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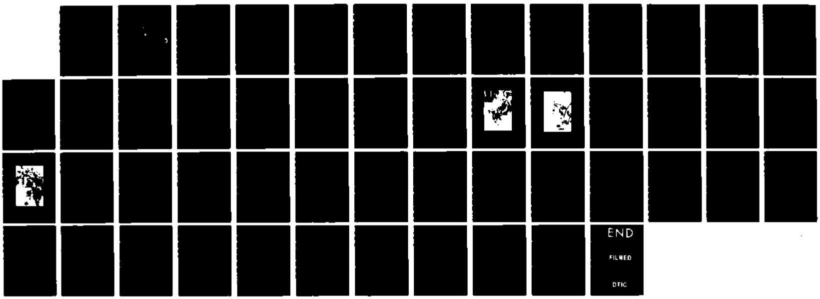

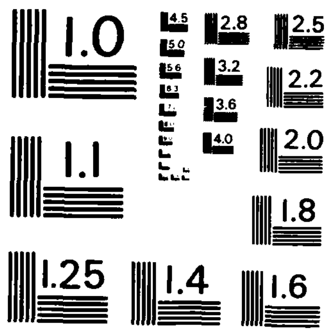

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Monterey, California

THESIS

AN EXPERIMENTAL INVESTIGATION OF COMBUSTION PRESSURE OSCILLATIONS IN BYPASS CONFIGURED SOLID FUEL RAMJETS

by

Daniel Charles Rigterink

September 1985

Thesis Advisor: David W. Netzer

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An Experimental Investigation of Combustion Pressure Oscillations in Bypass Configured Solid Fuel Ramjets

by

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requirements for the degree of

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ABSTRACT

An experimental investigation of the mechanisms involved in combustion pressure oscillations in bypass flow configured solid fuel ramjets was conducted. Testing was done using cylindrically perforated polymethylmethacrylate fuel grains in a solid fuel ramjet with 180^0 opposed dumps into a plenum ahead of an axial dump combustor inlet. Bypass flow into the aft mixing chamber was accomplished using two dumps located either 180^0 or 90^0 apart, perpendicular to the centerline. Split inlet feed line lengths into the plenum were varied with no apparent change of the dominant pressure oscillation frequency of approximately 167 hz for bypass tests. Hot wire measurements indicated that in the short-coupled axial inlet, there were no dominant vortex shedding frequencies in the separation/shear layer or at the reattachment point on the fuel grain wall. The observed pressure oscillation frequency did not appear to be related to vortex shedding from the inlet jet. Coupling of the driving disturbance from bypass flow could possibly be with a longitudinal mode of the combustor or a Helmholtz mode involving the head section plenum.

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TABLE OF SYMBOLS

A	flow area
a	speed of sound
Cd	discharge coefficient
d	diameter of flow passage, cylinder
E	voltage
f	frequency of oscillation
f/a	fuel/air ratio
g_c	acceleration gravity
L	length
M	Mach number
m	mass
$\dot{m}$	mass flow rate
p	pressure
P'	peak-to-peak amplitude of oscillatory pressure
R	gas constant
R_e	Reynolds number
Sr	Strouhal number
T	temperature
t	time
U	velocity
V	volume
x	distance
γ	ratio of specific heats
η	efficiency

ϕ fuel/air equivalence ratio $(f/a)/(f/a)_{stoichiometric}$

SUBSCRIPTS

a	air
aft	rear orifice plate
av	average
b	burn
bp	bypass
c	chamber
ex	experimental
f	final, fuel
h	head
H	Helmholtz
i	inlet
m	mixer
n	nozzle
p	fuel port
pmm	polymethylmethacrylate (Plexiglas)
r	reattachment
t	stagnation
th	theoretical, throat
w	wall, near wall
rms	root mean square value (of oscillation amplitude)

SUPERSCRIPT

$(\bar{\ })$	mean value
$(\ )'$	fluctuation value
$(\ )^*$	sonic conditions, characteristic

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I wish to thank Professor David Netzer for his guidance, patience, and unending enthusiasm in this project. A special thanks is also made to Mr. Glenn Middleton and Mr. Ted Dunton for their continuing cooperation and cheerfulness through all the machining and hot wire apparatus requirements and changes.

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I. INTRODUCTION

Although there has never been an operational solid fuel ramjet (SFRJ) system in the United States there has been considerable research and exploratory development. Interest in SFRJ boosted artillery has been evident since the 1930's. Developmental programs for gun launched applications have been numerous. Recently, a contract entitled "Solid Propellant Advanced Ramjet Kinetic Energy" was initiated by the U. S. Army for the design, development and initial production of flight test vehicles utilizing SFRJ propulsion. Renewed interest in SFRJs occurred when new low cost fuels became available and when the integral-rocket-ramjet packaging concept made tactical applications possible. These fuels also showed very good mechanical properties over previously available fuels. In 1973 the Chemical Systems Division of United Technologies (CSD) completed work on a contract entitled, "Solid Fuel Ramjet Combuster Development". Regression rates and combustion efficiencies for these fuels in nonbypass and bypass configurations were determined to establish a technology base.

In parallel, the Naval Postgraduate School has been active in SFRJ research since 1973. This research has included internal ballistic studies of the SFRJ [Ref. 1], combustion behaviors of various fuels [Ref. 2], SFRJ combuster flow characterisitic [Ref. 3], correlations of SFRJ cold flow and reacting flow [Ref. 4] and investigations of combustion pressure oscillations [Ref. 5]. Numerous other papers and reports done at the Naval Postgraduate School can be cited.

Propulsion systems with solid rocket boost to SFRJ takeover velocities offer some important gains over presently available systems. Inherent in the design of the SFRJ is the absence of fuel tanks, fuel pumps and active fuel controls. The fuel is simply cast or bonded to the motor case. Without the requirement for the oxidizer in the fuel as in a solid rocket, weight and volume penalties for the oxidizer are not felt. This can result in more range or performance for a given weight or volume constraint. Although there are some complexities in the design of systems to effect the transition from solid boost to SFRJ operation, the SFRJ still offers simplicity in overall design. The SFRJ is one of the lowest cost concepts with engine complexity only slightly in excess of a solid rocket system.

Conventional solid rockets used for longer ranges are boost and glide systems. The longer powered range performance of SFRJ's can provide longer times to counter target evasive maneuvering. Thus, simplicity, relative low cost and performance gains can be found in SFRJ systems.

However, the SFRJ design is highly dependent on mission requirements for proper inlet, combuster geometry and fuel property matching. The simple inlet performance losses due to shocks and drag limit the difference between maximum and minimum flight Mach numbers to between 1.5 and 2.0. Flammability limits due to fuel properties and combuster geometries fix the relationship between maximum altitude and flight Mach number. The SFRJ is constrained to keep the air velocity over the fuel grain surface to less than M=.3 for the initial period of the burn. The flameholder design and inlet performance dictate the rich and lean flammability blow off limits for acceleration and cruise performance. The gains in performance, cost and simplicity are traded somewhat for flexibility.

One area of considerable interest for the design of SFRJ inlets/combustors is that of combustion driven pressure oscillations during operation. This oscillatory operation is undesirable for reasons of vibrational effects on guidance systems, uncontrolled impulse, effects of inlet shock interaction and decreased performance with lower combustion efficiencies.

In 1981 Metochionakis, et al [Ref. 2] observed pressure oscillations with bypassed configured polymethylmethacrylate (PMM) fuel grains. The result was a lower combustion efficiency (η) due to increases in fuel regression rates ($\dot{r}$) and/or increased equivalence ratio (ϕ) in comparison to tests with similar nonbypass fuel grain lengths. It was not possible to determine whether the decreased performance was due to the presence of the pressure oscillations or the increased equivalence ratio ϕ. The oscillations were eliminated by sonically choking the primary and bypass air flows. However, the bypass air still adversely affected the combustion efficiency probably by quenching the combustion process occurring in the aft mixing chamber as depicted in Figure 1.

In 1982 Begley [Ref. 6] found an increase of approximately 5% in efficiency with bypass configurations over nonbypass configurations with sonically choked air inlets. With non-sonically choked air inlets and bypass operation, high efficiencies with low equivalence ratios and low efficiencies with high equivalence ratios were found during unstable

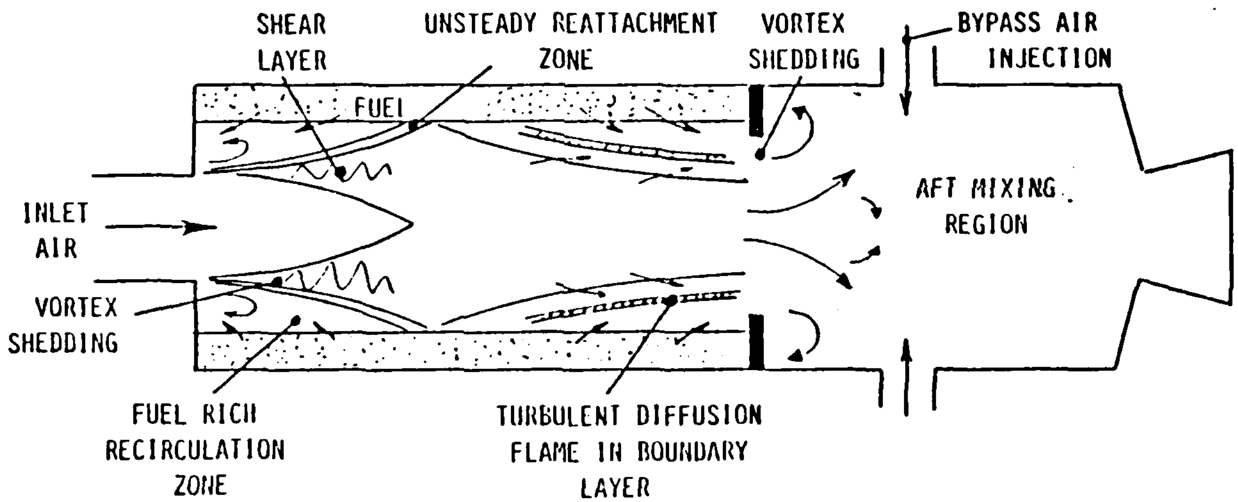


Figure 1

Axial Dump Solid Fuel Ramjet Combustor

operation. The pressure oscillations appeared to always increase the fuel pyrolysis rate but have different effects on the combustion efficiency, depending on the equivalence ratio. When φ was near unity within the fuel port (lean overall) the combustion process was enhanced and when φ was greater than unity the process was degraded.

Although it was seen that isolating the inlet feed system by sonic chokes did prevent the pressure oscillations from occurring, the actual mechanisms causing the coupling with the bypass air injection and overall causal factors were not understood. In Figure 1, some possible mechanisms capable of causing periodic disturbances and ensuing periodic energy releases are shown. They are: 1) vortex shedding at the inlet dump plane or aft mixer dump lane, 2) shear layer disturbances at the air inlet or aft mixing chamber inlet, 3) reattachment zone disturbances, and 4) chemical reaction rate variations in the flame stabilization or boundary layer combustion regions.

The expected driving mechanism for the disturbances is the bypass air injection into the aft mixing chamber. As these bypass jets impinge upon the main combustion flow, turbulence/distortion results. This downstream disturbance is then thought to affect the upstream conditions in the fuel grain area. In cold flow studies by Binn, Scott, and Netzer [Ref. 3] the oscillation behavior was thought to be linked to the interaction of the bypass air with one of the shear layers at the air inlet or aft orifice plate. In the same study it was seen that bypass air configurations had near-wall turbulence intensities in the fuel port that were higher than for the nonbypass tests.

In 1984 Parafiorito [Ref. 5] concluded that a possible explanation of the oscillations in bypass flow configurations is that the bypass flow induced disturbances are transmitted upstream to the flow reattachment zone. The oscillations of the reattachment zone could then cause oscillatory combustion in the flame-holder recirculation zone volume and/or in the turbulent boundary layer diffusion flame that develops downstream of the flow reattachment zone. It was then thought that this oscillatory energy release could couple with the inlet feed line acoustics. It was also found that the volume of the recirculation zone, the magnitude of distance between the inlet exit plane and the reattachment zone (X_r) and the total volume of the fuel port had no large effects on the frequency or the amplitude of the observed oscillations. Changes to the velocity of the bypass air and the aft mixer volume did have an effect on the amplitude of the oscillation, but not the frequency.

Other possible drivers of combustion instabilities or pressure oscillations have been reported by Schadow [Ref. 7, Ref. 8]. Studies were made of the fluid dynamic processes occurring in the shear layer near the inlet dump plane and their effect in driving the acoustic oscillations in the combustors. The vortex pairing and merging from the inlet jet were thought to be sources of acoustic energy. Large scale coherent flow structures were generated when the inlet vortex shedding frequencies matched the acoustic frequencies of the combustors.

In this investigation, tests were conducted using the Naval Postgraduate School Ramjet facility to determine the relationships of the coupling mechanisms with bypass air as the driver of combustion pressure oscillations. The near wall turbulence and inlet vortex shedding frequencies were measured in bypass and nonbypass configurations in cold flow tests using a hot wire anemometer. The acoustic lengths of the inlet feed system were varied in reacting flow tests to determine possible coupling modes.

II. DESCRIPTION OF APPARATUS

A. RAMJET MOTOR

The ramjet motor used in this series of experiments at the Naval Postgraduate School Ramjet facility has been the focus of many investigations. Figure 2 is a schematic diagram of the SFRJ motor. The head section takes two inlet feed lines that impinge flow on a wedge to turn the flow 90^{0}. The test fuel grains, in this test series, were cylindrically perforated polymethyl-methacrylate (PMM) grains, bolted in place between the head section and the aft mixing chamber. This arrangement allows flexibility in fuel grain lengths and geometries with fixed instrumented components. The inlet feed lines and bypass feed lines may also be varied. Figures 3 and 4 show the SFRJ assembly with the normally installed feed line system and the feed line system used in this test series to allow variations of the inlet feed system. The bypass lines and exhaust nozzle are in the foreground. The schematic setup and nomenclature of the inlet feed system is given in Figure 5.

Strain gage pressure transducers and thermocouple probes were used to obtain steady state pressure and temperature measurements. Piezo-electric pressure transducers were used to record oscillatory pressures. Signals from the transducers were recorded by a Hewlett Packard (HP) 9836 computer controlled data acquistion system and a Honeywell 1508 Visicorder system. The transducer locations are given in Figure 6.

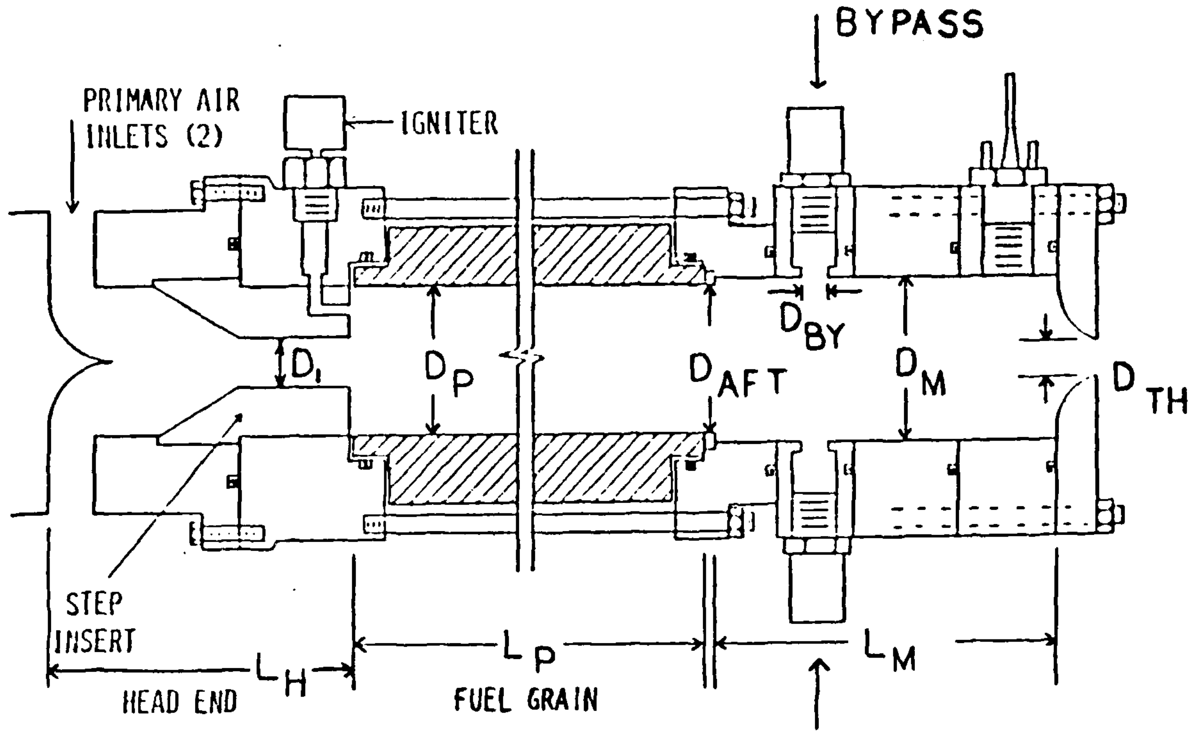


Figure 2

Schematic of Naval Postgraduate School
Solid Fuel Ramjet

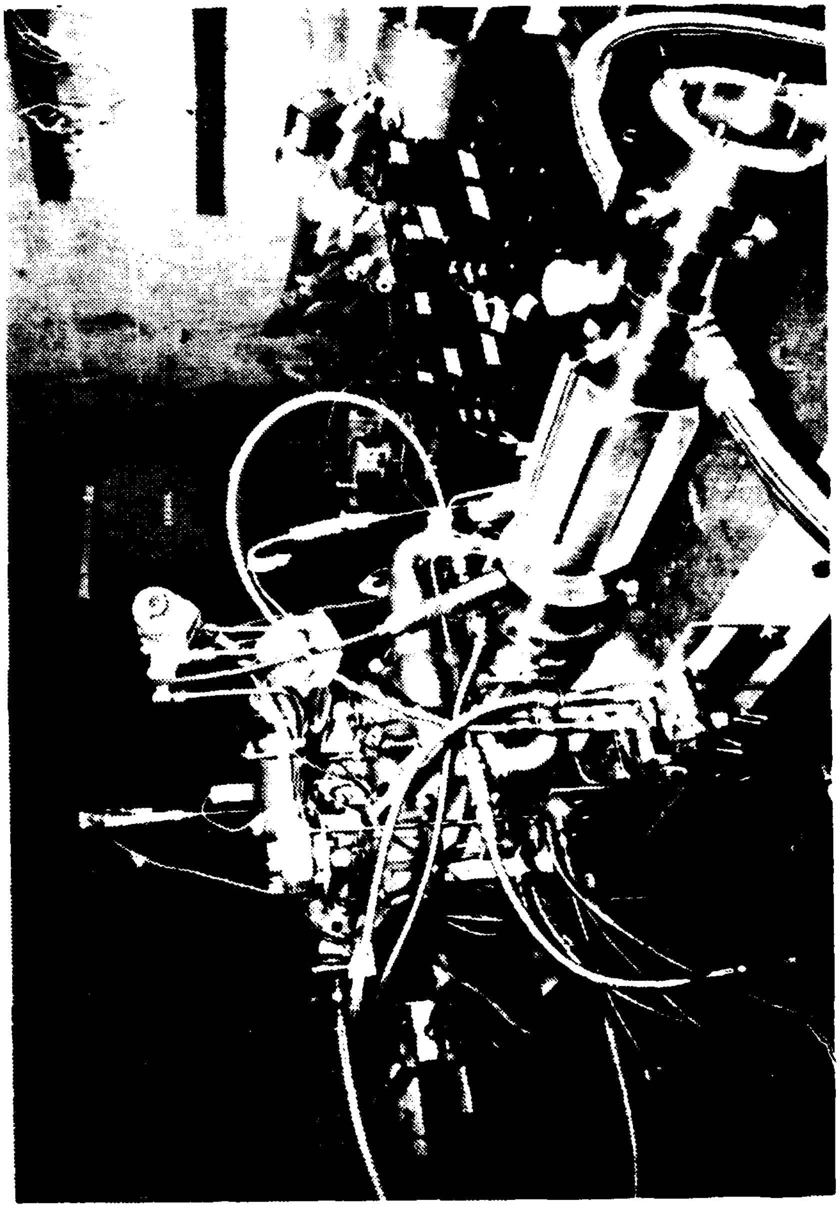


Figure 3

Original Split Inlet Feed Configuration

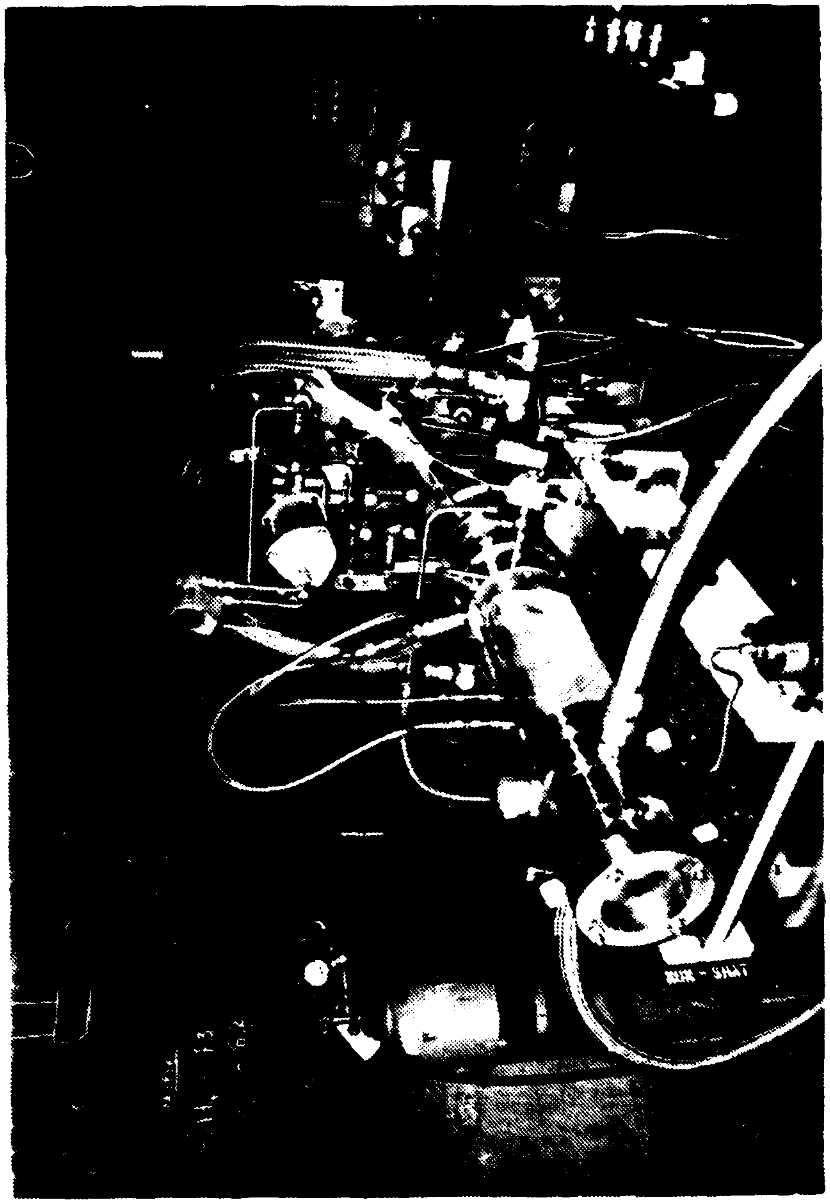


Figure 4

Modified Split Inlet Feed Configuration

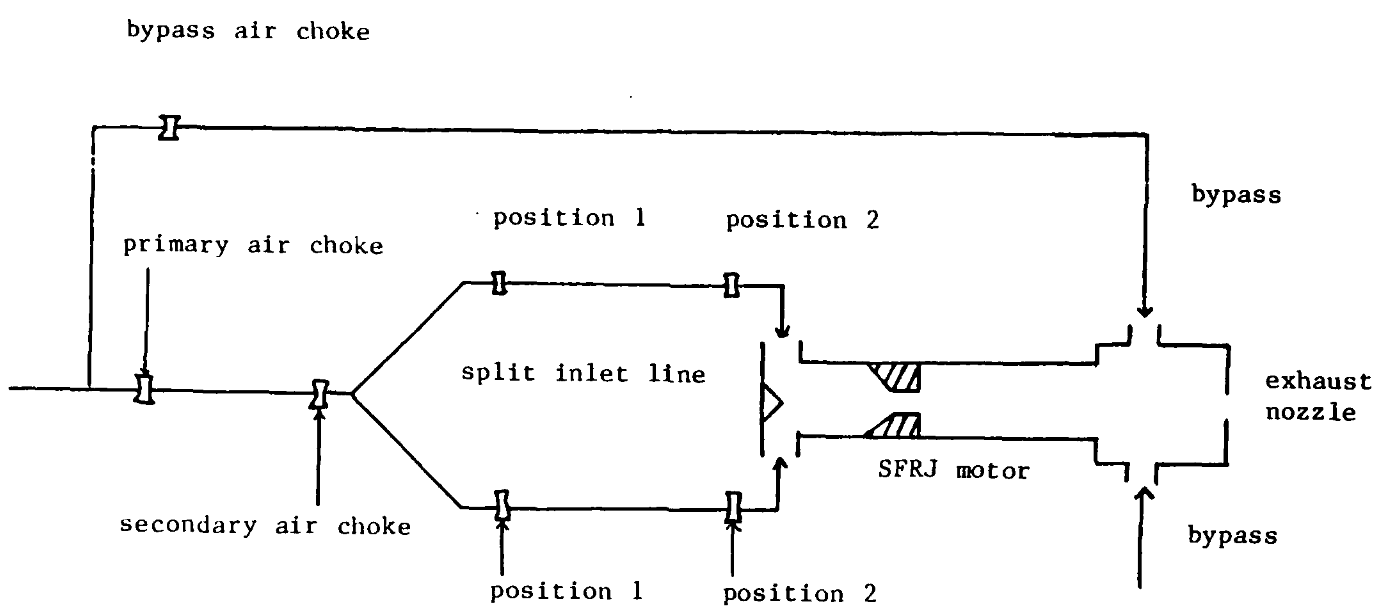
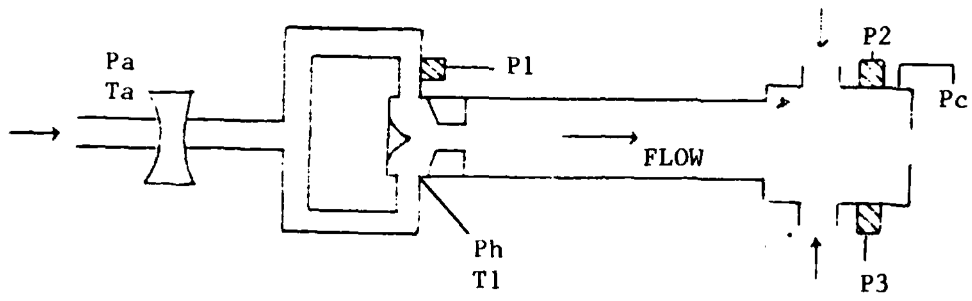


Figure 5

Modified Inlet Feed System Schematic



SFRJ Motor

Pa - pressure primary airchoke

Ph - pressure head

Pc - pressure aft chamber

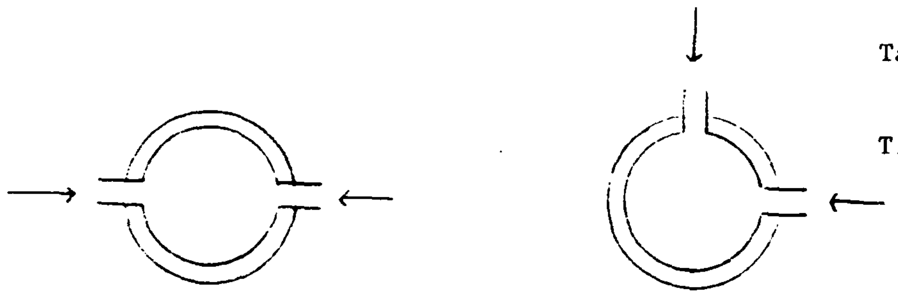
P1 - pressure head Kistler #1

P2 - pressure chamber Kistler #2

P3 - pressure chamber Kistler #3

Ta - temperature primary airchoke

T1 - temperature inlet



180^0 bypass air 90^0 bypass air

Aft Mixing Chamber Bypass Configurations

Figure 6

Transducer Locations and Bypass Configurations

B. AIR SUPPLY AND CONTROL SYSTEM

Figure 7 shows a schematic of the SFRJ air supply system. Tests were run from a control room where the primary inlet air pressure was remotely controlled, thereby controlling the flow rate through sonically choked flow nozzles. Solenoid-operated valves on primary air, ignition gas and purge gas lines were also controlled by the HP 9836 computer to allow fully automated test sequences for the reacting flow tests.

C. HOT WIRE ANEMOMETER SYSTEM

A Thermal System Incorporated 1054A series constant temperature hotwire anemometer was used with a single wire positioned normal to the flow direction. The non-linearized signal from the hot wire was used as input to a Spectral Dynamics SD335 Real Time Analyzer to determine the signal frequency content. An ensemble time averager was used to enhance the signal to noise ratio. An x-y plotter connected to the spectrum analyzer gave rms voltage vs. frequency plots. Figure 8 shows the hot wire probe traverse mechanism in place with the probe in the vortex shedding region of the inlet dump plane. Inlet shear layers and near-wall areas were surveyed as depicted in Figure 9.

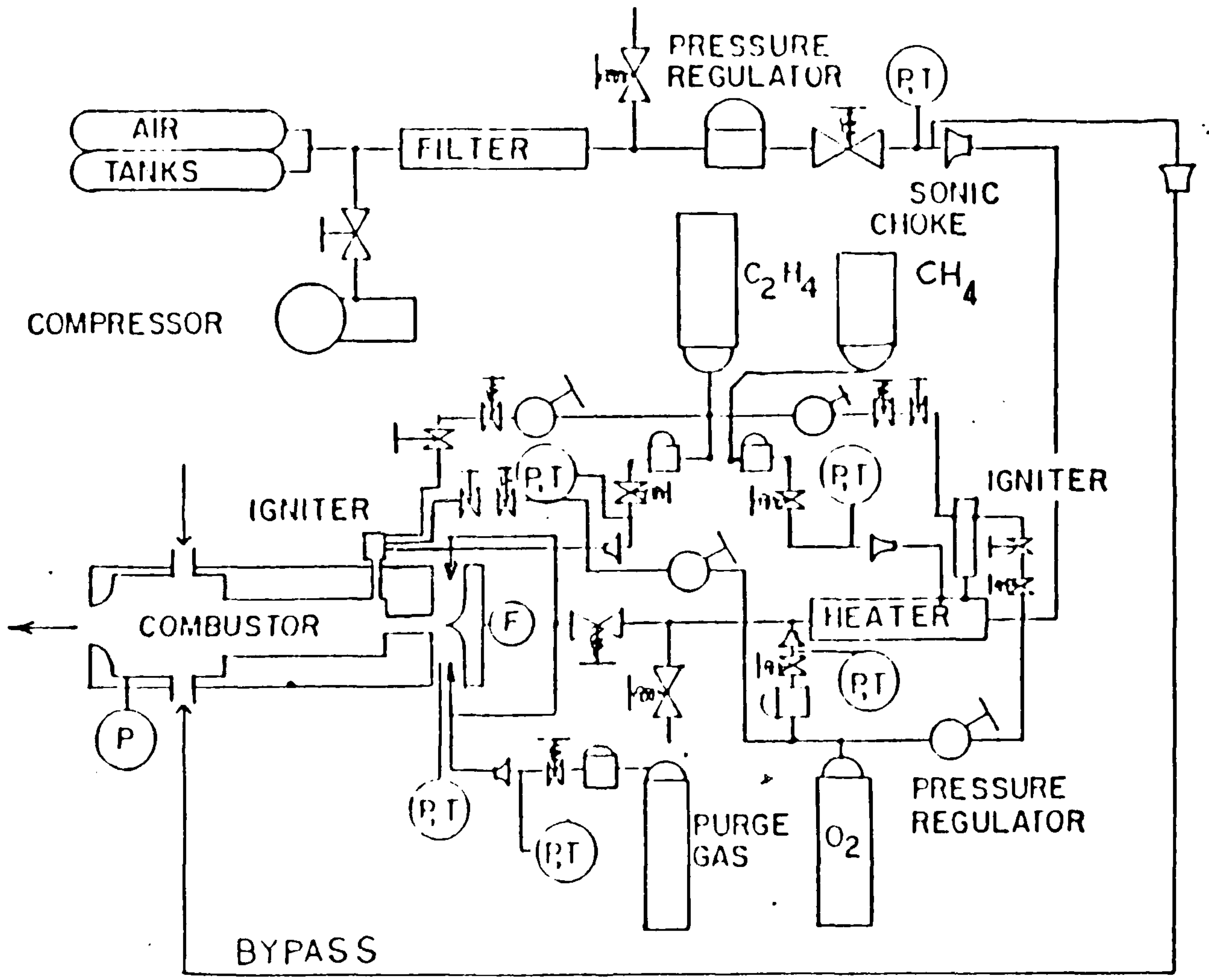


Figure 7
Schematic of Air Supply System

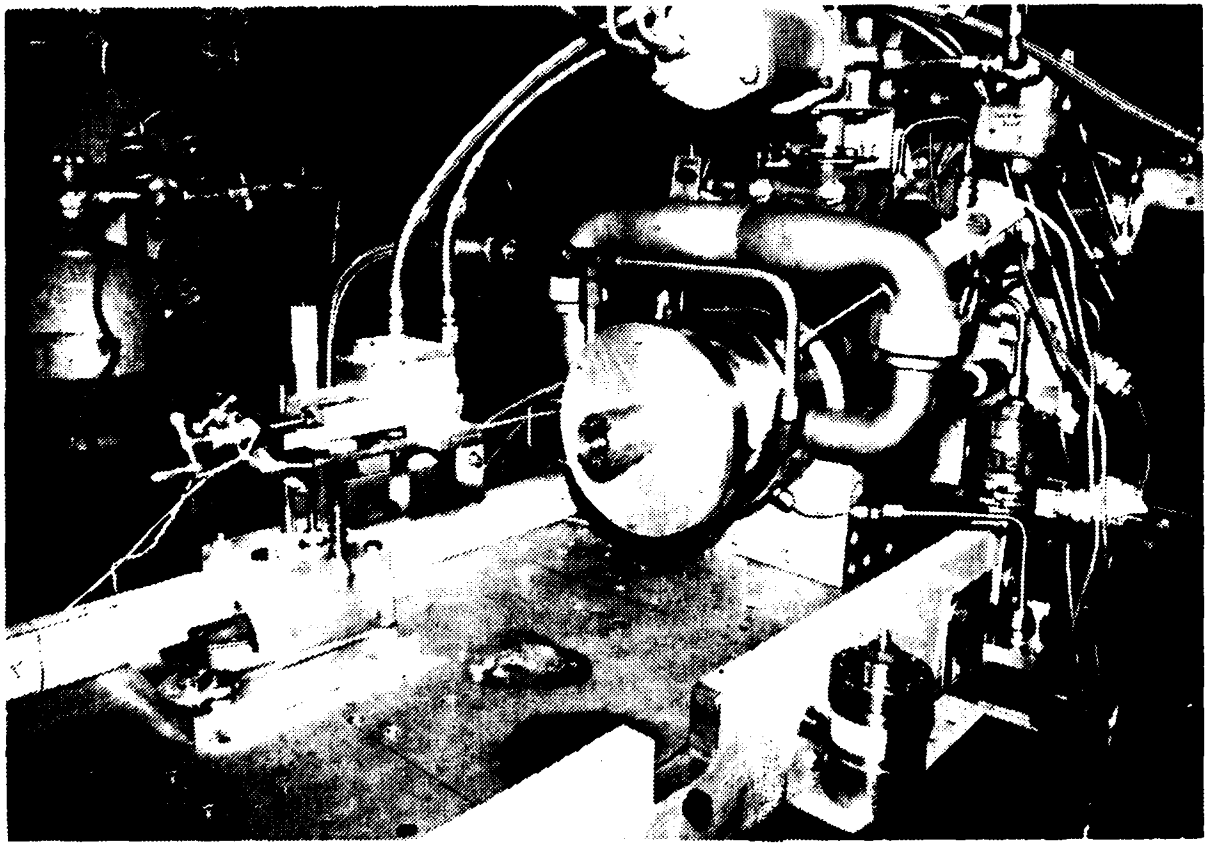


Figure 8

Hot Wire Traverse Mechanism at Inlet Jet

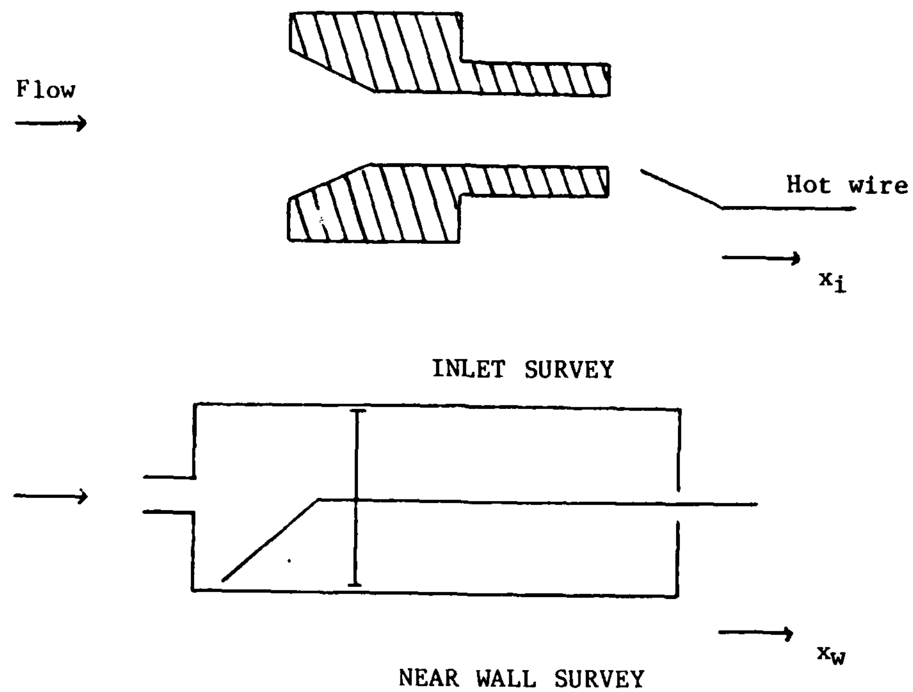


Figure 9

Hot Wire Survey Positions

III. EXPERIMENTAL PROCEDURES

A. CALIBRATIONS

The transducers for the primary air line, bypass air line, head and chamber pressures were calibrated over the expected ranges of operating pressures prior to each series of runs with a dead-weight tester. The Kistler water-cooled piezo-electric transducers were calibrated with a step input from the dead weight tester.

The hot wire apparatus was not velocity calibrated since the frequency content of the signal was the only desired data. The vortex shedding frequencies behind various small cylinders were measured to insure proper frequency response. Using data in Schlichting [Ref. 10] by A. Roshko, the Strouhal number (Sr) for the experimental Reynolds number (Re_{ex}) was determined. Knowing the Strouhal number, the diameter of the cylinder (d) and the velocity of the flow (U), the frequency could then be determined by

$$f = \frac{Sr\ U}{d} \quad \text{with } Sr = \text{func}[Re_{ex}]$$

The computed frequencies and measured frequencies were within 20%. The non-linearized hot wire signal was ensemble averaged and an ensemble averaged noise signal at zero flow rate was subtracted from the spectra.

B. DATA EXTRACTION

The signals from the Kistler pressure transducers were recorded on a Honeywell 1508 Visicorder along with ignition gas sonic choke pressure (P_{if}), purge gas sonic choke pressure (P_p) and primary air sonic choke pressure (P_a). The Visicorder was nominally run at 40 inches per second with 0.01 second timing divisions.

Inlet air temperature (T_i), primary air temperature (T_a), head section pressure (P_h), chamber pressure (P_c) and also primary air sonic choke pressure (P_a) were digitally scanned and recorded by the Hewlett Packard 9836 data acquisition system. The flow rate ($\dot{m}$) of the primary air flow was program calculated.

C. REACTING FLOW

The airflow rate was set by remotely controlling the dome pressure of the primary air pressure regulator. By controlling the pressure (P_a) upstream of primary air sonic chokes, knowing the sonic choke diameter, and the primary air temperature (T_a), the flow rate ($\dot{m}$) could then be calculated by

$$\dot{m} = C_d \; P_t \; A^* \sqrt{\frac{g_c \; \gamma}{R \; T_t} \; \frac{2}{\gamma+1}^{\left[\frac{\gamma+1}{\gamma-1}\right]}}$$

where the discharge coefficient, C_d, was assumed to be 0.97. The measured pressures and temperatures were considered to be stagnation values since the flow Mach numbers were very low.

The PMM fuel grains were ignited with a 3-second burst of an ethylene/oxygen torch and ethylene ignition gas injected into the head-end recirculation zone. Each run was terminated by terminating the primary air flow and purging the SFRJ motor with nitrogen for 5 seconds. Each run was initially computer controlled for initial air flow, ignition, reacting flow, and purge flow. Some runs were terminated prior to computer selected times once an oscillation had stabilized and been recorded.

The burn times (t_b) average chamber pressure ($\overline{P_c}$) flow rates ($\dot{m}_{pri}$ and $\dot{m}_{bp}$) and average air inlet temperature ($\overline{T_i}$) were computed from the HP 9836 output. The amplitude and frequency of the pressure oscillations were determined from the Visicorder outputs.

D. COLD FLOW

The airflow was set as in the reacting flow tests, with care being taken to increase the flow slowly (ramp) to avoid mechanically breaking the .00015 in. diameter, platinum coated tungsten hot wire. Once the desired air flow rate was reached, the ensemble averaging of the hot wire signal was initiated on the spectrum analyzer. The hot wire probe was placed at increasing distances from the inlet dump plane and along the wall of the PMM grain as depicted in Figure 9. For the near-wall measurements the probe was started at 0.28 in. from the dump plane and moved in 0.5 in. increments in the axial direction for a distance of 5 in. from the dump plane for both bypass and nonbypass airflow configurations. The probe was located 0.155 in. from the wall. For the inlet shear layer, measurements of the unducted jet from the inlet nozzle were taken at various x-direction (axial) distances up to 2.5 in.

IV. RESULTS AND DISCUSSION

A. INTRODUCTION

Cold flow tests were initially conducted utilizing the hot wire setup to look at the shear layer regions of the unducted jet from the inlet step. Near-wall surveys were then made in the nonbypass and bypass configurations with the inlet feed system as shown in Figure 3 and Figure 8. This configuration of short, split inlet feed lines was made in conjunction with the installation of a new vitiated air heater and constituted an improvement of the Naval Postgraduate School Ramjet facility capabilities for thrust measurement. However, no major dominant frequencies were noted in a large series of hot wire probe surveys. A typical spectrum is shown in Fig. 10. A series of reacting flow runs were then made that verified that the SFRJ motor operation was stable with the new shortened inlet feeds in bypass and nonbypass configurations. The possibility that shedding vortices from the inlet could be responsible for the instabilities in earlier investigations remained plausible.

The split inlet feed system was then modified as shown in Figure 4 and schematically represented in Figure 5. This configuration eliminated the tight inlet turns and the air heater. Reacting flow tests were then conducted with various split inlet line lengths. They were physically changed or effectively changed for acoustical length purposes with sonic chokes or flow restrictors. The split inlet line lengths are listed in Table 1. The choke and restrictor positions are given in Table 2. Inlet configurations that resulted in oscillatory operation and stable operation were then examined again in cold flow tests with the hot wire probe.

B. PRESSURE OSCILLATIONS

The test variation sequence for the reacting flow tests are given in Table 3. Table 4 gives the reacting flow results for air flow rates, average pressures, and average temperatures. The pressure oscillation characteristics are compiled in Table 5. A summary of the configurations giving oscillatory operation is shown in Table 6.

In Table 6, it is noted that combustion pressure oscillations occurred in all configurations except two. A nonbypass air flow configuration and a configuration with physically unsymmetrical split inlet line lengths showed operation with no coherent oscillations. These were runs 4 and 5 respectively. The P'/P_c % values were approximately 10% or less for run 4 and slightly greater than 10% for run 5. It is noted that these runs generally had pressure fluctuations with smaller amplitudes then the coherent oscillations. The tests resulting in coherent oscillation that had amplitudes close to that of runs 4 and 5 were the 90^0 dump bypass runs where the energy of the driving mechanism was probably reduced from the 180^0 opposed configuration.

Referring to Table 5 it is seen that coherent oscillations were generally in the range of 167 hz with an average P'/P_c % of approximately 16%. The variations in split inlet line lengths did not seem to affect the frequency of coherent oscillations to any great

TABLE 1
INLET AND BYPASS CONFIGURATIONS

RUN	INLET FEED EFFECTIVE LENGTH (IN) RIGHT*	LEFT	BYPASS AIR INPUT
#1	46	46	180^0
2	46	46	180^0
3	46	46	180^0
4	46	46	180^0
5	46	101	180^0
6	46	46	180^0
7	46	46	180^0
8	67	67	180^0
9	67	67	180^0
10	29	29	180^0
11	67	67	180^0
12	67	67	90^0
13	67	67	90^0
14	10	10	180^0
15	46	10	180^0

*facing in direction of flow
effective length due to flow restrictors or sonic chokes

TABLE 2

CHOKE POSITIONS

AIR SONIC CHOKE (DIAMETER IN.)

Run #	Primary	Bypass	Secondary	Position 1	Position 2
1	.128	.128	.1935	-	-
2	.128	.128	.1935	-	-
3	.128	.128	-	-	-
4	.128	no bypass	-	-	-
5	.128	.128	-	-	-
6	.128	.128	-	-	-
7	.128	.128	-	-	-
8	.128	.128	-	-	-
9	.128	.128	-	-	-
10	.128	.128	-	-	-
11	.128	.128	-	-	-
12	.128	.128	-	.148/both side	-
13	.128	.128	-	-	-
14	.128	.128	-	-	.148/both side
15	.128	.128	-	-	.148/one side

- indicates not installed

TABLE 3

TEST VARIATION SEQUENCE

RUN	VARIABLE	CONDITION (IN.)	PURPOSE/REMARKS
1	nominal	L_i split=46, d_i=.5 dp=1.5, d_{aft}=2.12, d_{bp}=.81, Lp=12, Lm=6.22, d_{th} = .73 bypass 180^0 opposed, Secondary choke installed	baseline oscillation check
2	recorder output	decreased range output on Kistler amplifiers	increased oscillation amplitude for recorder.
3	primary inlet feed line length	removed secondary choke	increase of primary inlet feed length by 645%
4	downstream disturbance	no bypass airflow	remove downstream disturbance
5	split inlet feed line length	increase one side of split inlet feed line length by 120%	remove possible split inlet feed line coupling
6	split inlet feed line length	equalize split inlet feed line lengths	verify oscillation baseline
7	split inlet feed line length	equalize split inlet feed line lengths	repeat due to recorder failure
8	split inlet feed line length	increase both sides of split inlet feed line length by 46% from baseline	increase acoustic cavity length of inlet feed system
9	split inlet feed line length	increase both sides of split inlet feed line length by 46% from baseline	verify increased volume configuration
10	split inlet feed line length	install flow restrictors at position 1 both sides to reduce split inlet feed line length by 37% from baseline configuration	decrease acoustic cavity length of inlet feed system

TABLE 3 (CONT.)

TEST VARIATION SEQUENCE

RUN	VARIABLE	CONDITION	PURPOSE/REMARKS
11	split inlet feed line length	remove flow restrictions at position 1 both sides	re-verify increased acoustic cavity length of inlet feed system
12	bypass configuration	make bypass configuration 90^0 opposed	change downstream disturbance
13	bypass configuration	make bypass configuration 90^0 opposed	verify and repeat due to recorder malfunction
14	split inlet feed line length	install flow restrictors at position 2 both sides of split inlet lines to reduce length by 78% from baseline	decrease acoustic cavity length of feed system
15	split inlet feed line length	install flow restrictors at position 2 for one side only to reduce its length by 78% from baseline	remove possible split inlet feed line coupling

TABLE 4

REACTING FLOW RESULTS

RUN	TIME(SEC) BURN	FLOW RATE (LBM/SEC) PRIMARY	BYPASS	TOTAL	$\overline{P}c$ (psia)	$\overline{T}i$ (^{0}R)
1	33	.106	.106	.212	48.9	528.5
2	35	.106	.106	.212	49.9	501.8
3	10.5	.107	.107	.214	53.8	518.7
4	12.5	.199	0	.199	55.6	512.4
5	11.5	.104	.104	.208	40.7	526.3
6	8	.099	.099	.198	37.9	523.4
7	13	.104	.104	.208	38.9	510.5
8	38.5	.090	.090	.180	31.4	520.5
9	9	.105	.105	.210	35.3	515.0
10	12.5	.100	.100	.200	34.6	522.8
11	8.5	.105	.105	.210	38.6	525.4
12	13	.102	.102	.204	38.7	528.4
13	14	.103	.103	.206	40.5	523.8
14	9.5	.102	.102	.204	37.9	522.6
15	9	.102	.102	.204	41.4	524.7

TABLE 5

PRESSURE OSCILLATION CHARACTERISTICS

RUN	TRANSDUCER NUMBER						REMARKS
	1		2		3		
	$\frac{P'}{P_c}$ (%)	freq (HZ)	$\frac{P'}{P_c}$ (%)	freq (HZ)	$\frac{P'}{P_c}$ (%)	freq (HZ)	
1	8.6	160	9.0	160	12.3	160	baseline
2	8.8	156	17.7	156	29.9	156	readjust transducer attenuation for baseline #1
3	7.6	162	14.7	162	26.4	162	increase primary inlet length by 644%
4	4.0	NCO	7.9	NCO	10.3	NCO	*no bypass*
5	7.3	NCO	10.8	NCO	14.7	NCO	unsymmetrical split inlet feed line length increase by 120%
6	-	-	-	-	-	-	recorder malfunction
7	7.7	166	19.3	166	21.8	166	verify baseline #1
8	-	-	26.8	175	-	-	symmetrical split inlet feed line length increase by 46%
9	-	-	11.9	162	-	-	verify split inlet feed line length increase #8

NCO no coherent oscillations
- indicates not installed

P´ amplitude peak to peak
% change refer to baseline dimensions

TABLE 5 (CONT.)

PRESSURE OSCILLATION CHARACTERISTICS

RUN	TRANSDUCER NUMBER						REMARKS
	1		2		3		
	$\frac{P'}{P_c}$ (%)	freq (HZ)	$\frac{P'}{P_c}$ (%)	freq (HZ)	$\frac{P'}{P_c}$ (%)	freq (HZ)	
10	–	–	13.0	169	–	–	symmetrical reduction of split inlet feed length by 37%
11	–	–	21.8	172	–	–	verify run #8
12	–	–	15.2	167	–	–	bypass flow 90^0 opposed input
13	–	–	16.4	170	–	–	verify bypass flow 90^0 opposed input
14	–	–	18.7	173	–	–	symmetrical reduction of split inlet feed line lengths by 78%
15	–	–	18.4	170	–	–	unsymmetrical reduction of split inlet feed line lengths by 78%

NCO no coherent oscillations
– indicates not installed

P´ amplitude peak to peak
% change refer to baseline dimensions

TABLE 6

PRESSURE OSCILLATION SUMMARY

CONFIGURATION (RUN)	COHERENT OSCILLATION	REMARKS/CHANGES
A (1,2)	yes	baseline
B (3,6,7)	yes	increase primary inlet feed line length
C (4)	no	no bypass flow
D (5)	no	unsymmetrical split inlet feed line length increase
E (8,9,11)	yes	symmetrical split inlet feed line length increase
F (10)	yes	symmetrical split inlet line effective length reduction
G (12,13)	yes	bypass flow 90^0 opposed input
H (14)	yes	symmetrical split inlet line effective length reduction
I (15)	yes	unsymmetrical split inlet line effective length reduction

degree. The recorded oscillation amplitudes from the Kistler P_1 transducer (inlet feed system) were much less than those from the aft mixing chamber. This is thought to be due to the small volume of the inlet feed line and the 90^0 location to the axial flow position of the transducer on the inlet feed line to the combustor. There was also a phase difference of approximately 30^0 lead or 330^0 lag. This indicates that the measured oscillation was probably a longitudinal wave rather than a bulk mode, in contrast to the results of Parafiorito [Ref. 5].

The measured frequency of approximately 167 hz could possibly be that of a longitudinal acoustic mode with an open-closed cavity where

$$f_1 = \frac{a}{4L}$$

with $\bar{a}_{520^0R} \cong 1117$ft/sec. and L of the combuster = 1.52ft., f $\cong$ 184 hz. An effective length of approximately 1.67 ft. would be needed to yield f $\cong$ 167 hz. If the length through the inlet nozzle to the head section wall was included, the length (L) would then be approximately 1.80 ft., resulting in a frequency of 156 hz. Due to the changes in the diameter of the cavity the effective acoustical length could yield frequencies of the first longitudinal mode with an open-closed cavity in the range of 167 hz. Parafiorito [Ref.6] varied the fuel grain and the aft mixing chamber lengths and noted no change in frequency. Further tests are needed to determine the dependence of frequency on length. Mady and others [Ref. 10] did report frequencies of about 150 hz in similar length test grains and amplitudes of approximately 20% of chamber pressure.

In trying to match the noted frequency with theory, consideration of Helmholtz or bulk mode oscillations was also made. The Helmholtz frequency, f, is given by

$$f = \frac{\bar{a}}{2\pi} \left[\frac{A_{in}}{l_{in} V_h} \right]^{1/2}$$

Using $\bar{a}_{520\,^0R} \cong 1117$ ft/sec. = 1.34×10^4 in/sec, a length of inlet nozzle (l_{in}) ≅ 3 in. an area of inlet nozzle (A_{in}) ≅ .196 in^2 and a volume of head section (V_h) ≅ 10 in^3 yields $f_H \cong 173$ hz.

The head section volume had not been changed between Parafiorito's tests and this series. However, Parafiorito [Ref. 5] did vary A_{in} with no effect on frequency. These results indicate that the frequency of both Helmholtz and longitudinal acoustic modes can be made to agree closely with the measured frequency. However, systematic variations in geometry did not result in expected frequency changes.

C. INLET SHEAR LAYER HOT WIRE RESULTS

The spectra recorded showed no dominant frequencies in shear layer regions of the inlet nozzle jet. Schadow [Ref. 7 and 8] measured vortex shedding frequencies in both free jets and confined jets and found a preferred jet frequency at the end of the jet core region. This was believed to be a result of vortex pairing and merging. In his test setup [Ref. 7] the flow was well developed in 8 pipe diameters behind a series of flow straighteners. In the Naval Postgraduate School SFRJ facility tests, the length of the free jet inlet nozzle was 4 pipe diameters with 90^0 turning flow prior to the inlet, and no flow straighteners. It is felt that developed pipe flow is needed to generate the coherent structures due to vortex pairing as in References 7 and 8.

It was therefore not surprising that coherent structures and associated dominant frequencies were not found in the shear layer surveys of the inlet dump jets during these tests since the flow was quite distorted. Additionally, Bradshaw [Ref. 11], has noted that discrete frequencies occur only in the early stages of transition from laminar to turbulent flow.

D. NEAR-WALL HOT WIRE RESULTS

When two configurations yielding oscillatory and non-oscillatory reacting flow were determined, the near-wall areas were surveyed again with the hot wire probe in cold flow. These configurations were for bypass and nonbypass flow with symmetrical inlet line lengths of 46 inches.

Again there were no dominant frequencies noted in the range of 0-5000 hz during the cold flow tests using bypass and nonbypass configurations. The same flow rate was maintained through the inlet nozzle, comparable to the reacting flow. This was done to have the same level of flow entrainment and turbulence structure.

Reynolds [Ref. 12] discusses turbulence scaling, where the largest elements of turbulence are non-viscosity dependent and are said to display Reynolds-number similarity. Intermediate elements of the turbulence are also not influenced by viscosity but have an adopted universal form defined by the energy dissipation rate. This region is termed the inertial sub-range and exists only when there are a large range of turbulence length scales. The smallest elements of turbulence, which are very dependent on viscosity, and coupled with the local rate of energy dissipation, define a small scale, dissipating structure.

Using this overly simplified concept some general comments can be made concerning the hot wire spectra obtained. Both bypass and nonbypass spectra showed a similar small scale energy dissipation range at the higher frequencies as expected (Figs. 10 and 11). Without introducing the complexities of the Kolmogaroff scaling law as discussed by Perry [Ref. 13], the slopes of the higher frequency ranges showed a -5/3 slope dependence on log-log plots of E_{rms} vs. frequency. Normally this type of turbulence correlation would use wave numbers rather than frequency. However, it is only a transformation and not critical in this discussion of the -5/3 law.

The E_{rms} differences for bypass and nonbypass configurations at all distances from the inlet dump plane all occurred at less than approximately 1500 hz. The E_{rms} values were greater for the bypass configurations. It seems that the downstream bypass disturbance affects the upstream large and intermediate scale structures with an energy transfer. The bypass configuration spectra still coalesced to the -5/3 power law as previously stated. However, there was more energy in the lower frequencies and thus, the larger turbulence structures. Again this discussion is greatly simplified in terms of turbulence modeling, but the enhanced mixing and resulting combustion efficiency increases have been noted in reacting flow.

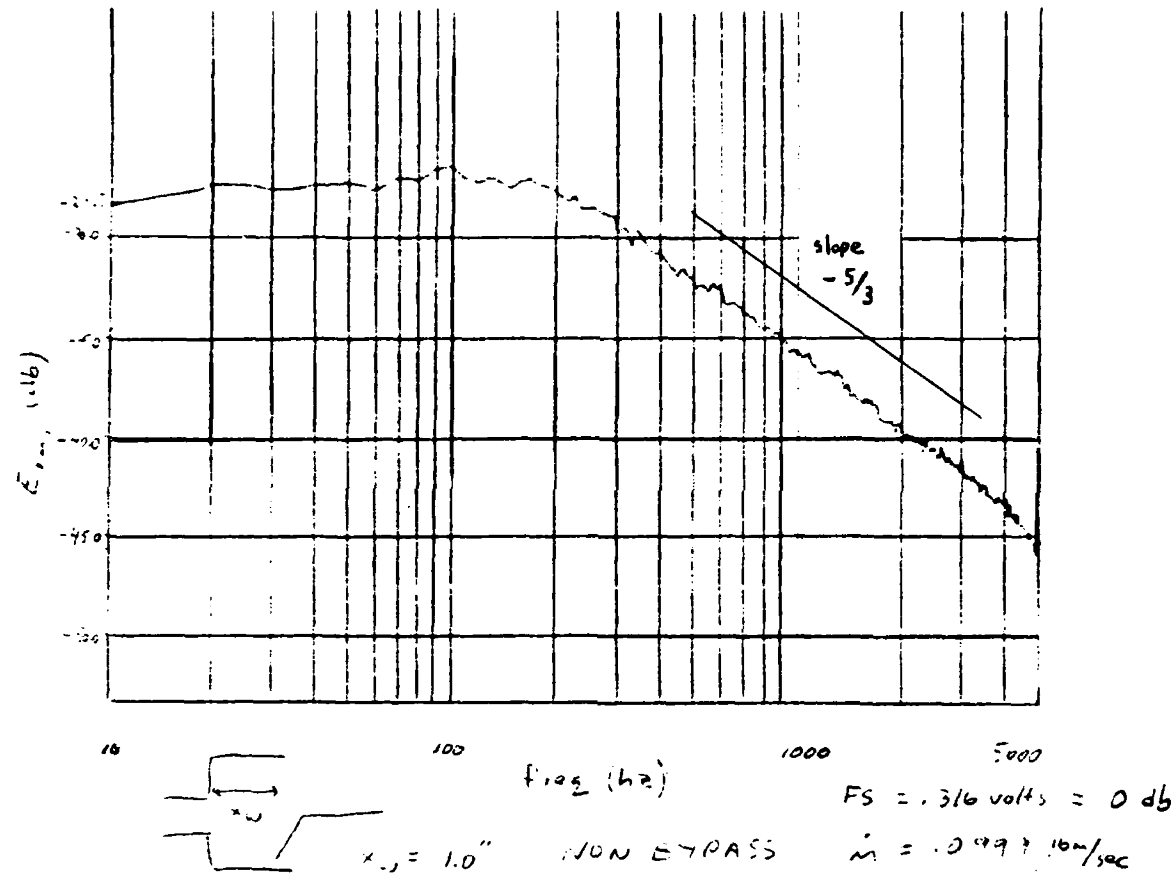


Figure 10

Nonbypass Hot Wire Spectrum

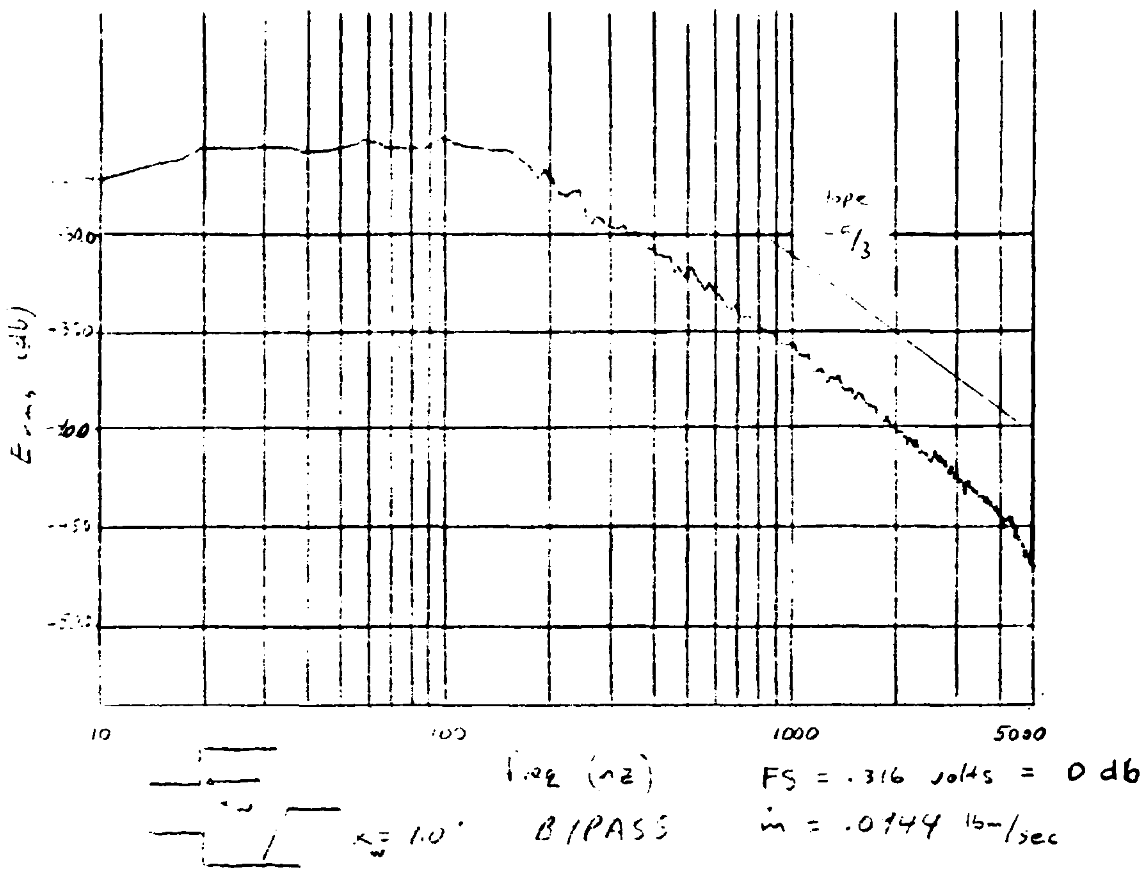


Figure 11

Bypass Hot Wire Spectrum

V. CONCLUSIONS AND RECOMMENDATIONS

Combustion pressure oscillations that occurred in bypass tests did not appear to be affected by the split head-end inlet line length (geometric or acoustic) changes, if the two inlet lines were symmetrically changed. It appeared that geometrically balancing the inlet line lengths promoted coherent oscillations. Nonbypass configurations showed stable operation.

The hot wire data showed no dominant frequencies in the shear layers from the inlet step flow. This is most likely due to the highly distorted flow from the relatively short coupled inlet used in the Naval Postgraduate School SFRJ motor.

The near-wall hot wire surveys of the bypass and nonbypass configurations showed more energy (E_{rms}) at the lower and intermediate frequencies for the bypass case. The energy dissipation regions at the higher frequncies were similar.

It was clear from the results of this investigation that bypass air injection resulted in combustion pressure oscillations. However the coupling mechanism/mode of the oscillation was not clear.

Recommendations for areas of further study include variations of the splitter wedge geometry in the head section to determine if it is the source of coherent flow structures, variations of the head section volume to check possibly Helmholtz modes and inclusion of flow straighteners prior to the axial inlet nozzle to possibly decouple the driving bypass disturbances from the head section.

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