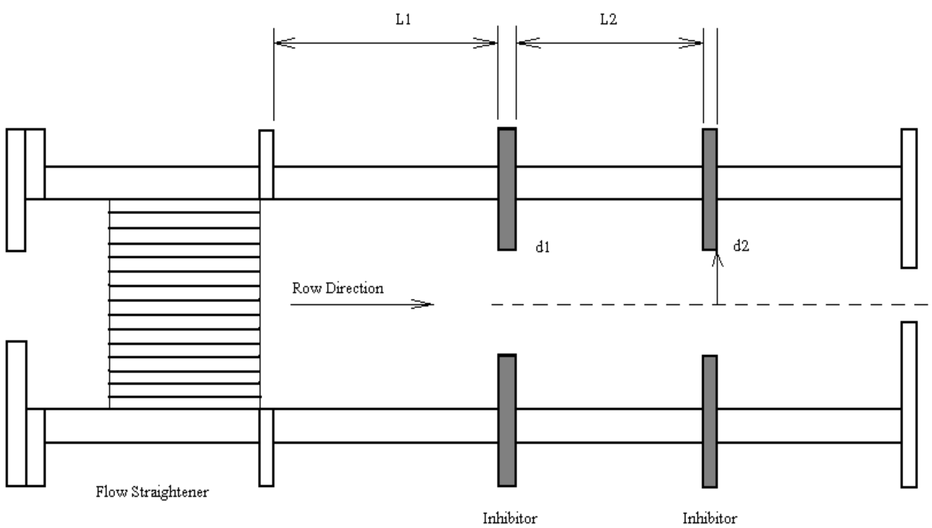

Figure 3.1 Schematic Diagram of the Test Section

Water flows past the MHD flow meter at a certain flow rate measured in gallons per minute through the flow straigthener before coming across the upstream baffle. The pump speed regulator is adjusted high or low in order to increase or decrease the flow rate of water passing through the section. Figure 3.2 shows the image of the flow pattern with die injection, while Figure 3.3 shows the image of the flow pattern with particle injection.

The flow rate of water in gallons per minute is then converted to velocity using the geometry of the test section by dividing the volume flow rate by the test section's area. The experiment was carried out in sequence, starting with 70 gallons per minute up to 120 gallons per minute with an interval of 10 gallons per minute.

Flow pattern images are obtained using dye and fine particles at different velocities. The laser is turned on to produce a red light while a filter is attached to the camera when injecting particles. The use of the filter is not necessary when injecting dye into the test section. Particles unlike the dye are more visible at high velocities and are more preferred to the die since the die tends to vanish faster at high velocities. Vortex shedding distances are measured in order to determine the shedding frequency corresponding to the flow velocity, this is then used to obtain the Strouhal number corresponding to the flow velocity.

Figure 3.2 Internal Cavity of Test Section With Dye Injection for Flow Pattern Visualization

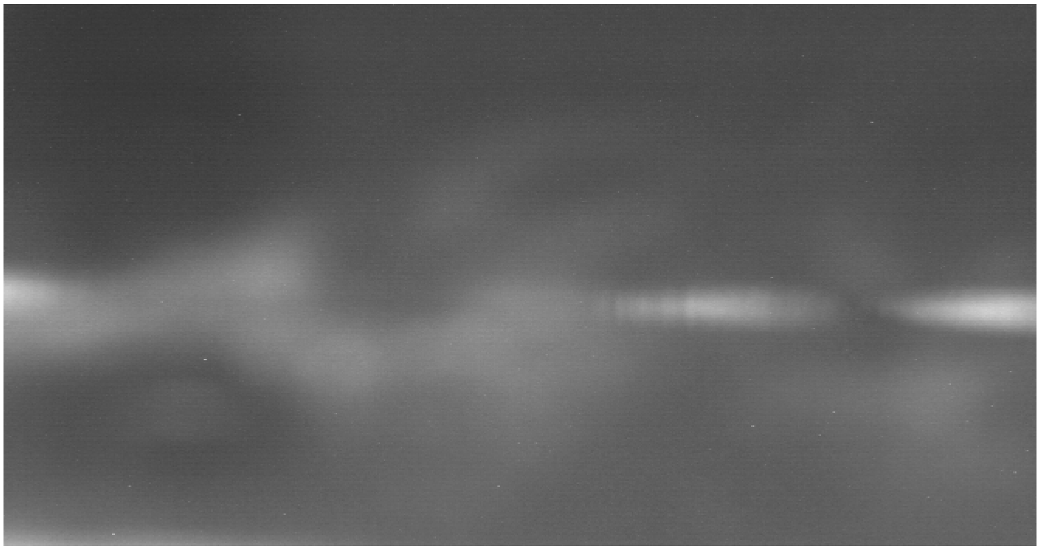

Figure 3.3 The Flow Pattern Image Obtained Using Particle Injection for Flow Visualization

Figure 3.4 20 mW Coherent Laser

The laser is a 20 mW capacity, and it was used to produce a red light through the test section for the purpose of flow pattern visualization.

3.2 Image Visualization

Visualizing images and flow patterns in the test section can be quite difficult and cumbersome due to light scattering effects. Images are clearer and more accurate when viewed at an angle compared to when viewed from a vertical position at 90°. The use of a high powered laser was employed in order to capture a clear image of flow pattern and vortices along the flow line. The power of the HeNe (2mW) laser that was initially used was not enough to produce a clear and visible image of the flow pattern. The laser was then changed to a 20mW coherent laser that was able to produce a clearer image. Basically, the use of the die injection and particle injection was adopted in this experiment for flow pattern visualizations.

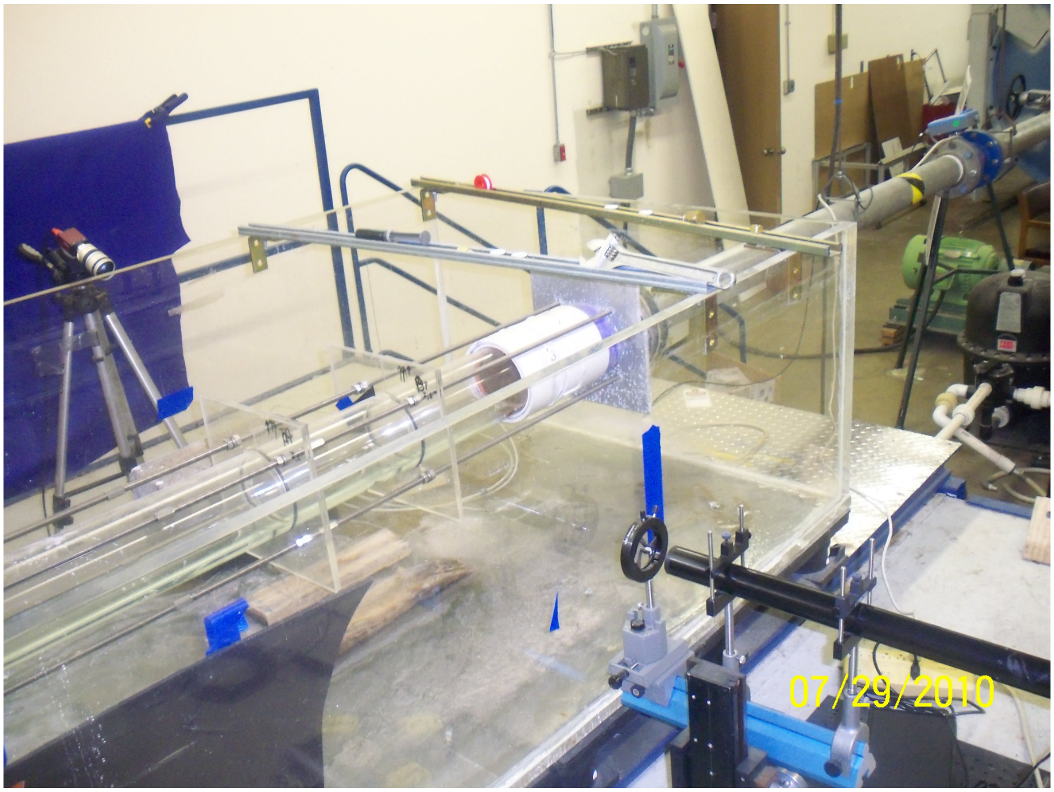

Figure 3.5 Test Section Set Up

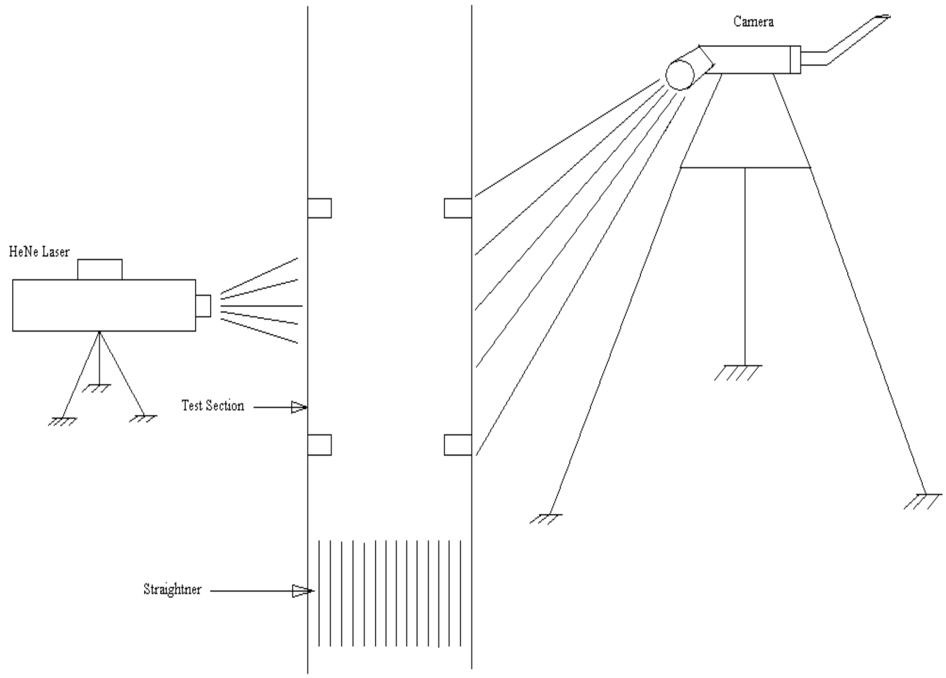

Figure 3.6 Schematic of Test Section Set Up

3.3 Light Scattering

Scattering is a general process where some forms of radiation such as light, sound, or moving particles are forced to deviate from a straight trajectory by one or more localized non-uniformities in the medium through which they travel. When reflections undergo scattering, they are called diffused reflection while un-scattered reflections are called specula (mirror-like) reflection [10].

The scattering effect is one of the major problems in the flow visualization process as it always affects the clarity and accuracy of the image obtained. Basically, there are three main light scattering phenomena based on a dimensionless size particle, α, which is defined as

$$\alpha = \pi D_p / \lambda \quad , \tag{3.1}$$

where πDp is the circumference of a particle and λ is the wave length of incident radiation. Based on the value of α, these three domains are:

$\alpha \ll 1$; Rayleigh scattering where particles are small compared to the wave length of light.

$\alpha \approx 1$; Mie scattering where particles are about the same size as the wave length of light.

$\alpha \gg 1$: Geometric scattering where particles are much larger than the wave length of light.

The degree of scattering varies as a function of the ratio of the particle diameter to the wavelength of the radiation, along with other factors including polarization, angle, and coherence [10].

CHAPTER IV

RESULTS AND DATA ANALYSIS

Several tests were carried out using the water tunnel facilities at the Johnson Propulsion Research Center; results and data obtained were analyzed; various graphs and charts were also plotted in order to verify if results obtained match existing analytical or experimental solutions.

4.1 Water Tunnel Configuration

The water tunnel facility used for this research work has the configurations listed in Table 4.1.

Table 4.1 Test Facility Configuration

Total length of test section	76inches	1.93m
Diameter of test cylinder	6.5 inches	0.1651m
Diameter of upstream baffle	3 inches	0.0762m
Diameter of downstream baffle	3 inches	0.0762m
Distance between upstream and downstream baffles	12 inches	0.3048m

4.2 Flow Conditions

Water is admitted into the test section at a regulated volume flow rate in gallons per minute. This is then converted into velocity per second using the geometry of the

water tunnel. Flow velocities past the baffles were varied in order to excite different vortex shedding frequencies.

4.3 Strouhal Number

The Strouhal number is a non dimensional quantity that can be determined using the measured vortices generated across the upstream baffle (inhibitor), and the frequency generated during a particular flow condition.

$$f = \frac{S_t V}{d} \tag{4.1}$$

$$S_t = \frac{fd}{V} \, , \tag{4.2}$$

where

f is the Vortex shedding frequency (Hz)

S_t is the Strouhal number (dimensionless)

v is the flow velocity and

d is the baffle diameter (characteristic length)

$$V = d / t \tag{4.3}$$

$$V / d = 1 / t$$

$$V / d = 1 / t = f\,(\text{Hz}) \quad . \tag{4.4}$$

With the calculated frequency, a known flow velocity and baffle diameter, the Strouhal number can be determined for a particular flow velocity. Different flow velocities were then generated in order to obtain a corresponding Strouhal number. The Strouhal number is a function of the Reynolds's number, typically between $20 < R_e > 20{,}000$.

4.4 Flow Rates and Velocity

The main pump pumps in water through the test section in gallons per second as measured by the flow meter; this is then converted to velocities using the measured vortices and the test section geometry.

Area of the test section is

$$A = \frac{\pi d^2}{4} \quad , \tag{4.5}$$

where A = area of the test section

d = diameter of the cylinder = 0.1651m

$A = 0.0214 m^2$.

$$v = \frac{Q}{A} \quad . \tag{4.6}$$

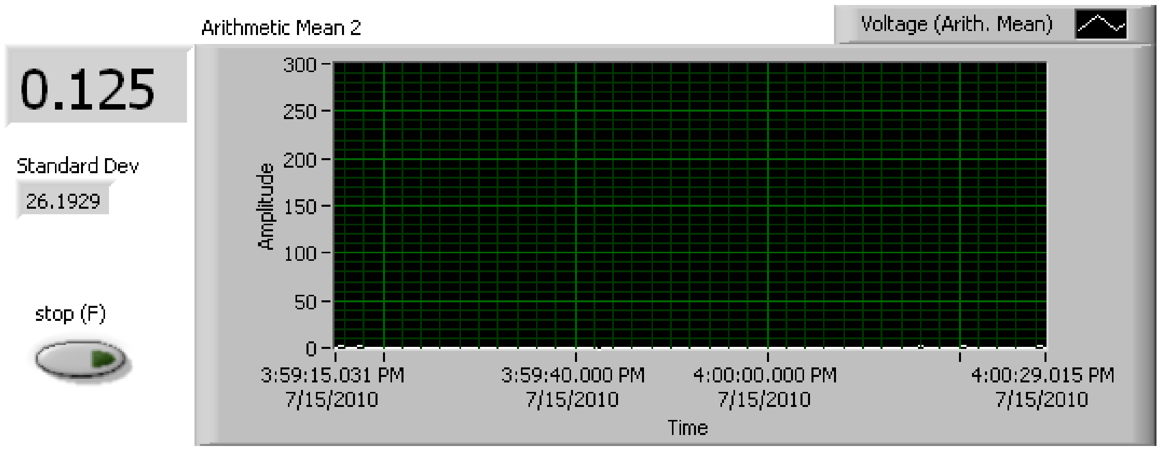

Figure 4.1 Flow Meter Digital Reading 0 Gallons per Minute

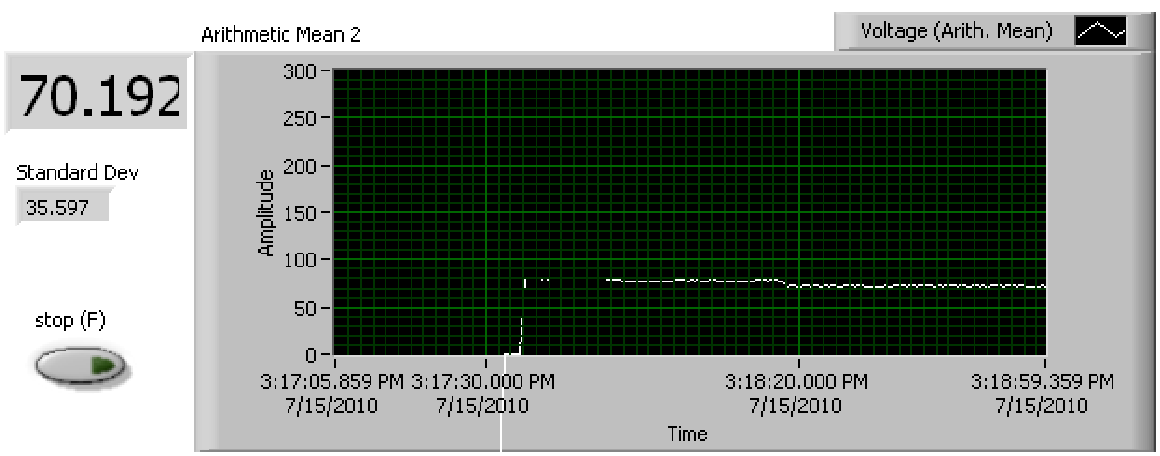

Figure 4.2 Flow Meter Reading 70 Gallons per Minute

This is where the particle or die injection is done when reading stabilizes on the desired flow level before the measurement is taken.

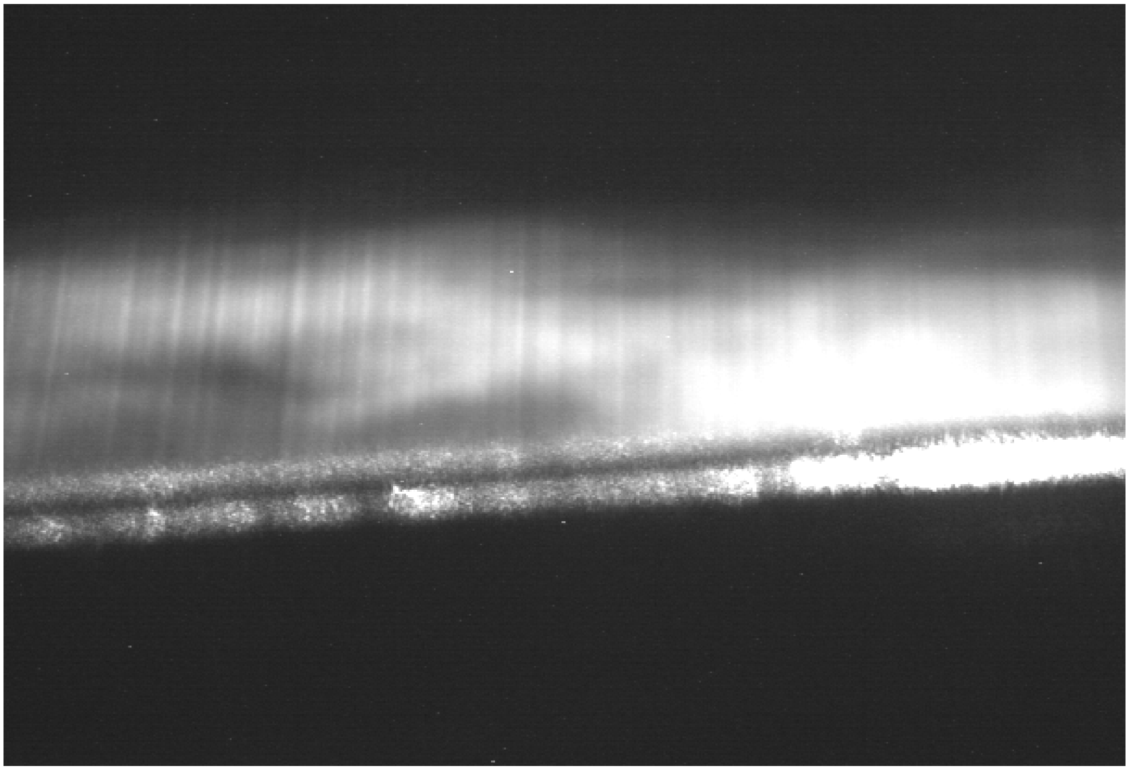

Figure 4.3 Flow Pattern at a Flow Rate of 70 Gallons per Minute

$$V_1 = \frac{4.414 * 10^{-3}}{0.0214} \frac{m^3}{m^2 s}$$

$$V_1 = 0.21\, m/s.$$

Using equation (4.4),

$$f = v / d \quad , \tag{4.7}$$

where

f is the frequency

d is the measured vortex length

and

v is the flow velocity

$$f_1 = \frac{0.21}{0.27}\frac{m}{s} * \frac{1}{m} = \frac{1}{s}$$

$$f_1 = 0.78Hz$$

$$S_{t1} = \frac{fd}{v}$$

$$S_{t1} = 0.28 \quad .$$

4.5 Tables

The above calculations were carried out for the six different runs; the data obtained are tabulated in the tables below.

Table 4.2 Velocity

V_1	0.21 *m/s*
V_2	0.24 *m/s*
V_3	0.27 *m/s*
V_4	0.30 *m/s*
V_5	0.32 *m/s*
V_6	0.35 *m/s*

Table 4.3 Frequency

f_1	0.78 *Hz*
f_2	0.80 *Hz*
f_3	0.82 *Hz*
f_4	0.85 *Hz*
f_5	0.86 *Hz*
f_6	0.89 *Hz*

Table 4.4 Stouhal Number

S_{t1}	0.28
S_{t2}	0.25
S_{t3}	0.23
S_{t4}	0.21
S_{t5}	0.20
S_{t6}	0.19

Table 4.5 Summary of Data Obtained

Flow rate (gallons/min)	Velocity (*m/s*)	Frequency (*Hz*)	Strouhal number
70	0.21	0.78	0.28
80	0.24	0.80	0.25
90	0.27	0.82	0.23
100	0.30	0.85	0.21
110	0.32	0.86	0.20
120	0.35	0.89	0.19

Table 4.5 shows the summary of the data obtained for the six runs. The flow rate of water through the test section was the controlled parameter, while the frequency was determined from the measured vortex shedding distance; the Strouhal Number was calculated from the relating equations.

4.6 Graphs

Various graphs were plotted to verify the relationship between the different parameters.

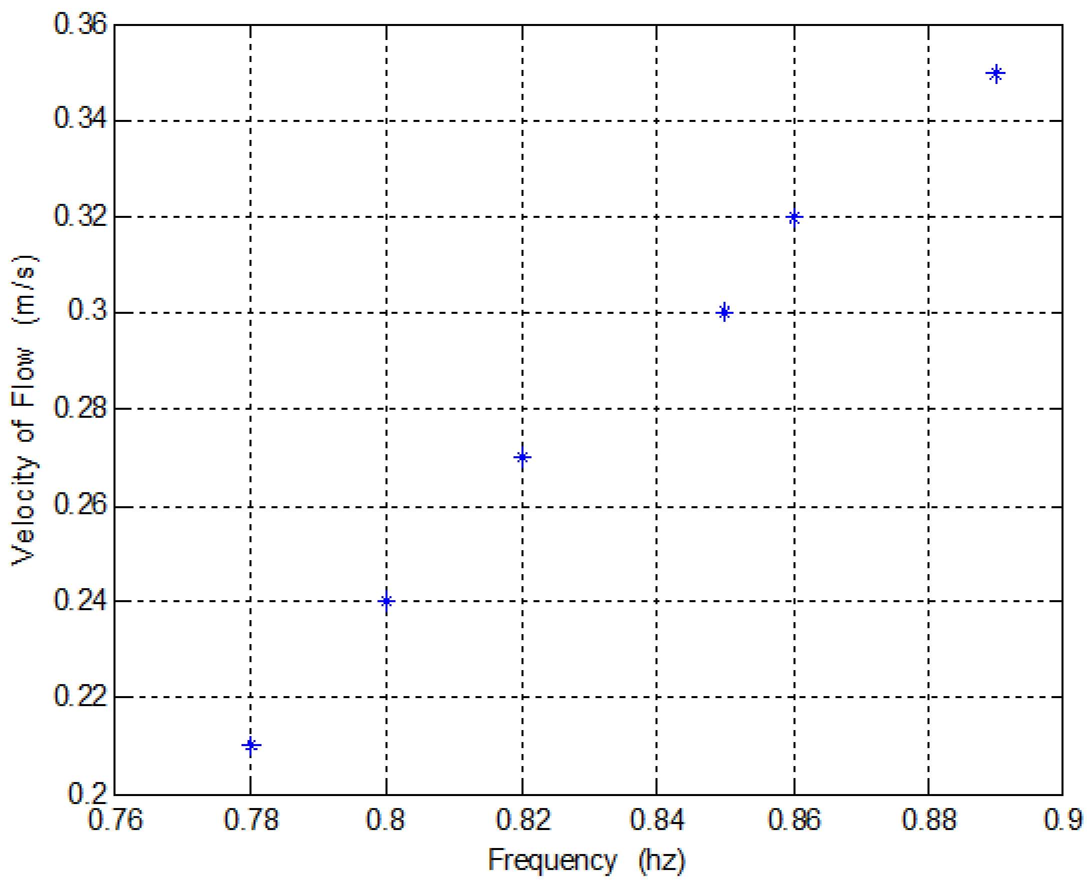

Figure 4.4 Graph of Velocity Against Frequency

Figure 4.4 is a plot of velocity against frequency; it shows an almost linear relationship between velocity and frequency.

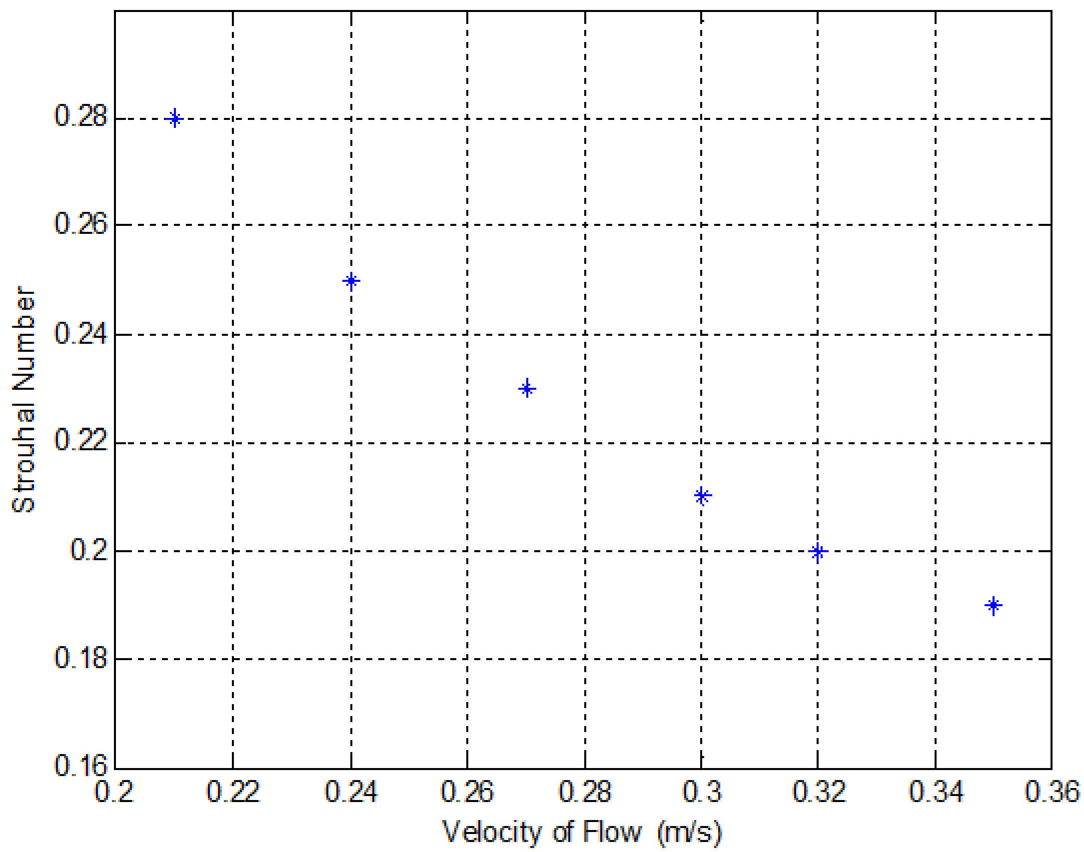

Figure 4.5 Graph of Strouhal Number Against Velocity

Since the Strouhal number is a function of the Reynolds number, it means the vortex interaction is only pronounced at a certain range of Reynolds numbers, typically $20<R_e<20{,}000$. This is why vortex shedding was not pronounced at lower velocities and at a velocity where the Reynolds number is greater than 20,000.

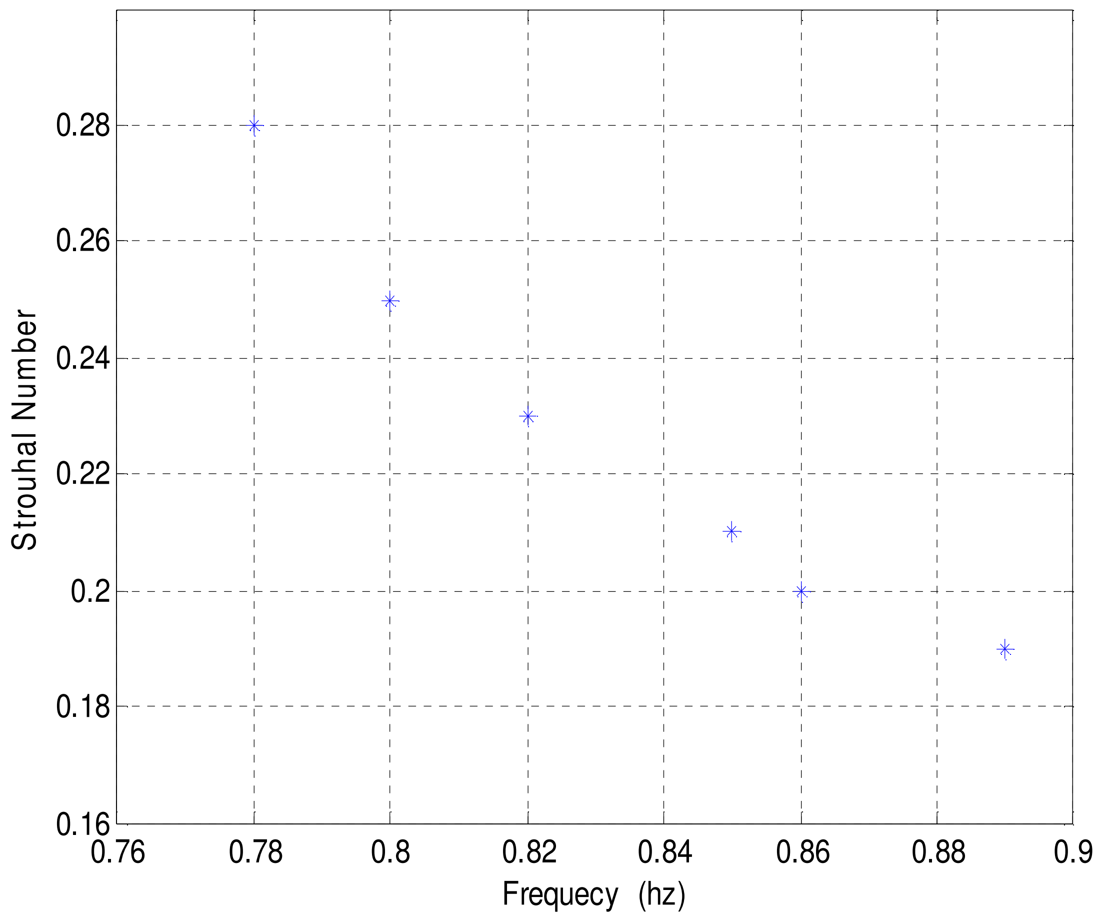

Figure 4.6 Graph of Strouhal Number Against Frequency

Since frequency has an almost linear relationship with velocity, vortex shedding is expected at a frequency range that is similar to the velocities.

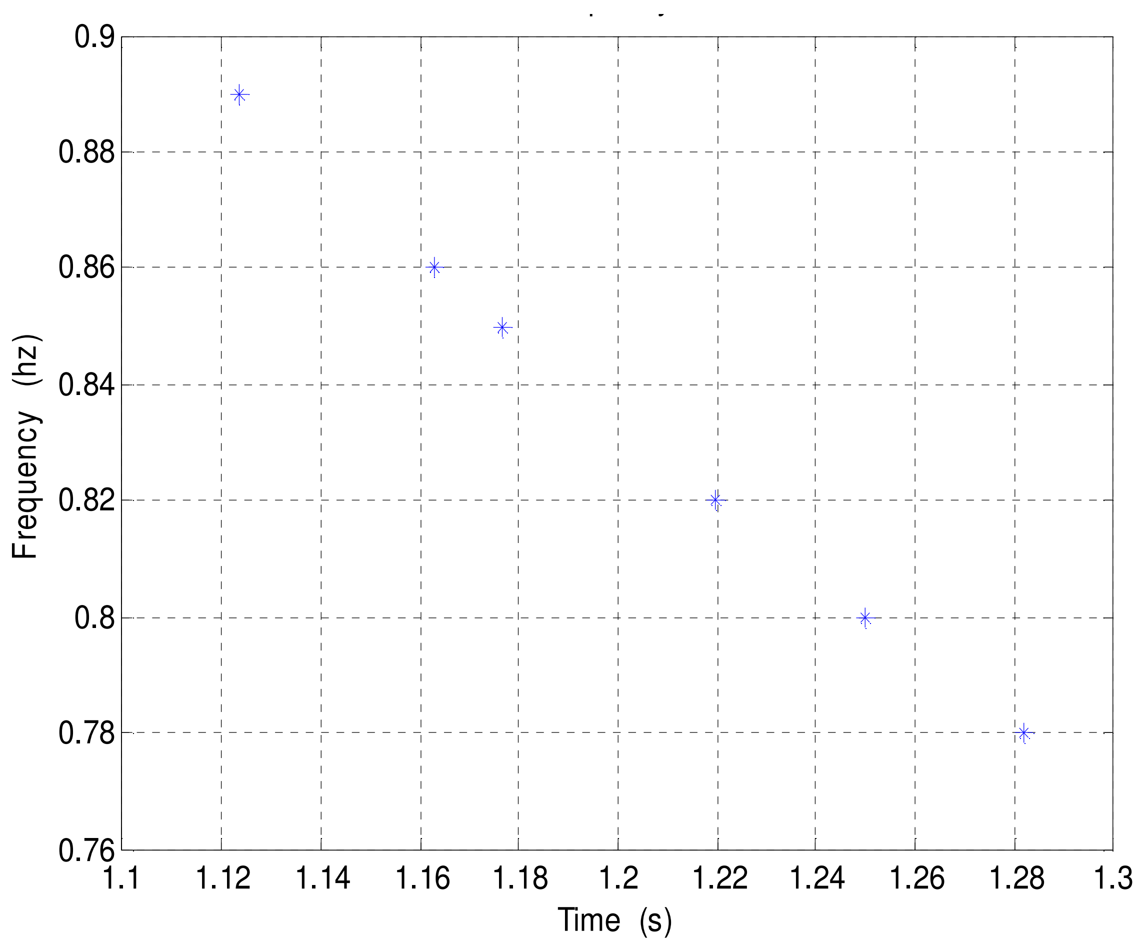

Figure 4.7 Graph of Frequency Against Time

Figure 4.7 indicates a drop in frequency as time increases. The chamber cavity increases as the propellant burns out; this led to a decrease in velocity, which has an almost linear relationship with the frequency.

CHAPTER V

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The process of visualizing flow pattern in a water tunnel experiment is not a simple process, as it involves the use of sophisticated and high powered lasers and lenses.

The facilities used for this experiment were able to generate data to justify numerically and experimentally determined data by researchers who have done similar work in the past. Some of the results from this research work have shown that vortex shedding only occurs at a certain range of Strouhal number, 185 < S_t <0.20. This means that there are certain velocities below and above which vortex interactions will not take place. This has also justified the relationship between Strouhal number and Reynolds number which is also a function of fluid velocity.

5.2 Recommendation

It is important to mention at this juncture that the facility used for this experiment is also capable of generating data to determine the effects of vortex interactions on longer or shorter segments of a large solid rocket booster. But this will require several constructions and reconstruction work on the test facilities in order to be able to vary the distance between baffles at each time the experiment is to be run so as to generate different sets of data for the different baffle distance. This could be a possible area of research interest if given the opportunity for my PhD program.

APPENDICES

APPENDIX A

STANDARD OPERATING PROCEDURE

Date: 03-22-2010

Red Team Members**:**

Dr. Moser ___________________________

Dr. Lineberry ___________________________

Tony Hall ___________________________

Rasheed Durojaye ______________________

Other operators or Red Team Members not shown on this document must be certified by the Test Engineer or Dr. Lineberry

Procedure Approval;

Rasheed ___________________________

Dr. Moser: ___________________________

Dr. Frederick ___________________________

Dr. Lineberry ___________________________

Tony Hall: ___________________________ (Test Engineer)

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Waiver for Pending Safety-Enhancing Modifications

The following safety-enhancing measures criteria are not yet implemented for this test procedure:

Safety Enhancing Item	Safety Issues	Temporary Measures to Compensate	Actions Underway to Provide Item	Person Responsible for Fix
HeNe Laser rays	Laser is positioned such that emitting rays could cause severe damage to the eyes of an observer.	Use of black cardboard to cover affected areas		David Lineberry/ Marlow Moser
SAFETY TRAINING TAGS	EMERGENCIES Proper identification of control valves and components.	CPR/AED TRAINING	completed	Dr. Lineberry Tony Hall

ALL BUDDY NON RED TEAM MEMBERS MUST BE CPR/AED CERTIFIED

TEST MUST ONLY BE CARRIED OUT IN THE PRESENCE OR WITH THE AWARENESS OF A RED TEAM MEMBER OR A CPR/AED CERTIFIED BUDDY.

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The undersigned acknowledge they have read this waiver and understand the safety issues involved:

Dr. Marlow D. Moser ________________________ Date: ______________

Dr. David Lineberry __________________________ Date: ______________

Mr. Tony Hall ______________________________ Date: ______________

Rasheed Durojaye ___________________________ Date: ______________

Emergency Phone Numbers	
Police	911 or 824 – 6911 (6911 from campus phone)
Fire Department	
Hazardous Materials Incident	
Utility Failure	
PRC Contacts	
Tony Hall	Office : 824-2887
David Lineberry	Office : 824-2888 Cell : 348-8978
Robert Frederick	Office : 824-7200 Cell : 503-4909
Marlow Moser	Office : 824-7201 Cell : 651-9373
PRC Main Office	824-7200
JRC Test Stand	824-1756 or 824-1759
Bobby Dempsey	824-2352

Other Emergency Numbers of Interest	
Huntsville Police Department	722-7100
Madison County Sheriff's Office	722-7181
Alabama state Troopers	533-4202
Crestwood Medical Center	882-3100
Huntsville Hospital Main	265-1000

Test Preparation And Procedure

1.0 Physical Observation

Ensure a physical observation and inspection of facilities for any abnormalities within facilities and surroundings, e.g., water leakage, improper placement of tools etc.

2.0 Tank Filling (Transfer from catch tank to run tank)

2.1 Open catch tank outlet valve

2.2 Set filter selector to filter

2.3 Start pump to fill tank

2.4 Stop pump when tank level reaches the desired level (pump stops automatically) when run tank is full or turn off pump when catch tank is empty.

Filling with fresh water

2.5 Open valve above run tank to fill with fresh water.

Do not leave unattended, close valve when run tank is full.

3.0 Backwashing

This is done occasionally for the purpose of cleaning the filters

3.1 Adjust valve to backwashing position

3.2 Ensure that catch tank outlet valve is in open position

3.3 Ensure waste hose is directed to drain

3.4 Start pump

3.5 Partially close catch tank outlet valve so that drain does not over flow

3.6 Wait until clear water starts coming out from outlet valve to drain

3.7 Stop pump

4.0 Rinse

4.1 Set selector to rinse position

4.2 Start pump and let it run for several minutes

4.3 Stop pump

4.4 Adjust valve back to filtering position

TRANSFER PUMP CAN BE LEFT ON DURING RUN.

5.0 Main Operation

5.1 Open outlet valve from flow line (leads directly to the catch tank under test stand)

5.2 Open main valve from pump

5.3 Connect power cable

5.4 Turn on main power

5.5 Set speed selector to desired speed (start slow)

5.6 Lift safety cover

5.7 Turn on pump

6.0 Laser Set Up

6.1 Ensure there is adequate barricade around experiment area

6.2 Connect laser to power source

6.3 Turn on laser

6.4 Check for stray beam

6.5 Adjust rays to focus on flow line.

NEVER leave experiment running without monitoring.

Check out test procedures only needed at the beginning of testing series

At any point, if a Red Team Member sees a questionable situation he can, and should, call for a solution discussion or experimental shut-down

7.0 Shut-Down Sequence

7.1 Decrease speed from control box

7.2 Turn off pump

7.3 Turn off main power from the wall

7.4 Turn off return pump

7.5 Close valves

7.6 Turn off laser

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Failure Analysis

FAILURE MODE	MITIGATION	SOLUTION	EFFECT
supply pump does not start	Check power source		Delay in experiment
Power failure	Shut-down main power		Stops experiment
Over Pressurization	Shut down pump, open outlet valves	Install gauge to monitor	Damage to components and flow line shower.
Stray laser beam	Turn off laser		Injurious to personnel
Massive water leakage	Stop pump		Damage to equipment

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APPENDIX B

Flow Meter Indicator

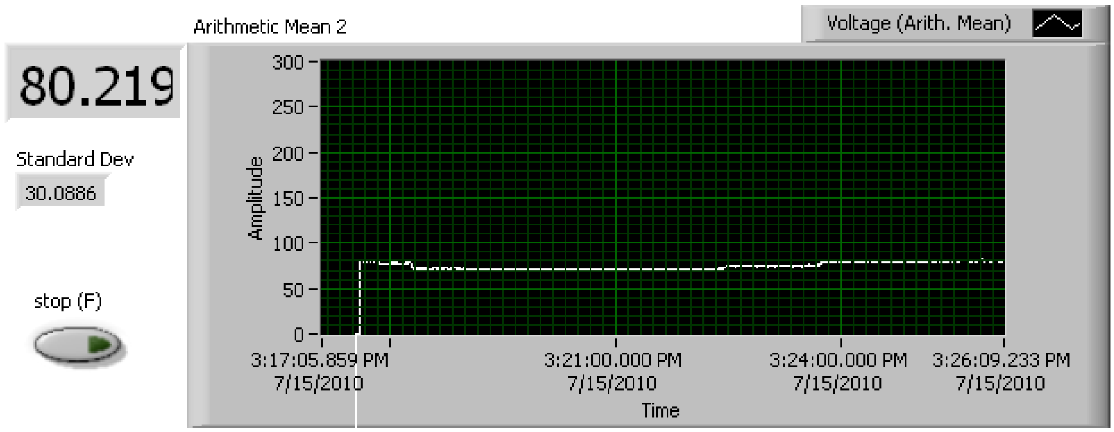

Figure B.1 Flow Meter indicating a Volume Flow Rate of 80 Gallons per Minute

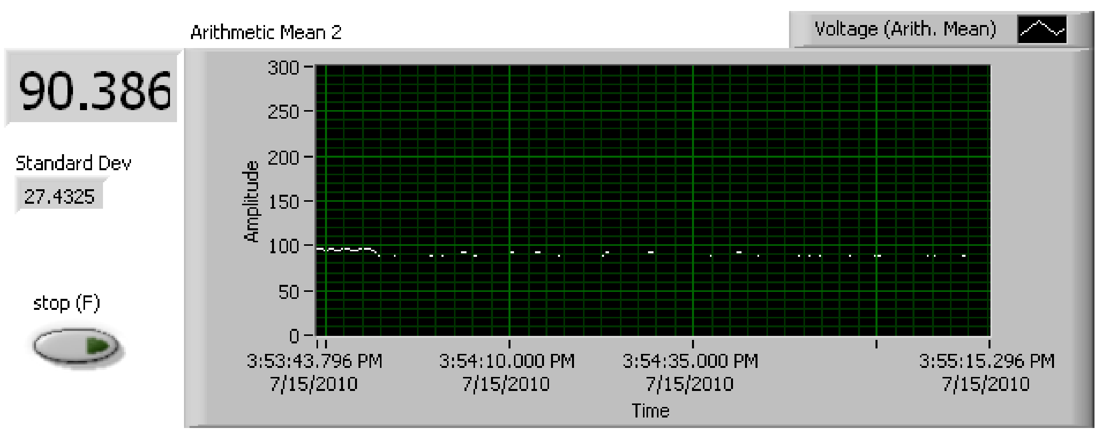

Figure B.2 Flow Meter Reading at a Volume Flow Rate of 90 Gallons per Minute

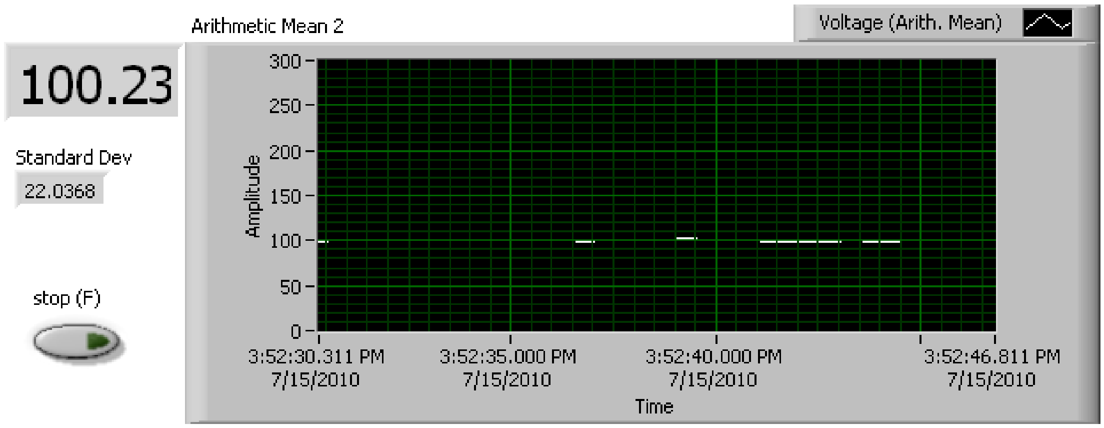

Figure B.3 Flow Meter Reading at a Volume Flow Rate of 100 Gallons per Minute

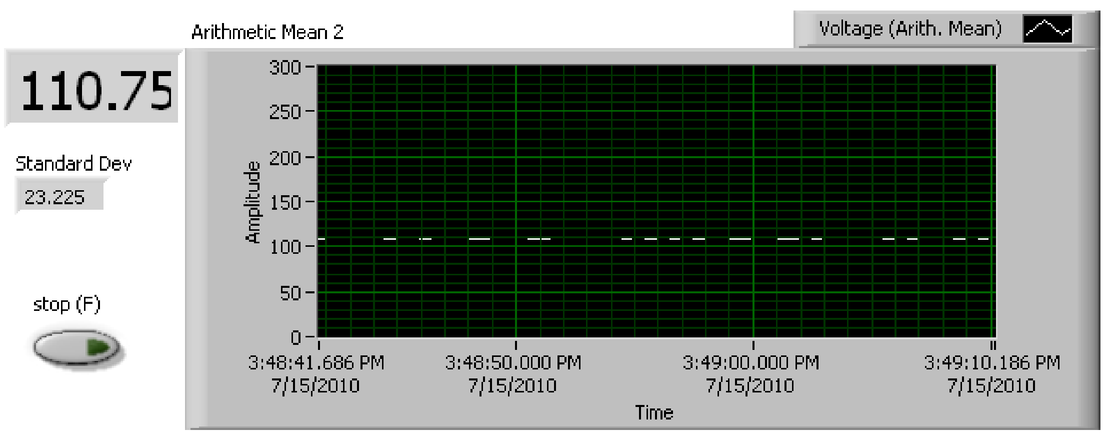

Figure B.4 Flow Meter Reading at a Volume Flow Rate of 110 Gallons per Minute

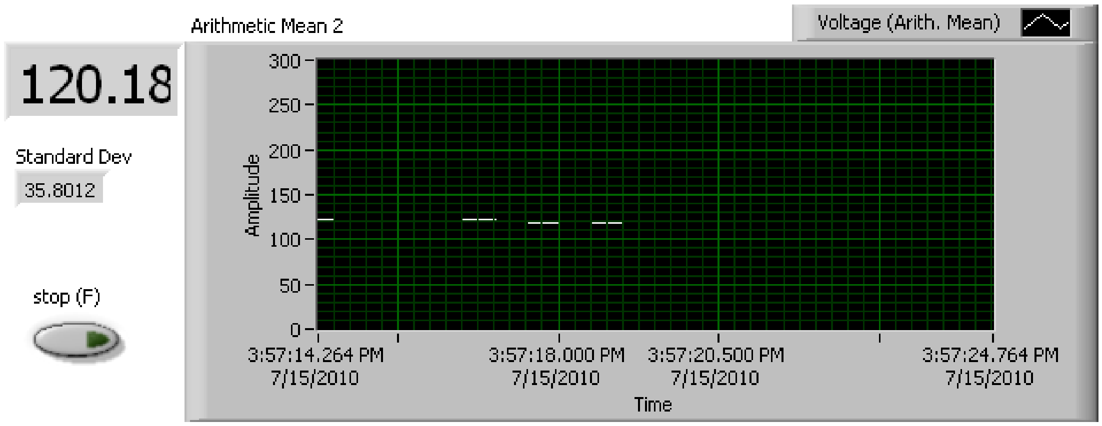

Figure B.5 Flow Meter Reading at a Volume Flow Rate of 120 Gallons per Minute

APPENDIX C

Flow Image Patterns

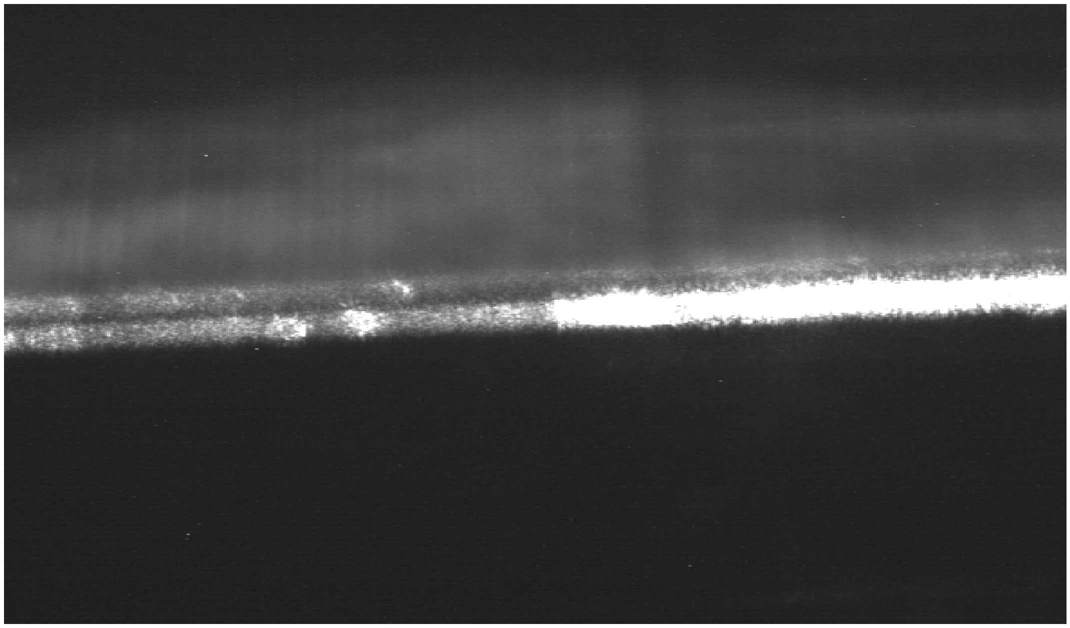

Figure C.1 Flow Pattern at a Flow Rate of 80 Gallons per Minute

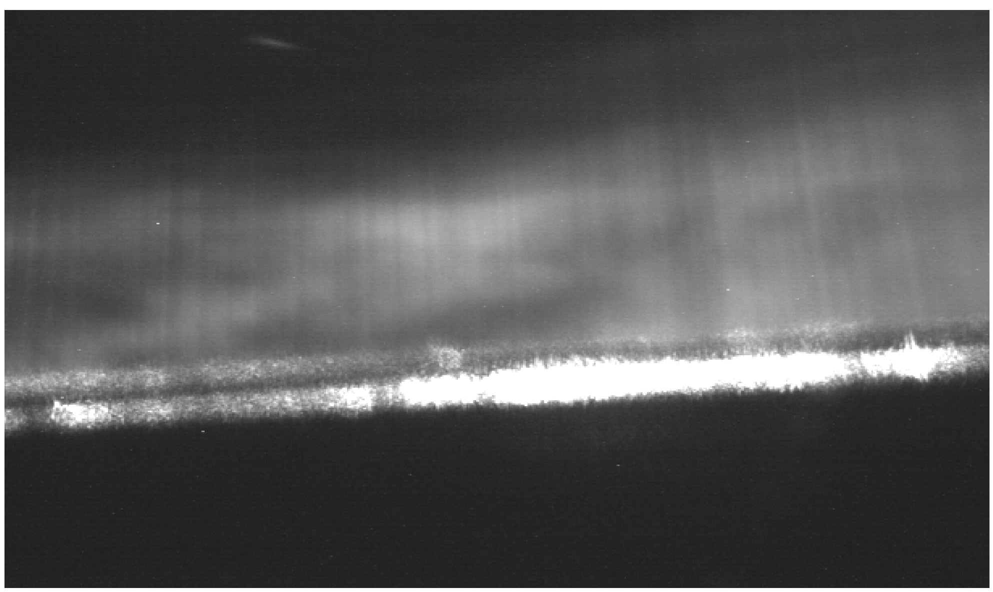

Figure C.2 Flow Pattern at a Flow Rate of 90 Gallons per Minute

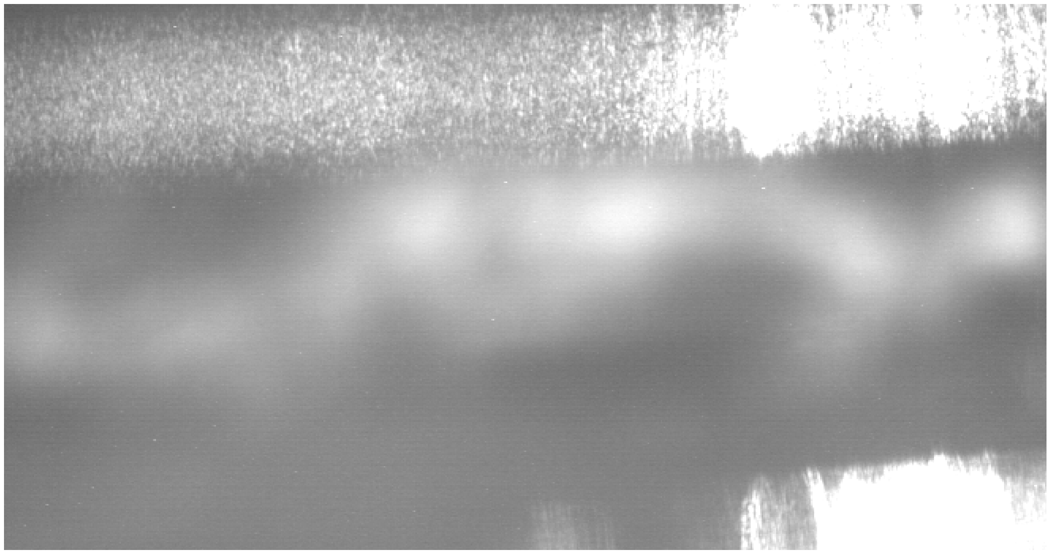

Figure C.3 Flow Pattern at a Flow Rate of 100 Gallons per Minute

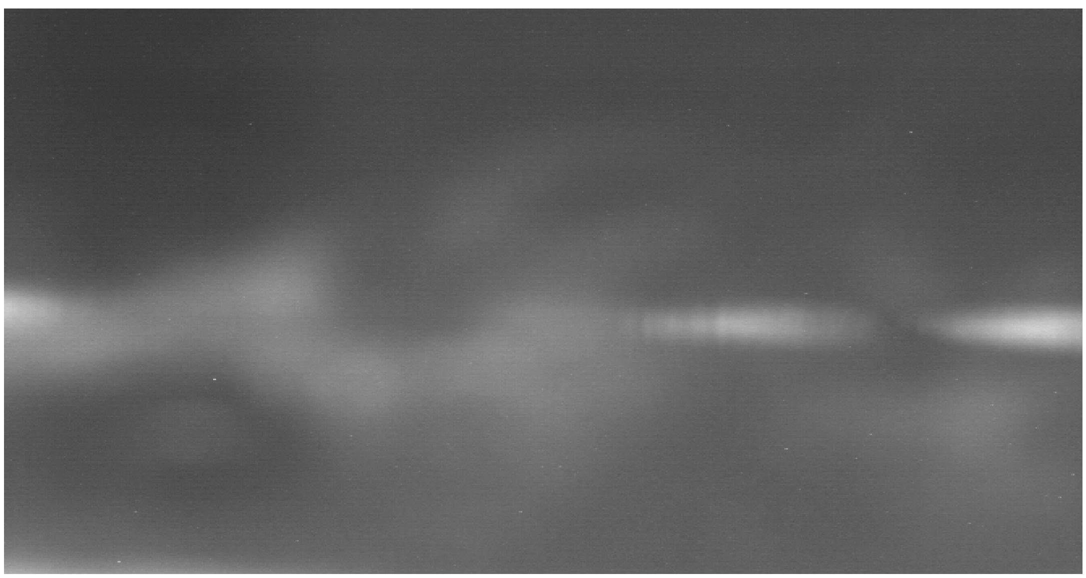

Figure C.4 Flow Pattern at a Flow Rate of 110 Gallons per Minute

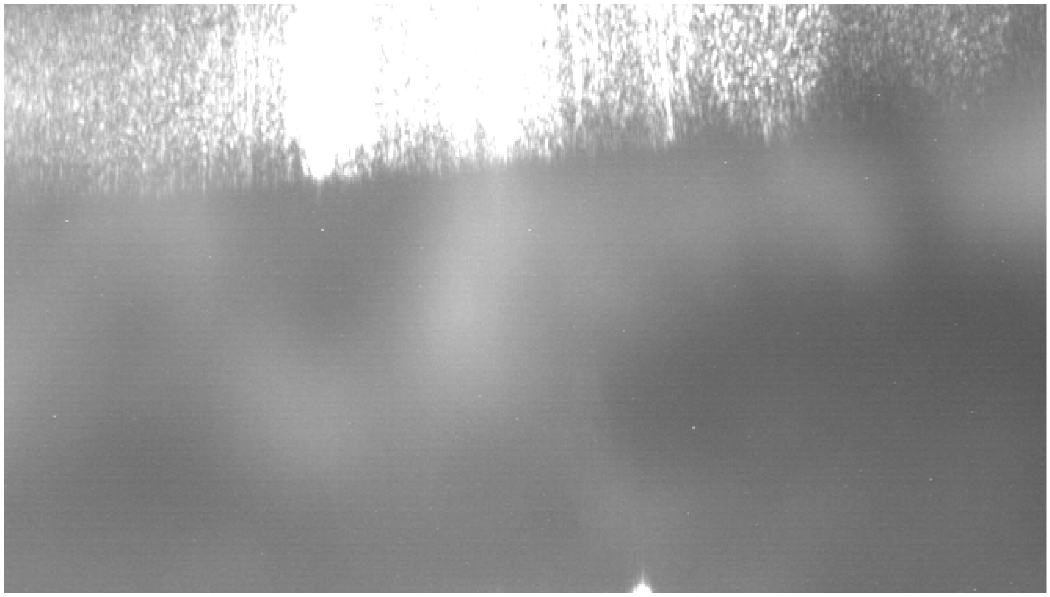

Figure C.5 Flow Pattern at a Flow Rate of 120 Gallons per Minute

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[2] Alison, F., VanMoorhem, W.K., "Vortex Shedding Induced Sound Inside a Cold-Flow Simulation of Segmented Chamber", Journal of Propulsion and Power, Vol.19, No.2, March-April 2003, pp 287-295.

[3] Brown, R.S., Dunlap, R., Young, S.W., and Waugh, R.C., "Vortex Shedding as a Source of Acoustic Energy in Segmented Solid Rockets", Journal of Spacecraft, Vol.18, No.4, 1981, pp 312-319.

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