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DESIGN ANALYSIS AND TEST OF FLUIDIC COMMUNICATION COMPONENTS

Robert J. Knowles, Jr.

Air Force Institute of Technology
Wright-Patterson Air Force Base, Ohio

June 1971

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WRIGHT-PATTERSON AIR FORCE BASE, OHIO

75

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Air Force Institute of Technology (AFIT/EN) Wright-Patterson Air Force Base, Ohio 45433	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP

3. REPORT TITLE

DESIGN ANALYSIS AND TEST OF FLUIDIC COMMUNICATION COMPONENTS

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Thesis

5. AUTHOR(S) (First name, middle initial, last name)

Robert J. Knowles Jr.
1Lt USAF

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
June 1971	~~74~~ 75	19

8a. CONTRACT OR GRANT NO. b. PROJECT NO. c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) GAW/ME/71-3 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

DISTRIBUTION STATEMENT

·oved for public release, distribution unlimited.

11. SUPPLEMENTARY NOTES Approved for public release; IAW AFR 190-17 JERRY C. HIX, Captain, USAF Director of Information	12. SPONSORING MILITARY ACTIVITY Air Force Institute of Technology Wright-Patterson AFB, Ohio 45433

13. ABSTRACT

A fluidic communication system using turbulent two-dimensional flow as an operating medium was constructed. Input signals were amplified by means of amplitude modulation. Transmission lines of plastic tubing were used to transmit the modulated signal to the demodulation section. The inherent instability of a two-dimensional jet was used to provide a means of demodulation. Results reveal that modulation is successful if the input signal has a sound amplitude of at least 12% of the sound amplitude of the carrier frequency. The demodulator did not respond as predicted to the carrier frequency produced by the fluidic oscillators and thus did not demodulate the input frequencies with the degree of clarity as would be thought possible.

DD FORM 1 NOV 65 1473

UNCLASSIFIED

Security Classification

UNCLASSIFIED

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT

UNCLASSIFIED

Security Classification

AD 767882

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FLUIDIC COMMUNICATION COMPONENTS

THESIS

Presented to the Faculty of the School of Engineering

of the Air Force Institute of Technology

Air University

in Partial Fulfillment of the

Requirements for the Degree of

Master of Science

by

Robert J. Knowles Jr., B.S.A.E.

1 LT USAF

Graduate Aerospace Weapons

June 1971

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Preface

Communication systems using air as the communicating medium have been known for a long time. Electronics gradually replaced all of these systems. However in severe environments (high temperature, explosion hazard, high electromagnetic interference) conventional electronic communication systems fail to operate satisfactorily. In these situations a fluidic speaker system could offer advantages.

Fluidic systems can perform many of the functions of a conventional electronic system. In the communication system designed, fluidic components amplify the input acoustic signal, transmit this signal along conventional fluidic transmission paths, and then regenerate the input at the termination of the system. The results of this study indicate that amplification is possible using turbulent jet flow as an operating medium. However the regeneration of an input signal by means of a two dimensional jet demodulator was not of sufficient clarity to consider the system a success.

This thesis topic was suggested by Dr. Milton Franke whose helpful suggestions kept me going in the pursuit of my goal.

Special thanks are due to the personnel of the AFIT shops and especially to Mr. Howard Wolf, who interpeted my drawings and Mr. Carl Shortt who fabricated my hardware.

Robert J. Knowles Jr.

Contents

List of Figures

List of Tables

List of Symbols

Symbol	Quantity	Units
a	Experimental Constant	ft
A	Cross Sectional Area	ft^2
b	Plane Jet Velocity Profile Parameter	ft^{-1}
b'	Experimental Constant	ft/sec
c	Sonic Speed	ft/sec
c_p	Specific Heat at Constant Temperature	BTU/lb-^oF
e	Cavity End Correction	ft
f	Frequency	Hz
f_c	Cavity Eigenfrequency	Hz
h	Inlet-to-edge distance	ft
j	Empirical Edge-tone Constant	---
k	Empirical Vortex Spread Constant	ft^{-1}
K	Momentum of Two Dimensional Fluid	ft^3/sec^2
L	Cavity Length	ft
L_o	Cavity Length	ft
Q	Volume Flow Rate	ft^3/sec
r	Pipe Radius	ft
R_e	Reynolds Number	---
R_g	Gas Constant	ft/^oF
S_t	Strouhal Number	---
t	Width of Inlet	ft
T	Temperature	^oR
u	Velocity	ft/sec
V	RMS Voltage Reading	volts
x	Downstream Distance from Inlet	ft

Symbol	Quantity	Units
y	Vortex Spread	ft
α	Attenuation in a Circular Pipe	nepers/ft
γ	Ratio of Specific Heats	---
η	Coefficient of Shear Viscosity	lb-sec/ft^2
η_e	Effective Coefficient of Shear Viscosity	lb-sec/ft^2
κ	Thermal Conductivity	BTU/ft sec$^\circ$F
ν	Kinematic Viscosity	ft^2/sec
ρ	Density of Air	lb/ft^3
ω	Angular Frequency	radians/sec

Abstract

A fluidic communication system using turbulent two dimensional flow as an operating medium was constructed. Input signals were amplified by means of amplitude modulation. Transmission lines of plastic tubing were used to transmit the modulated signal to the demodulation section. The inherent instability of a two dimensional jet was used to provide a means of demodulation. Results reveal that modulation is successful if the input signal has a sound amplitude of at least 12% of the sound amplitude of the carrier frequency. The demodulator did not respond as predicted to the carrier frequency produced by the fluidic oscillators and thus did not demodulate the input frequencies with the degree of clarity as would be thought possible.

DESIGN ANALYSIS AND TEST OF FLUIDIC COMMUNICATION COMPONENTS

I. Introduction

Background

Communication systems using air as the transmitting medium have been known for well over a hundred years. Lord Rayleigh (Ref 14:3) describes speaking tubes which were being used in 1877 to communicate over long distances. These systems worked on the principle that a confining wall will diminish the attenuation that would normally occur for an unconfined signal. However the effects of viscosity and heat conduction between the wall and the acoustic pressure waves eventually eliminated the signal (Ref 9:241). Furthermore, the original intensity of the signal at the sending end of the system was the maximum that could be achieved at the output. There were no means of amplification available.

Faced with the problem of designing a communication system for use in an environment which precludes electronic systems (high electromagnetic interference, explosive environment) engineers have turned to fluidic systems. Fluidics is that field of technology that deals with the use of fluid flow to perform functions such as signal amplification, temperature sensing, logic, and computation.

Fluidic Communication Systems

One way to build a communication system would be to design the fluidic counterpart of an electrical system.

While the individual components for such a design solution exist, combining these components into a complete system presents many problems to the designer.

Information signals must ultimately be transmitted over some medium separating the input from the output. The medium may be air, a set of wires, or a hollow conducting tube. Efficiency of transmission requires that this input be processed in some manner before being transmitted over the medium. The step of processing that signal is called the modulation process.

Continuous-wave modulation is the process in which the amplitude, phase, or frequency of a specified sine wave (the carrier) is altered in accordance with the input. This type of system lends itself to fluidic development. A fluidic oscillator can be used to generate the carrier frequency. Transmission can be achieved through the use of pneumatic lines. Detection of the modulated carrier has been discussed by Unfried (Ref 19:276) and Bowles and Dexter (Ref 2:D5-76). The generalized fluidic communication system is shown in Fig. 1.

A fluidic speaker system was developed by Unfried (Ref 19:267-296). He used an amplitude modulation concept to develop a broad band amplifier. Instability of a fluid jet to an acoustic signal was used by Unfried to develop a demodulator for the speaker system. However this system was limited to laminar flow. Turbulent flow will allow higher power output and broader band signals to be demodulated.

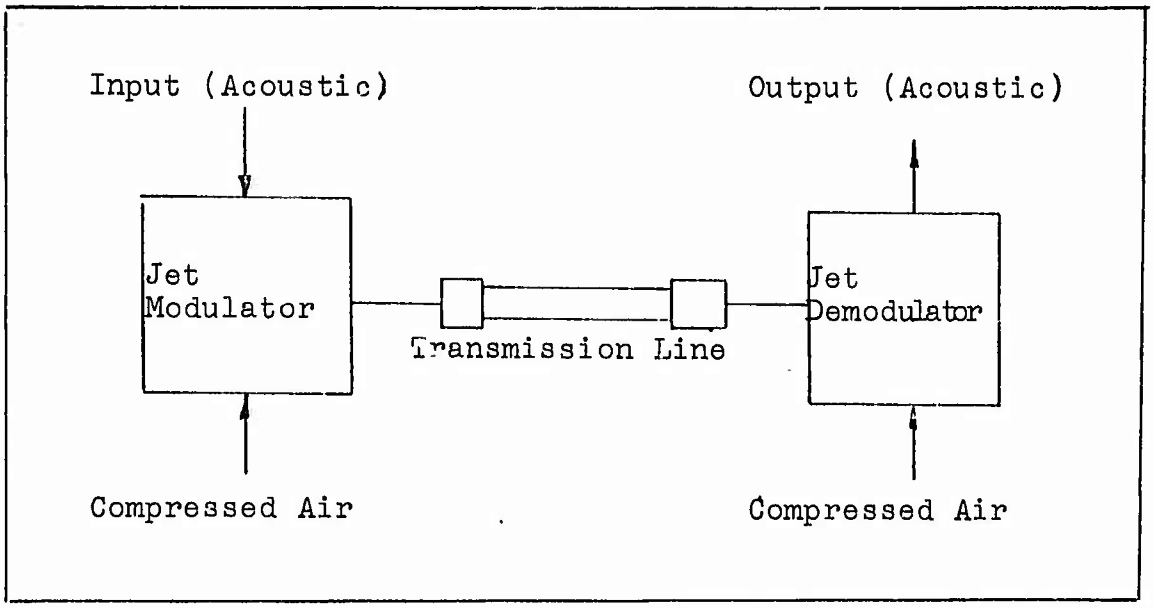


FIGURE 1 SCHEMATIC REPRESENTATION OF FLUIDIC COMMUNICATION SYSTEM

Purpose and Approach

The purpose of this study is to determine whether it is possible to construct a fluidic communication system using turbulent flow. The basic design philosophy of Unfried was retained as much as possible so as to retain a basis for comparison.

This project was divided into four basic areas. These were:

1. Design of a fluidic oscillator.
2. Methods of superimposing an acoustic signal onto a carrier frequency.
3. Transmission of the modulated signal.
4. Reconstruction of the input signal.

II. Design Theory

The basic idea behind fluidic communication systems is that jet flow is used to amplify and transmit an input signal and also to recover that signal at the receiver end of the system. Whereas in electrical systems acoustical signals can be directly converted into electrical signals through the use of various types of microphones, fluidic systems must be designed so as to allow the input acoustic signal to in some way deflect the jet flow. Having imparted the input signal onto the jet flow it is then possible to amplify the signal by using the disturbed jet flow to drive a fluidic oscillator.

It is then necessary to transmit the modulated signal to the receiver end of the communication system. Since most fluidic AC signal transmission is conducted by plastic tubing, transmission lines were constructed accordingly.

At the receiver end there must be a device to demodulate the incoming signal so as to recover the amplified input signal. Fluid jet flows have been found to be sensitive to acoustic signals (Ref 3:493). In this sensitive stage two characteristics of the disturbed flow are outstanding. First the flow begins to shed vortices with the same frequency as the frequency of the disturbing frequency. Secondly, these vortices spread at a predictable rate (Ref 16:248). These characteristics can be used to design a fluidic demodulator.

There were four areas calling for designs in this study. These were a high flow oscillator, a demodulator section, a method to input the desired signal, and transmission lines. Each of these will be discussed in turn.

<u>Oscillators</u>

In the case of a modulation system an oscillator is an extremely important part of the system. Two basic criteria were established for the design of an oscillator. These were that the oscillator furnish a strong, clean sinusoidal signal and that this signal be furnished at high flow rates (turbulent flow). Two different oscillators were constructed to accomplish this.

<u>Edgetone Oscillator with a Resonating Cavity</u>. This type of resonator has produced considerable interest in recent studies (Ref 4:7-11). Fig. 2 shows the basic configuration. When the jet flow impinges on the wedge set a short distance from the inlet definite tones are produced.

The frequencies of oscillation produced by the jet impinging on the wedge have been predicted by G. B. Brown (Ref 3:501). They are given by

$$f = 0.466 \; j \; (u-a) \left(\frac{1}{h} - b' \right) \qquad (1)$$

where a and b are experimental constants, u is the stream velocity, h is the inlet-to-edge distance and the value of j depends on the mode of the jet oscillation. For the laminar case of Brown's work a = 40cm/sec and b' = 0.07cm. However with u >> 40cm/sec and b' >> 0.07cm the formula reduces to

$$f = 0.466 \; j \; \frac{u}{h} \qquad (2)$$

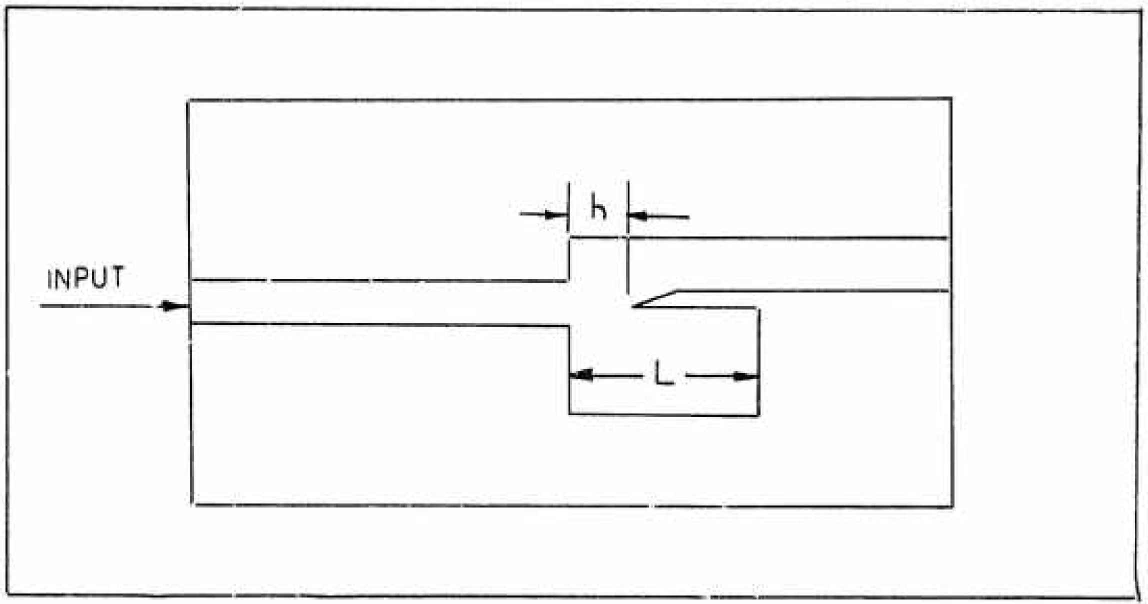


FIGURE 2 EDGETONE OSCILLATOR WITH A RESONATING CAVITY

The inclusion of a resonating cavity produces a complex system. Experimental studies (Ref 4:9) have shown that the oscillation of the complete system is a function of closed cavity length L and the capacitance of the cavity chamber.

The resonating cavity tunes the jet edge oscillations at approximately the cavity eigenfrequencies (Ref 12:140), which are expressed by

$$f_c = \frac{(n-\frac{1}{2})\ c}{2(L+e)} \qquad (3)$$

where n=1,2,3,4, respectively, c is the speed of sound, L is the cavity length and e is an end correction. This end correction is usually neglected (Ref 5:8).

To design the edgetone oscillator cavity for a specific function, initially a desired frequency must be designated. Then the cavity can be designed to tune the edgetone frequency.

Sonic Oscillator with Internal Feedback Loop. The sonic oscillator with an internal feedback loop operates by coupling the jet-edge frequency with the cavity eigenfrequencies. When two symmetric cavities are placed on either side of the jet flow, continuous oscillations are maintained.

A typical design of this type of fluidic oscillator is given in Fig. 3. Assuming that the first mode of oscillation (n=1) is excited, the resonant frequency of the cavity depends on the acoustic velocity and on the cavity length

$$f_c = \frac{c}{4L_o} \tag{4}$$

where L_o is the cavity length as defined in Fig. 3 and c is the adiabatic speed of sound.

Since the acoustic velocity is a function of temperature the output frequency can be expressed by

$$f_c = \frac{(\gamma R_g T)^{\frac{1}{2}}}{4L_o} \tag{5}$$

where γ is the ratio of specific heats, R_g is the gas constant and T is the temperature of the gas.

Fig. 4 gives a typical plot of frequency versus input pressure. No distinct oscillations are produced until the input pressure reaches a threshold value. At this value the frequencies of oscillation produced by the flow impinging on the edges at the exhaust (predicted by equation 2) begin to match the cavity eigenfrequencies predicted by equation 5. This coupling produces excellent sinusoidal signals.

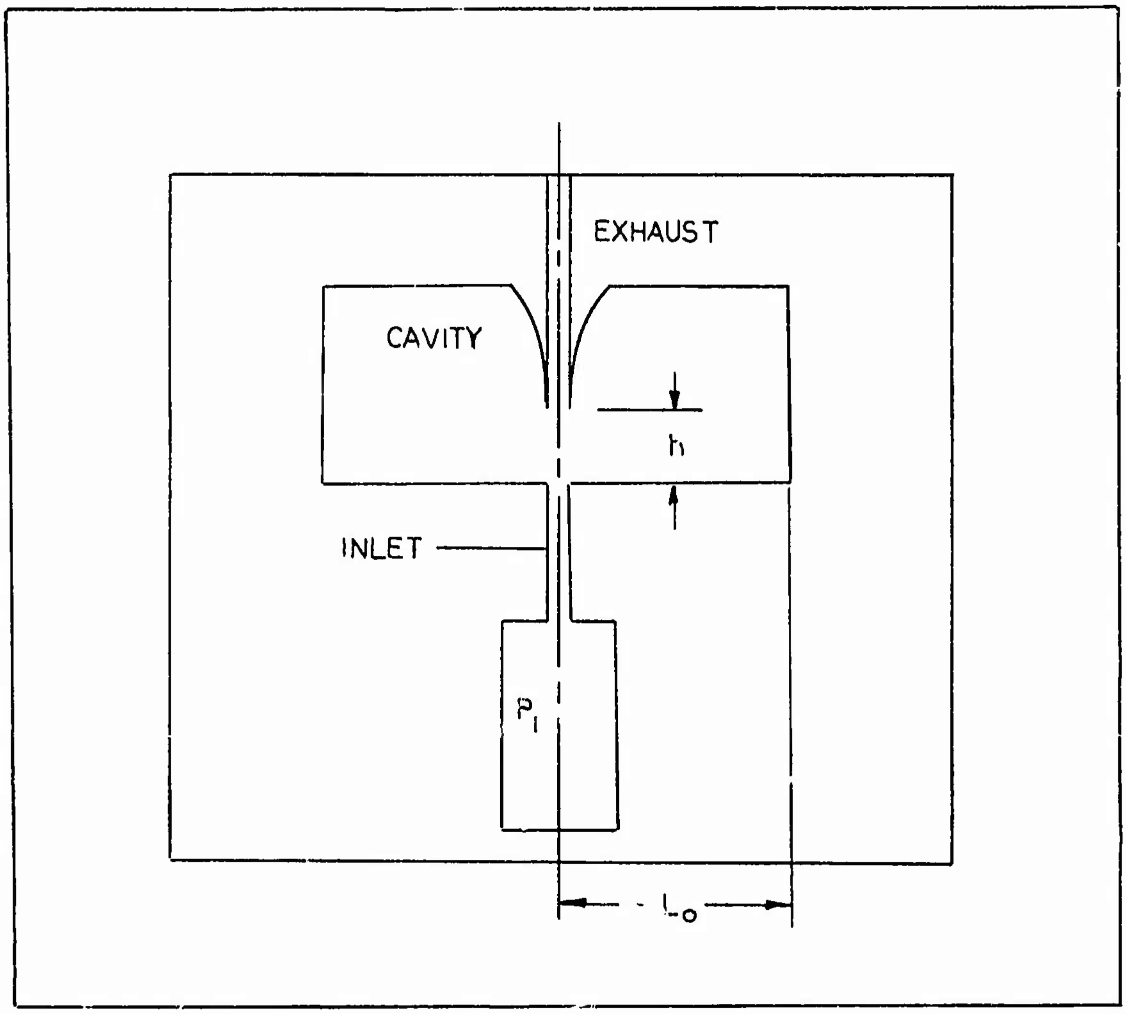


FIGURE 3 SONIC OSCILLATOR WITH INTERNAL FEEDBACK

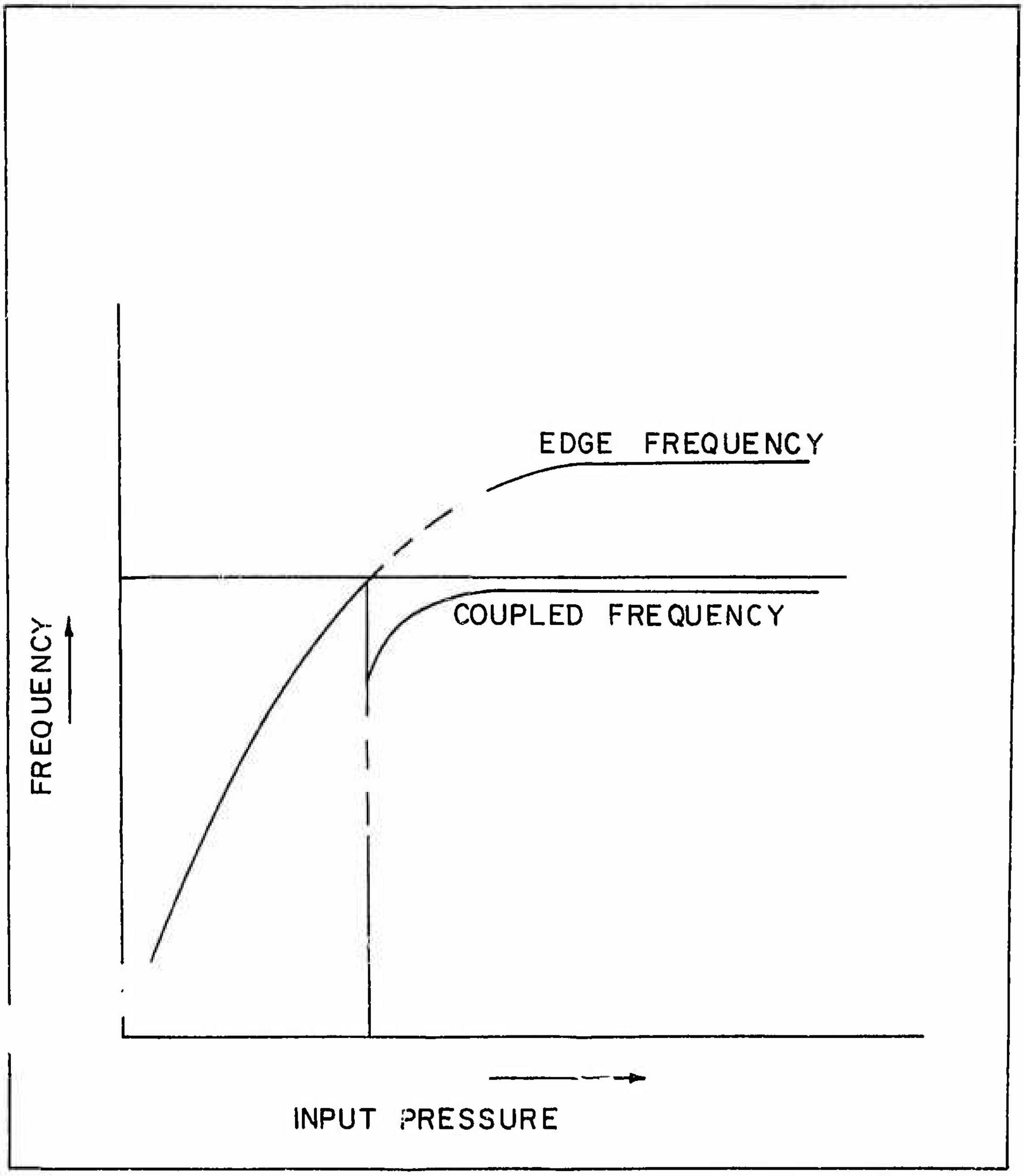


FIGURE 4 COUPLING OF CAVITY AND EDGE FREQUENCIES

Demodulation

The design of the demodulator is based on the theory of the interaction of an acoustic signal with jet flow. The basic idea behind the demodulator is to construct a device which will split the subsequent vortex flow at the center of the produced vortices. If the demodulator is designed to be sensitive to the carrier frequency and splitting is accomplished, the subsequent sound produced by the flow is the input signal.

Effect of Sound on Jets. Experiments have shown that the spread of a bounded, two dimensional jet will increase when exposed to a lateral sound field (Ref 11:4 and Ref 15: 1161). Unfried (Ref 19:283) has shown the region of sensitivity on a Strouhal number vs. Reynolds number graph. This graph (Fig. 5) was produced through various experimental studies assuming a parabolic velocity profile for the jet.

When a jet is in a sound sensitive state and is disturbed by an acoustical signal, vortex growth begins as shown in Fig. 6. These vortices appear at the same frequency as the frequency of the disturbing signal (Ref 3:500). Maximum sensitivity of the jet to an acoustical signal (dotted line in Fig. 5) produces maximum vortex growth and maximum spread (Ref 19:273).

The spread of the center of vortices from the center line of the flow y was predicted by Savic (Ref 16:248) to follow the equation

$$\tanh by = \frac{1}{2bk} \tag{6}$$

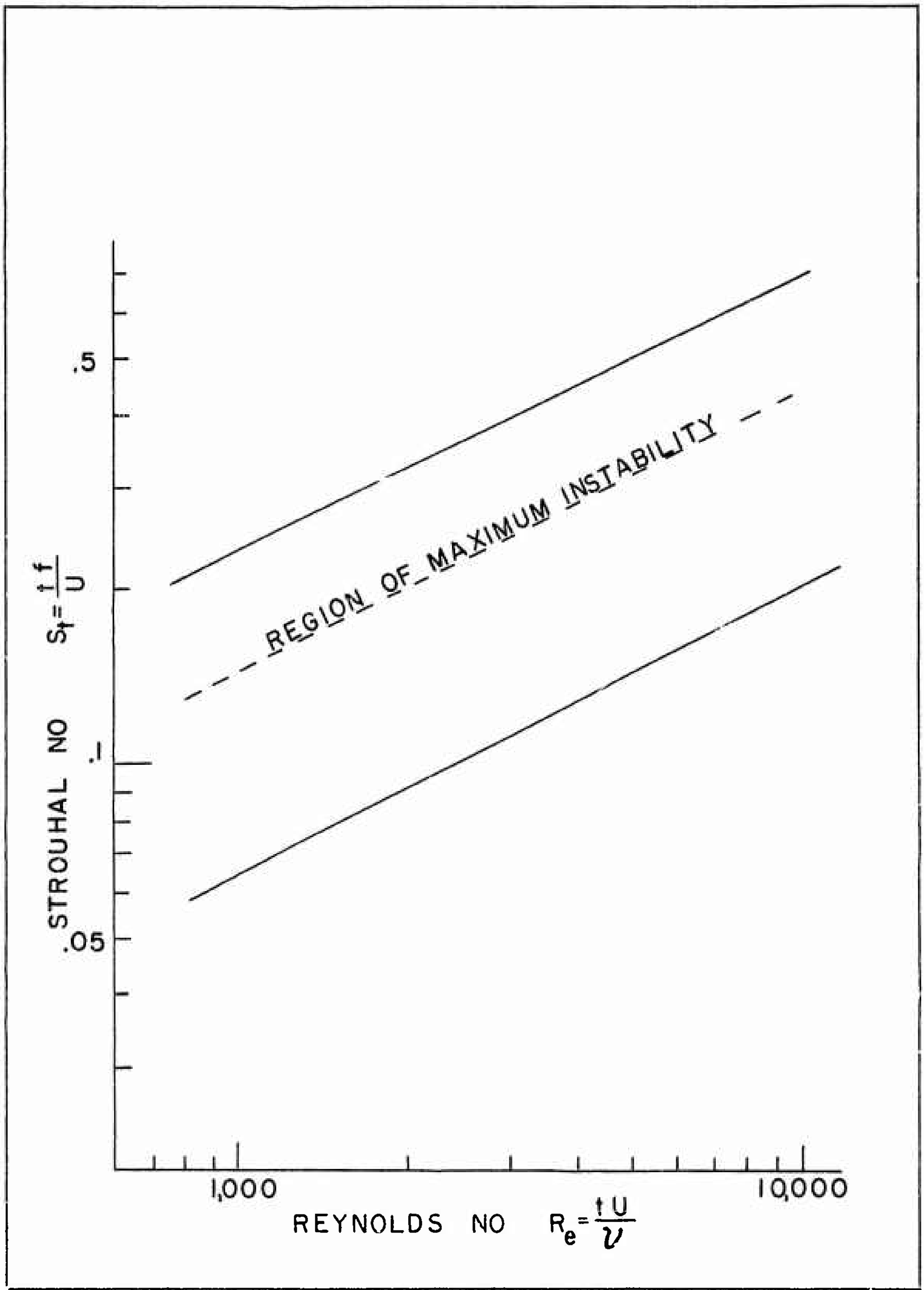


FIGURE 5 REGION OF INSTABILITY OF TWO DIMENSIONAL JET TO ACOUSTIC FREQUENCY(FROM REF 19:283)

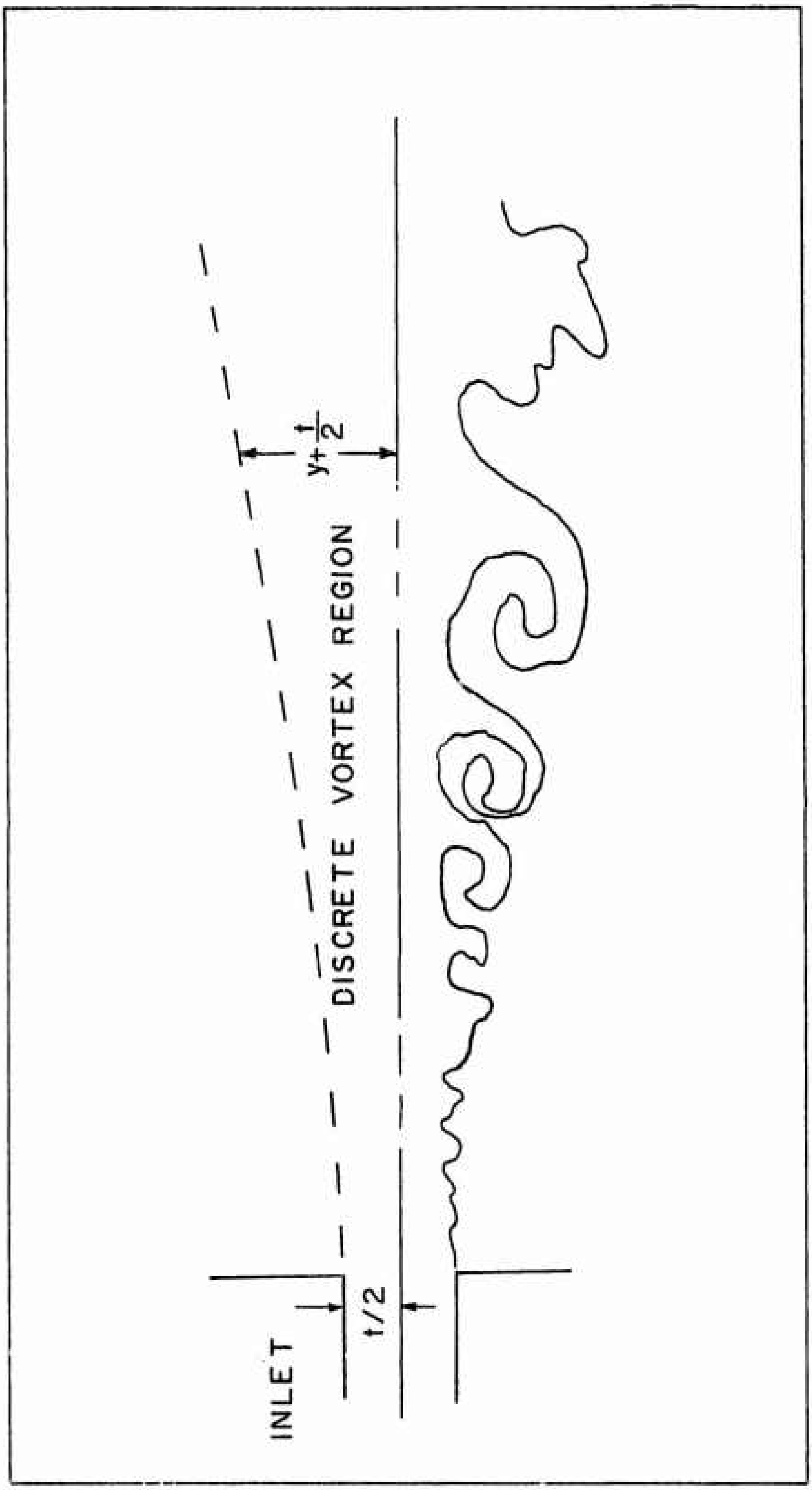


FIGURE 6 VORTEX GROWTH OF DISTURBED JET

where k is a arbitrary constant and b is given by the equation

$$b = 0.2751 \, (K/\nu^{2}) \, x^{-\frac{2}{3}} \tag{7}$$

where ν is the kinematic viscosity and K is the momentum of the fluid per unit time and unit length of the slit. Sample calculations using the above equations are given in Appendix A.

Design of the Jet Demodulator. The existence of jet spreading can be applied to the designing of a jet demodulator. A device with the general configuration of Fig. 7 can be used as the demodulator.

As mentioned in the previous section when a fluid jet is in a sound sensitive state, vortex spread can be predicted through the use of Savic's equations. The fluid flow in the demodulator can be adjusted to be sensitive to the carrier frequency by varying the flow rate until the region of maximum instability is achieved (see Fig. 5). By varying the splitter width, the jet flow can be split at the predicted centers of the produced vortices.

This in itself does not produce sound. However when the carrier frequency is modulated by the input signal the following happens. Since there is a distinct band width to which the jet flow is sensitive, additional vortices are produced at the values of the modulating frequency. Mass flow rates are varied because of the different spreading rates of the flow attributable to the different disturbing signals. This change in mass flow rate emering from the exhaust produces sound.

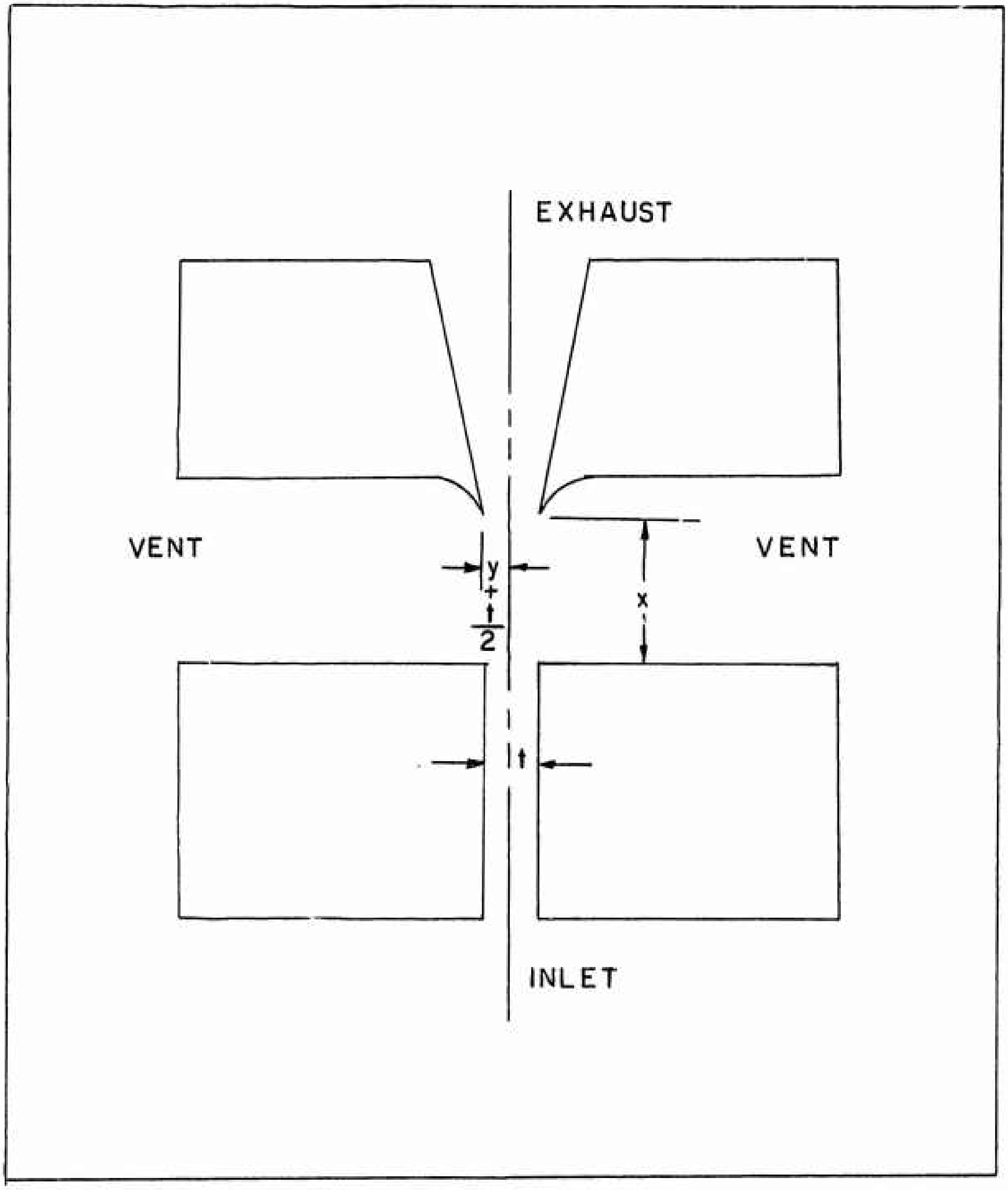


FIGURE 7 DEMODULATOR DESIGN

Superimposing Input Signal onto Flow

Two methods can be used to superimpose an acoustic signal onto the DC flow needed to drive the oscillators. One method is to use a pneumatic AC signal generator to drive the oscillators. The second method is to superimpose the input signal onto the flow by using a wave guide perpendicular to the flow.

The pneumatic AC signal generator would have a hollow chamber attached to a standard electrical speaker. Flow could be induced into the chamber. At the same time acoustic signals could be generated by the speaker. The resulting exit flow from the chamber would have both a DC and an AC component. The DC component would be produced by the exiting jet flow from the air tight chamber, the AC component by the output of the speaker.

The use of a channel perpendicular to the main flow channel would provide a second means of inputing the signal. The input signal could be generated at the entrance to the channel and would in turn be transmitted onto the main jet flow channel and therefore downstream into the communications system.

Transmission Lines

The modulated carrier must be transmitted from the modulator section to the demodulator section in some way. For this study 0.25-in-ID poly flow tubing was selected as the transmission path.

Both heat conduction and viscosity contribute to the attenuation of acoustic signals in sound tubes. Attenuation in a circular pipe has been shown (Ref 10:241) to be given by

$$a = \frac{1}{rc}\sqrt{\frac{\eta_e \omega}{2\rho}} \tag{8}$$

where r is the pipe radius, c is the speed of sound, ω is the angular frequency of the signal and ρ is the density of air.

The term η_e is the effective coefficient of shear viscosity. Rayleigh (Ref 14:319-328) has found this term to be given by

$$\eta_e = \eta\left[1 + \left(\sqrt{\gamma} - \frac{1}{\sqrt{\gamma}}\right)\sqrt{\frac{K}{c_p \eta}}\right]^2 \tag{9}$$

where K is the thermal conductivity of the fluid, γ is the ratio of specific heats, c_p is the specific heat at constant temperature, and η is the coefficient of shear viscosity.

Qualitatively speaking the attenuation coefficient a is proportional to the square root of the frequency and inversely proportional to the radius of the pipe. Therefore high frequencies would be attenuated to a greater extent than lower ones.

The attenuation was the only parameter considered in the design of this fluidic communication system. Since attenuation is greater for higher frequencies it was decided to construct two oscillators, one low and the other high frequency so as to allow for comparisons between the two ranges.

III. Experimental Apparatus

The test apparatus can be separated into five basic sections: AC signal generator, fluidic oscillators, fluidic demodulator, pneumatic transmission line, and monitoring equipment. Only the monitoring equipment was commercially available. Details of these can be found in the operator manuals of the individual components. A schematic of the apparatus is shown in Fig. 8.

AC Signal Generator

A source of acoustic signals was necessary to serve as an input to the fluidic speaker system. Figs. 9 and 10 show the AC signal generator. The generator consisted of an 8 watt tweeter cone speaker to which was attached a brass cap. Two short 0.25 inch ID nozzles were welded onto the face of the cap. One nozzle served to let DC air flow into the chamber while the other nozzle served as an output with AC sinusoidal signals superimposed on the DC flow. A typical signal is shown in Fig. 11.

The AC signal generator was used to drive the sonic oscillator in the following manner. An air source was connected to one of the two nozzles connected to the brass cap. The other nozzle was connected to the oscillator undergoing the test. The flow of air into the AC generator was increased until a desired frequency was produced by the oscillator. Then the driver on the AC generator was turned on and acoustic signals were generated by the speaker.

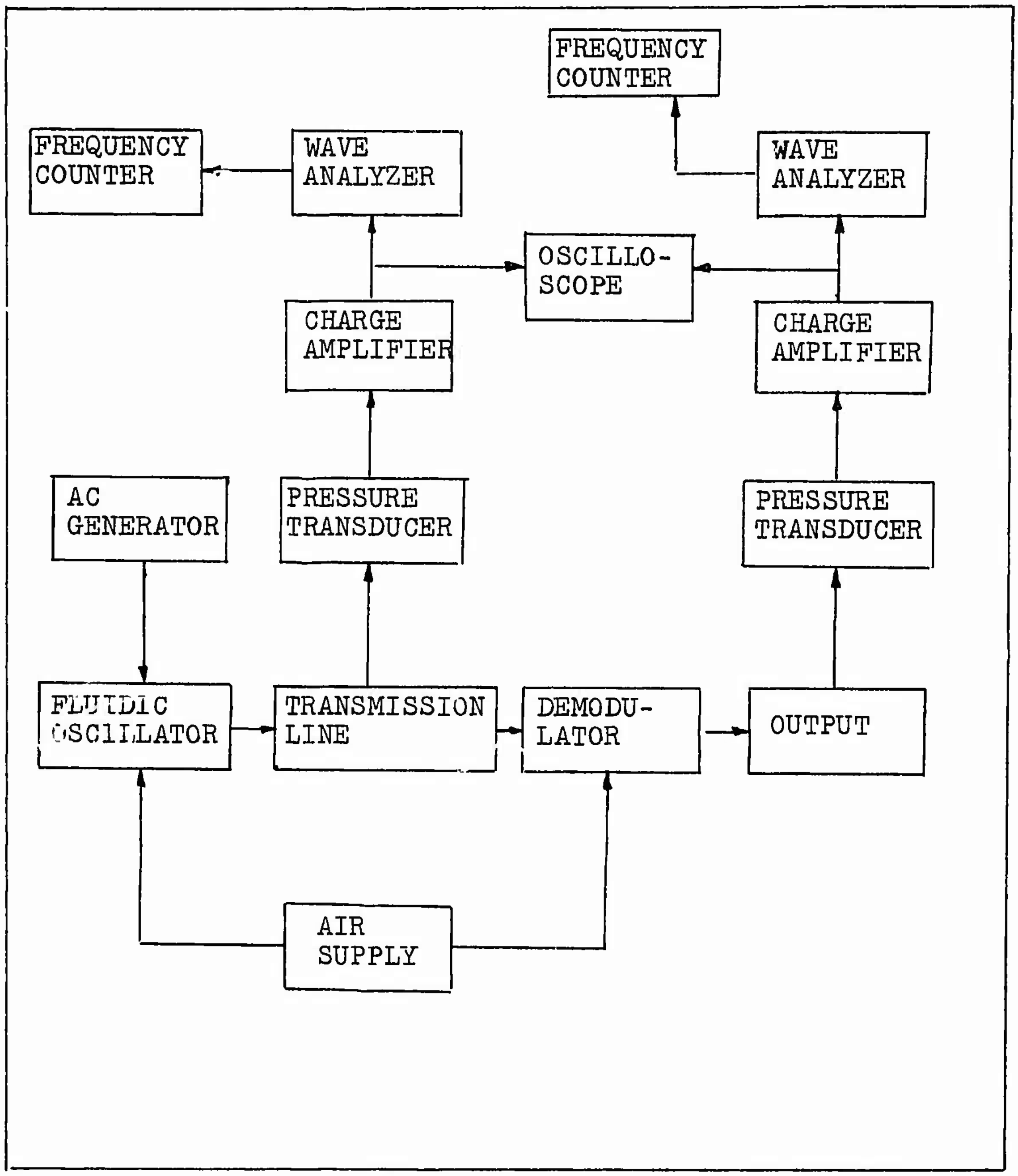


FIGURE 8 SCHEMATIC DIAGRAM OF TEST SYSTEM

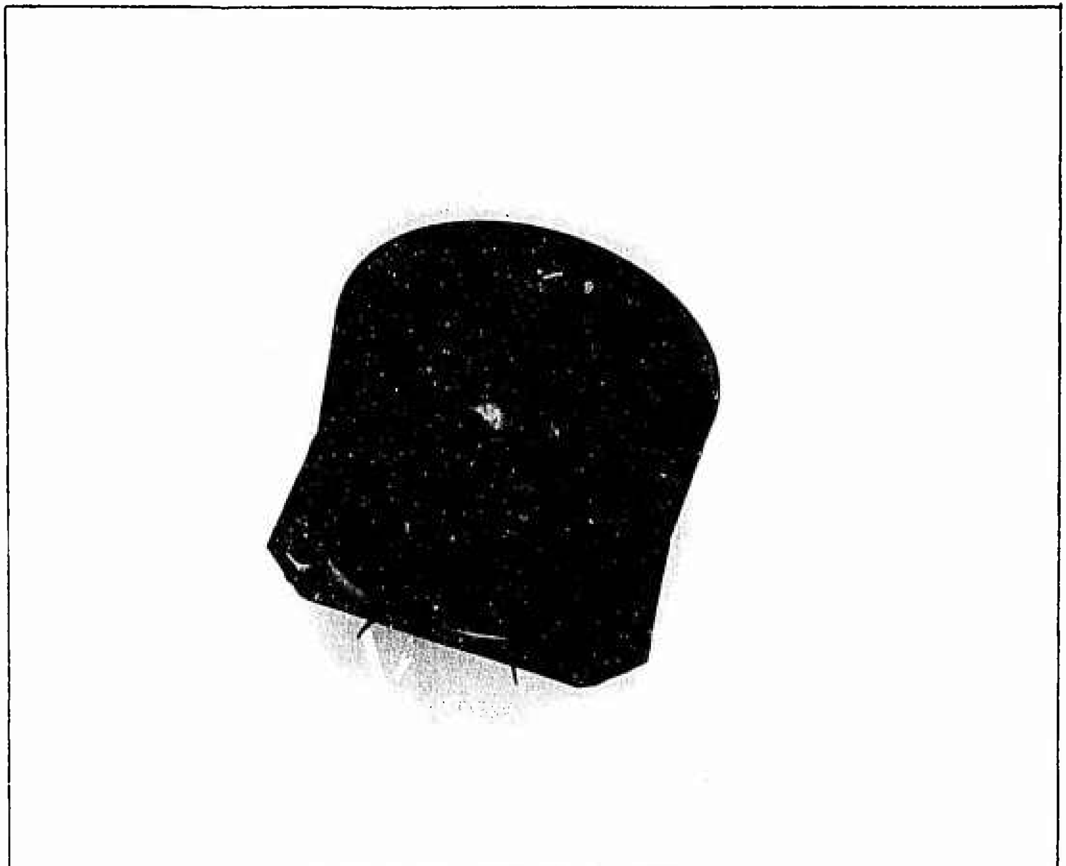


FIGURE 10 BOTTOM VIEW OF AC GENERATOR

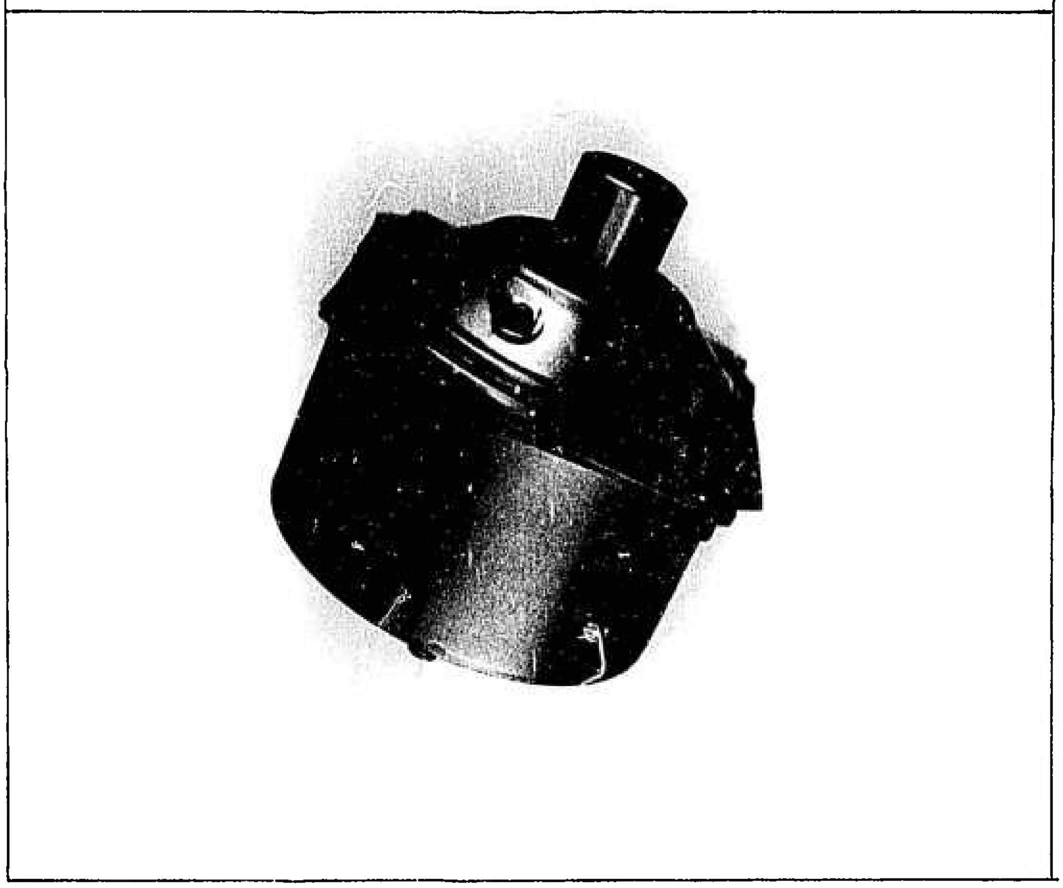
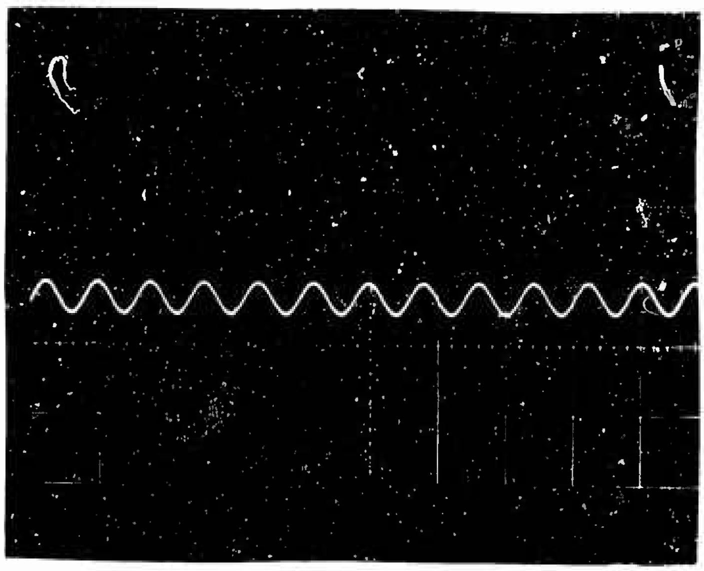


FIGURE 9 TOP VIEW OF AC GENERATOR



Frequency = 1250 Hz

FIGURE 11 TYPICAL AC GENERATOR OUTPUT

Fluidic Oscillators

Two fluidic oscillators were designed in accordance with the theory of Section II.

Edgetone Oscillator. The edgetone oscillator was designed to resonate at a frequency of 14000 Hz and at a $R_e = 4790$. This design was based on the theory of Nyborg (Ref 12:139) for which equation 2 was used to determine the splitter distance. The center line velocity was approximated by dividing the flow rate Q by the cross sectional area A of the duct. Equation 4 was used to design the cavity which tuned the edgetone frequency.

The configuration of this oscillator is given in Fig. 12. It consisted of 0.0625 inch thick aluminum plates sandwiched between two 0.0375 inch thick pieces of plexiglass. Connectors for transmission lines and AC signal input were attached to the plexiglass.

Sonic Oscillator. This oscillator was designed to resonate at a frequency of 2260 Hz. This design was based on the theory of Carter (equation 5) which states that the cavity length L_o is the governing parameter for oscillation as long as a constant temperature is maintained. Therefore assuming a temperature of 70^oF as typical, the cavity length necessary for a 2260 Hz signal was found to be 1.5 inches.

The configuration of this oscillator is shown in Fig. 13. The inlet channel was machined out of 0.375-in-thick plexiglass to a depth of 0.125 inches. The splitters were cut out of 0.125-in-thick aluminum plate. Again a

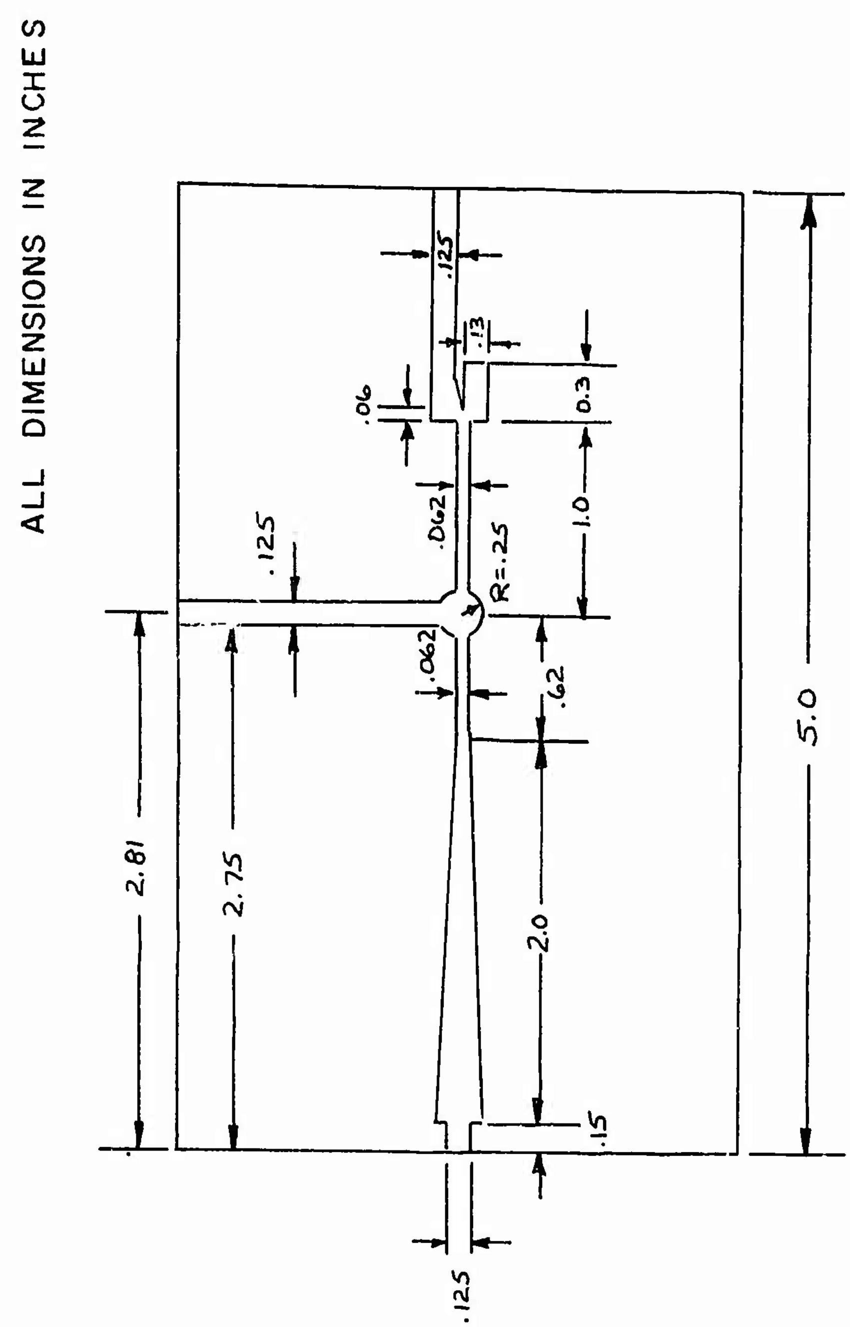


FIGURE 12 EDGETONE OSCILLATOR

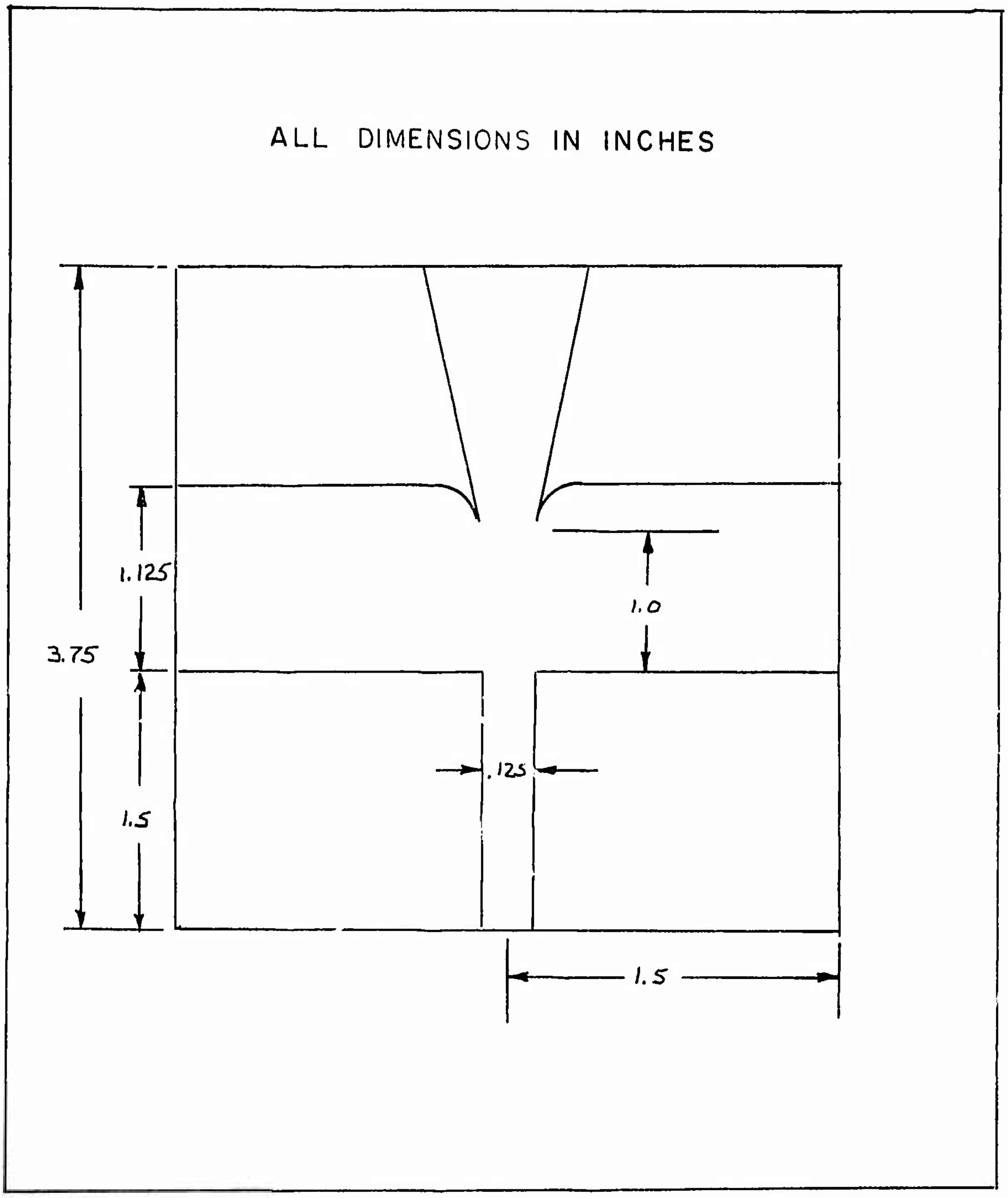


FIGURE 13 SONIC OSCILLATOR

sandwich technique was used to secure the splitters in the proper configuration. Exhaust nozzle spacing could be varied by loosening the plexiglass cover and adjusting manually the splitter orientation and spacing. Tightening the cover locked the splitter into position for a test run.

Fluidic Demodulator

The fluidic demodulator is shown in Fig. 14. It consists basically of a sound sensitive jet with certain parts of the developing vortex flow removed.

The inlet channel was machined to a depth of 0.125 inches out of 0.375-in-thick plexiglass. This channel allows jet flow to emerge into the interaction region.

Once the jet flow has been adjusted so that it is sensitive to an acoustic signal (Fig. 5), that acoustic signal must be allowed to disturb the jet flow. Experiments have shown (Ref 15:1166) that the most sensitive region for acoustically disturbing the jet flow is at the inlet. Therefore a sound probe was constructed so as to allow the transmitted modulated signal to be delivered to the inlet region.

The disturbed jet was then allowed to spread. Savic predicted the location of the vortex centers (equations 6 and 7) in such an acoustically disturbed flow field. Splitters were positioned at the predicted vortex centers. These splitter plates were adjustable so as to allow changes in splitter separation when carrier frequencies were changed.

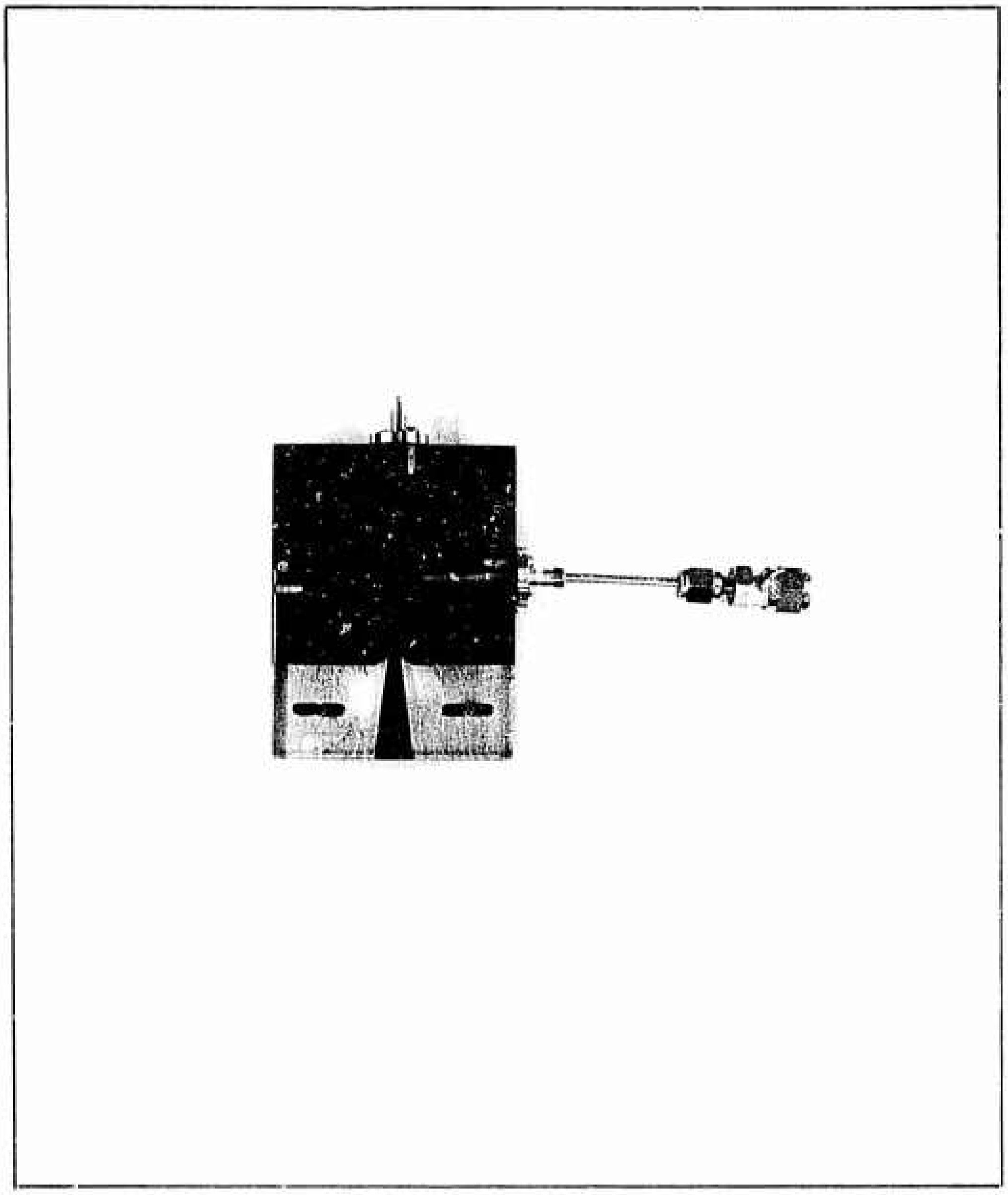


FIGURE 14 FLUIDIC DEMODULATOR

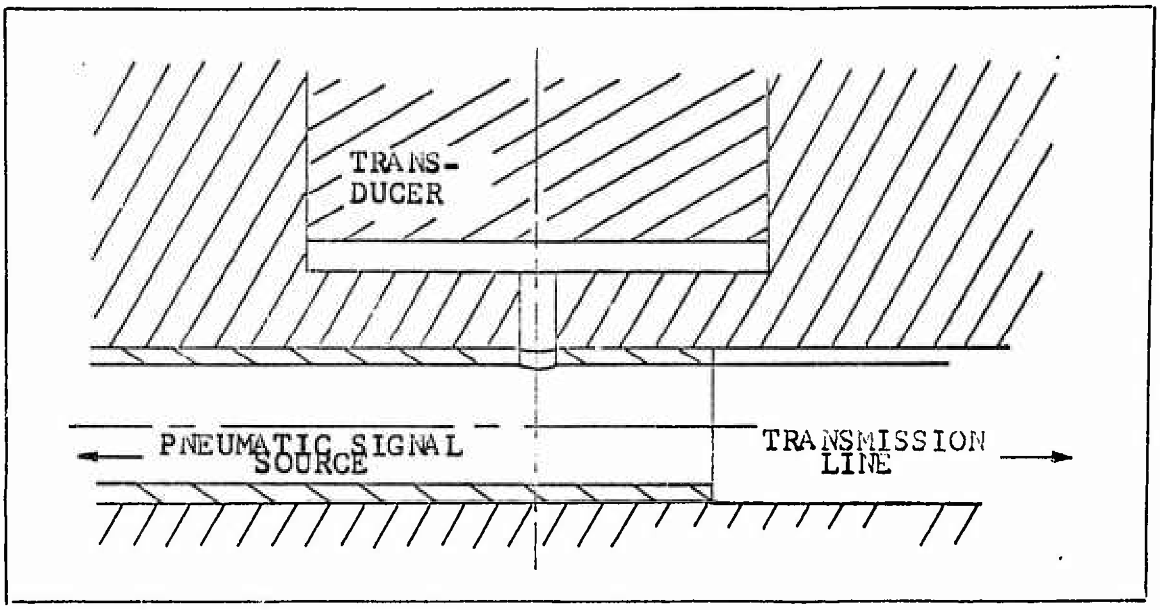


FIGURE 15 TRANSDUCER RECEIVING ASSEMBLY

Pneumatic Transmission Line

The transmission lines used throughout the system were 0.170-in-ID, 0.250-in-OD plastic tubing. The transmission lines served only as waveguides from the transmitter to the fluidic demodulator. No attempt was made to analyze the effects the length of transmission line had on the system.

Monitoring Equipment

Pressure transducers were mounted in receiving assemblies as shown in Fig. 15. The dynamic pressure measured by the transducer was converted into a varying voltage and amplified by a charge amplifier. The output of the amplifier was measured in two ways. An oscilloscope was used for visual observation of the AC signals. Pictures of the traces were taken for amplitude measurement and noise evidence. The second method was to use a wave analyzer to measure the fundamental component of the signal. The frequency of these signals were measured by electronic counters.

Air Supply

The air used in these tests was laboratory shop air. It was filtered once before it entered the components requiring fluid flow for operation. Flow rates were measured by use of a Brooks flowmeter. Static pressure measurements were made with a 25-inch, U-tube mercury manometer.

IV. Experimental Procedure

The objectives stated in Section I required that data be taken experimentally to determine the feasability of a fluidic communication system of this type (Fig. 1). Therefore it was necessary to analyze the frequency response of the entire system to a variety of inputs and at different flow rates.

General

Once experiments were begun, power was left on to all test equipment to assure stability. Ambient temperatures were taken before each run and were monitored for change if the run lasted over one hour. The tests were divided into three basic areas: determination of oscillator characteristics, modulation of carrier frequency, and demodulator response. Each of these tests required separate procedures.

Oscillator Characteristics

Two oscillators (Fig. 12 and Fig. 13) were constructed and tested. These devices were tested with various flow rates and the frequency and rms amplitude of the sound was recorded by use of pressure transducers. In the case of the edgetone oscillator the pressure pickup was downstream of the edge. For the sonic oscillator the transducer was located at the edge of the cavity.

When high rates of flow were being used, measurements of static pressure were obtained rather than actual flow rates. Once the limitation of the Brooks flowmeter had been reached, there was turbulent flow. Static pressure measurements were taken in these cases.

Modulation of the Carrier Frequency

Because of the different configurations of the carrier producing oscillators, two different methods of modulating were used and tested.

For the edgetone oscillator, the pneumatic signal generator was connected to the input waveguide. Air flow was started until a good, clean frequency was being produced by the oscillator. This flow rate was noted and maintained throughout the test. Having generated the carrier frequency the signal generator was turned on and various frequencies were inputed into the system. Two pressure transducers were used for data pickup during the test. One was located between the signal generator and the input waveguide. The second transducer was located downstream of the oscillator. Fig. 16 shows the test setup.

The sonic oscillator required a different setup to test its modulating characteristics. The main difference was in the fact that the pneumatic signal generator was used to drive the oscillator. This was accomplished by using the DC flow feature inherent in the design of the signal generator to provide the air flow necessary to power the oscillator. AC signals were then induced onto the flow and hence into the oscillator.

Again two pressure transducers were used to measure the response. The first measured the sending signal of the

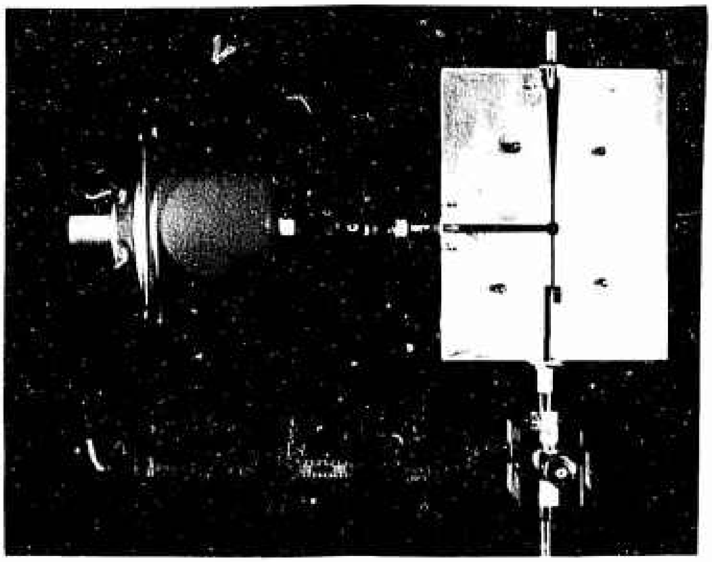


FIGURE 16 MODULATION TEST SYSTEM - EDGETONE OSCILLATOR

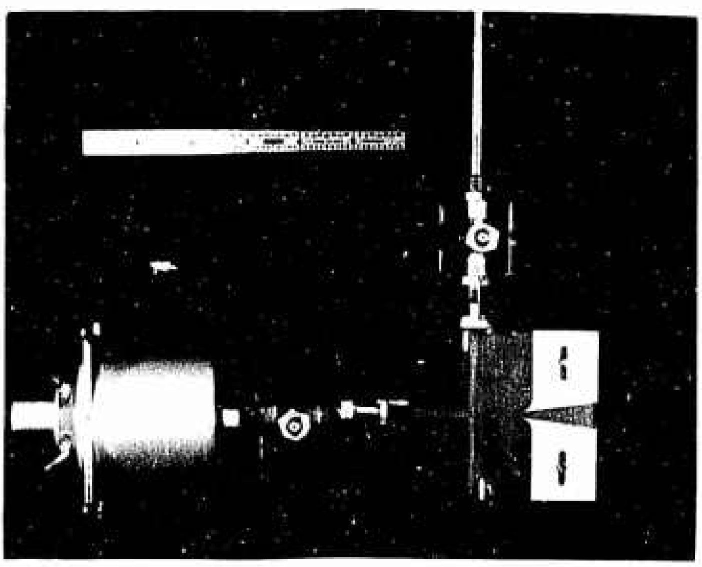


FIGURE 17 MODULATION TEST SYSTEM - SONIC OSCILLATOR

generator. The transducer was located between the generator and the oscillator. The second transducer was located at the end of the cavity. Fig. 17 shows the test setup for the sonic oscillator.

Demodulator Response

Demodulator characteristics were obtained in the following manner. Jet flow into the demodulator was adjusted by mean of flow rate so that it was at a point of maximum sensitivity to the carrier frequency being produced by the oscillator. These points of maximum sensitivity are given in Fig. 5. Knowing the flow rate allowed calculation of the theoretical spread of the vortex centers (equations 6 and 7). The splitters were then adjusted to these points.

Data was obtained as follows. A pressure transducer pickup was located in the vent area. As various modulated signals were transmitted into the demodulator, the output of the demodulator was recorded at the input frequencies. This was then compared with the signal strength obtained by just transmitting the input signal with no flow in the entire system.

V. Results and Discussion

The operation of a fluidic communication system using turbulent flow depends on the successful completion of three stages of operation. As discussed in the theory section previously, they are:

1. Development of a carrier frequency by fluid flow
2. Modulating that frequency with an input signal
3. Demodulating the carrier frequency so as to obtain the original signal.

The results of each of these stages will be discussed.

Carrier Frequency Development

Edgetone Oscillator. The edgetone oscillator, Fig. 12, provided clean sinusoidal signals at low turbulent flow ranges. Turbulent flow in a two-dimensional duct is usually considered to occur when the Reynolds number ($R_e = tu/\nu$) is greater than 2300. By approximating the velocity by the flow rate (Q) divided by the area of the channel (A) and using the width of the inlet (t) as the characteristic length, it was found that the best operating range for the edgetone oscillator was with $4500 < Re < 5500$. At higher flow rates the signals were mostly noise.

The output frequencies are given in Fig. 18. The differences in output due to flow rate can be clearly seen in Fig. 19. Since a good sinuoidal signal was desired for a carrier frequency no attempt was made to analyze the outputs at high flow rates.

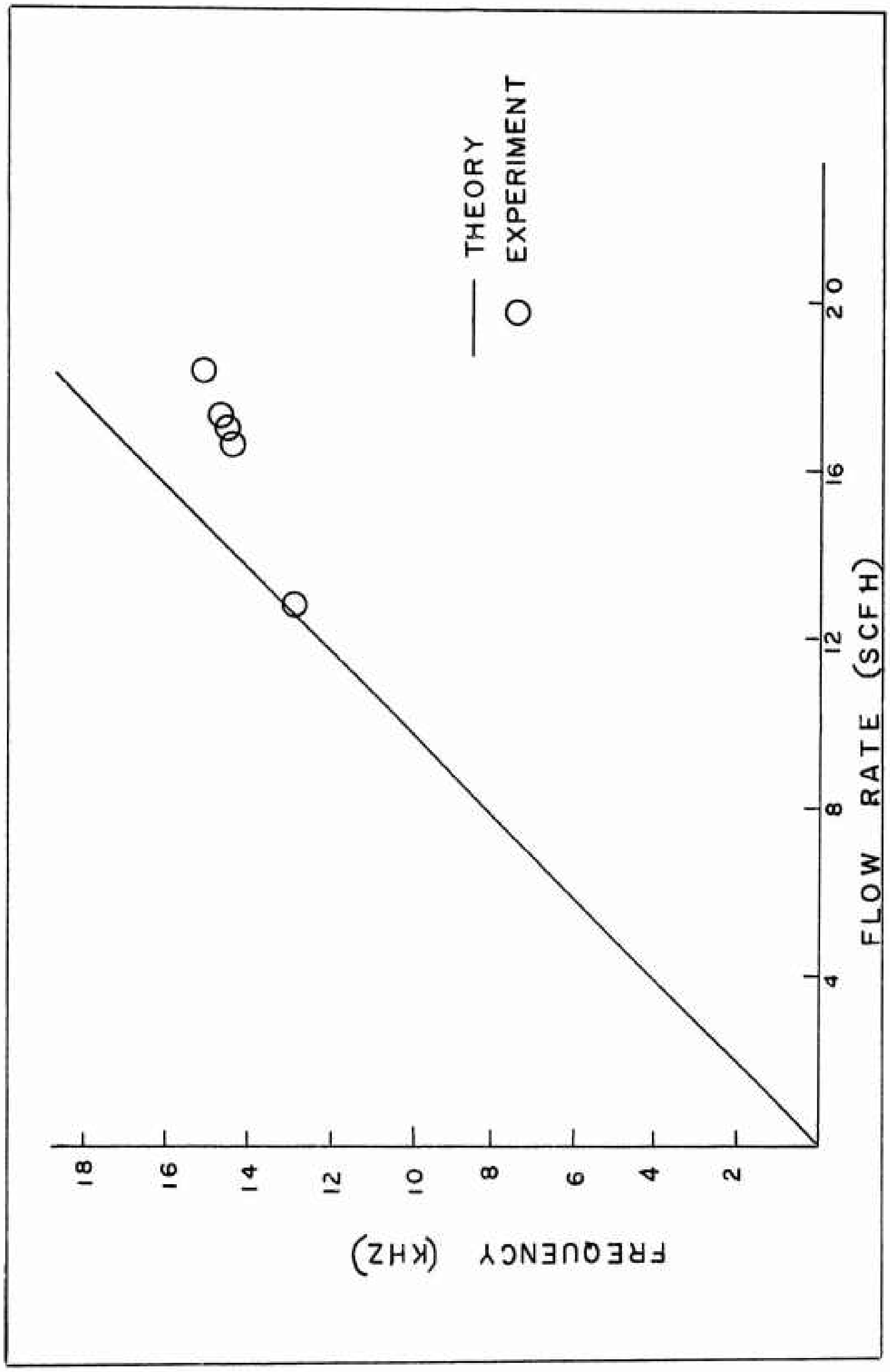


FIGURE 18 EDGETONE OSCILLATOR RESPONSE

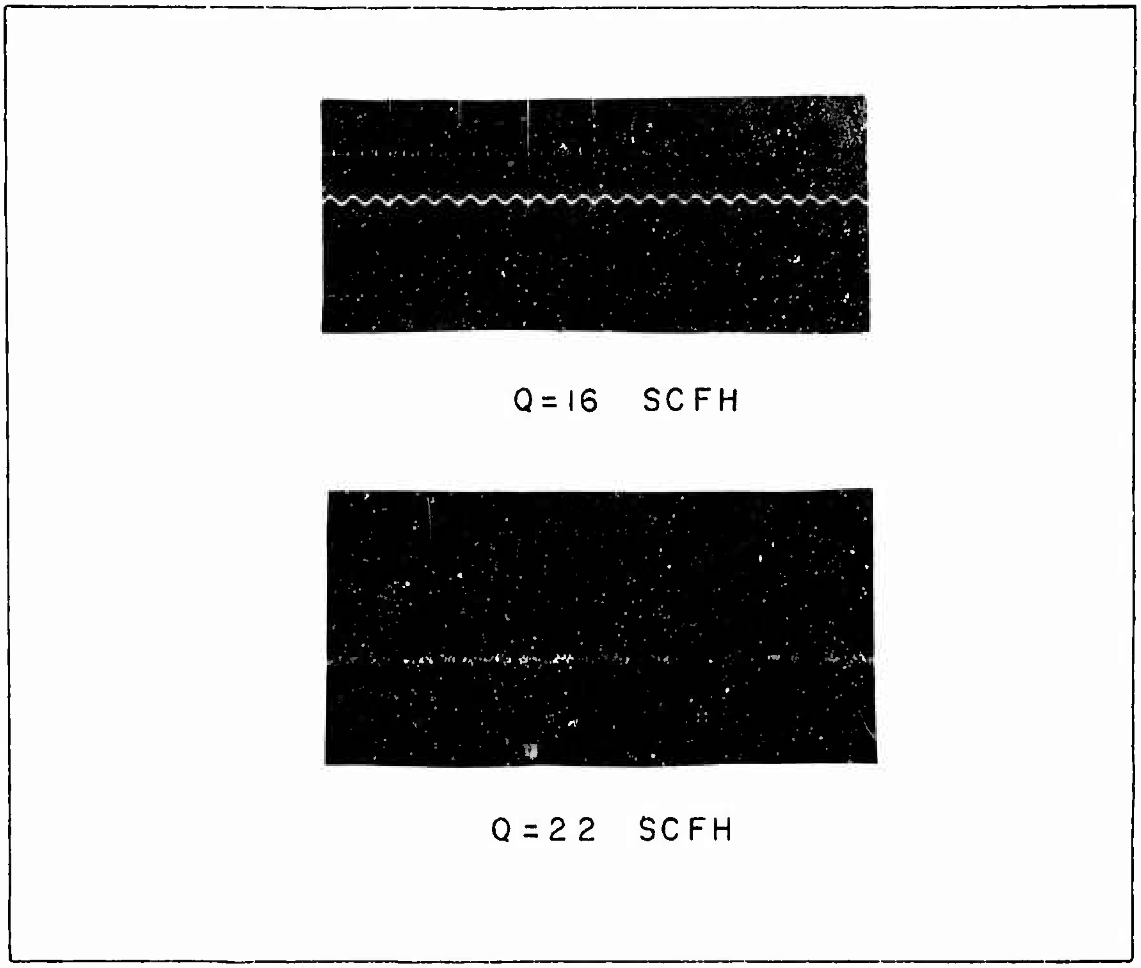


FIGURE 19 TYPICAL SCOPE TRACE - EDGETONE OSCILLATOR

Sonic Oscillator. The sonic oscillator provided undistorted sinusoidal signals throughout most of its operating range. Fig. 20 indicates the range of frequencies at which the oscillator resonates. As can be seen from the graph these points of resonance agree well with theory.

Fig. 21 gives a comparison of the outputs at various static pressures. As can be seen at the higher regions of pressure the signals began to be affected by leaks in the oscillator. Again, as in the case of the edgetone oscillator,

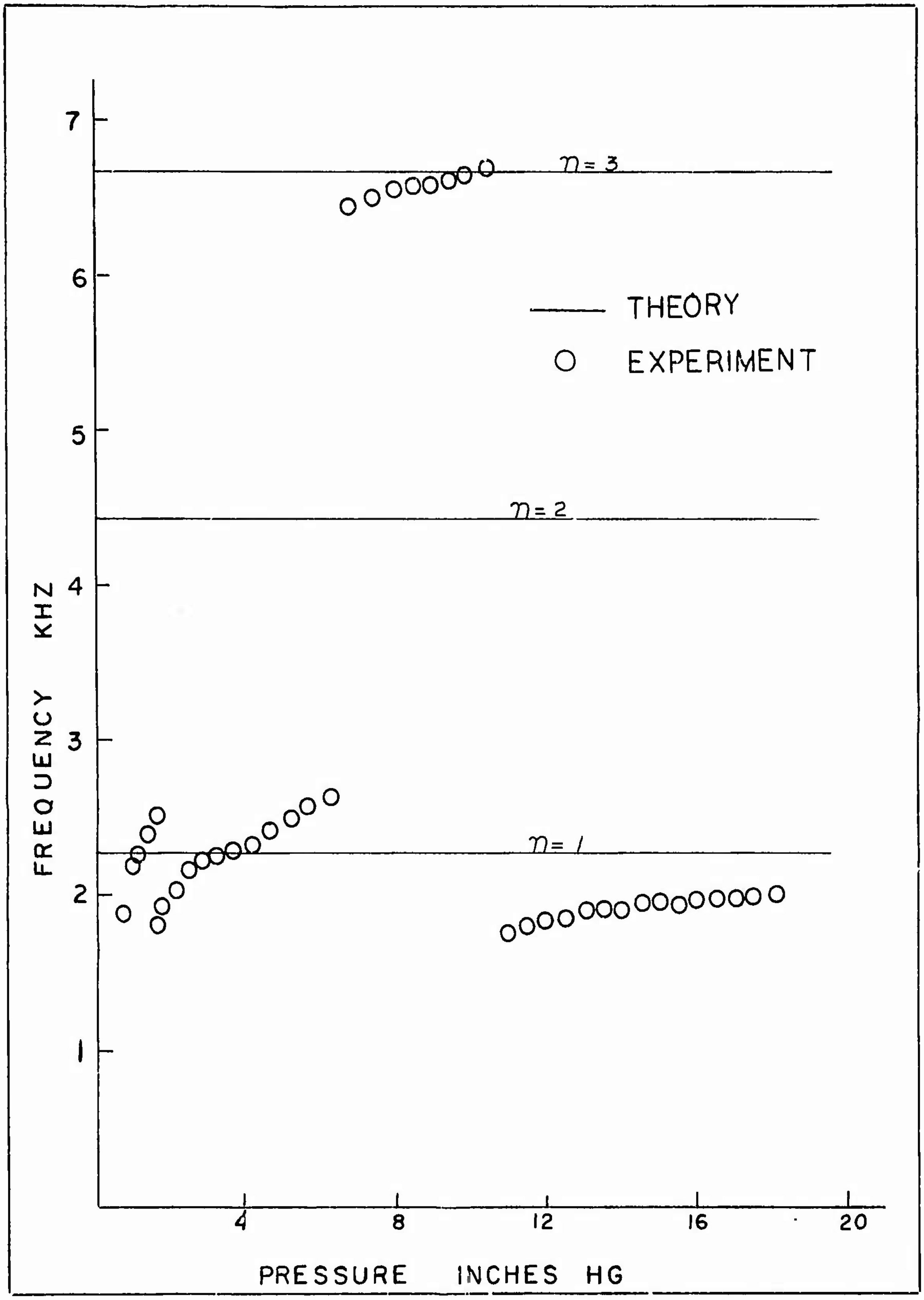
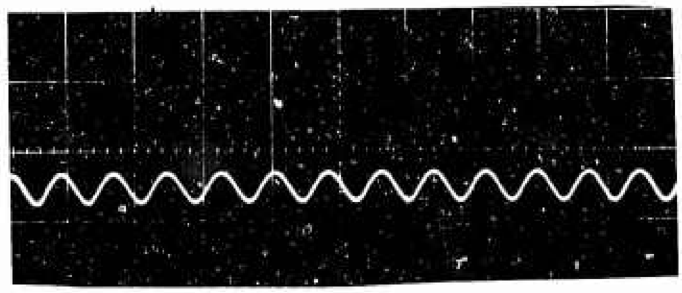
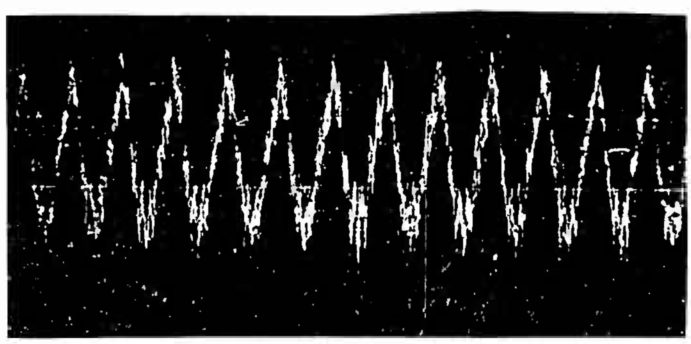


FIGURE 20 SONIC OSCILLATOR RESPONSE



P = 3.1" HG

P = 10.0" HG



P = 15.0" HG

FIGURE 21 TYPICAL SCOPE TRACE - SONIC OSCILLATOR

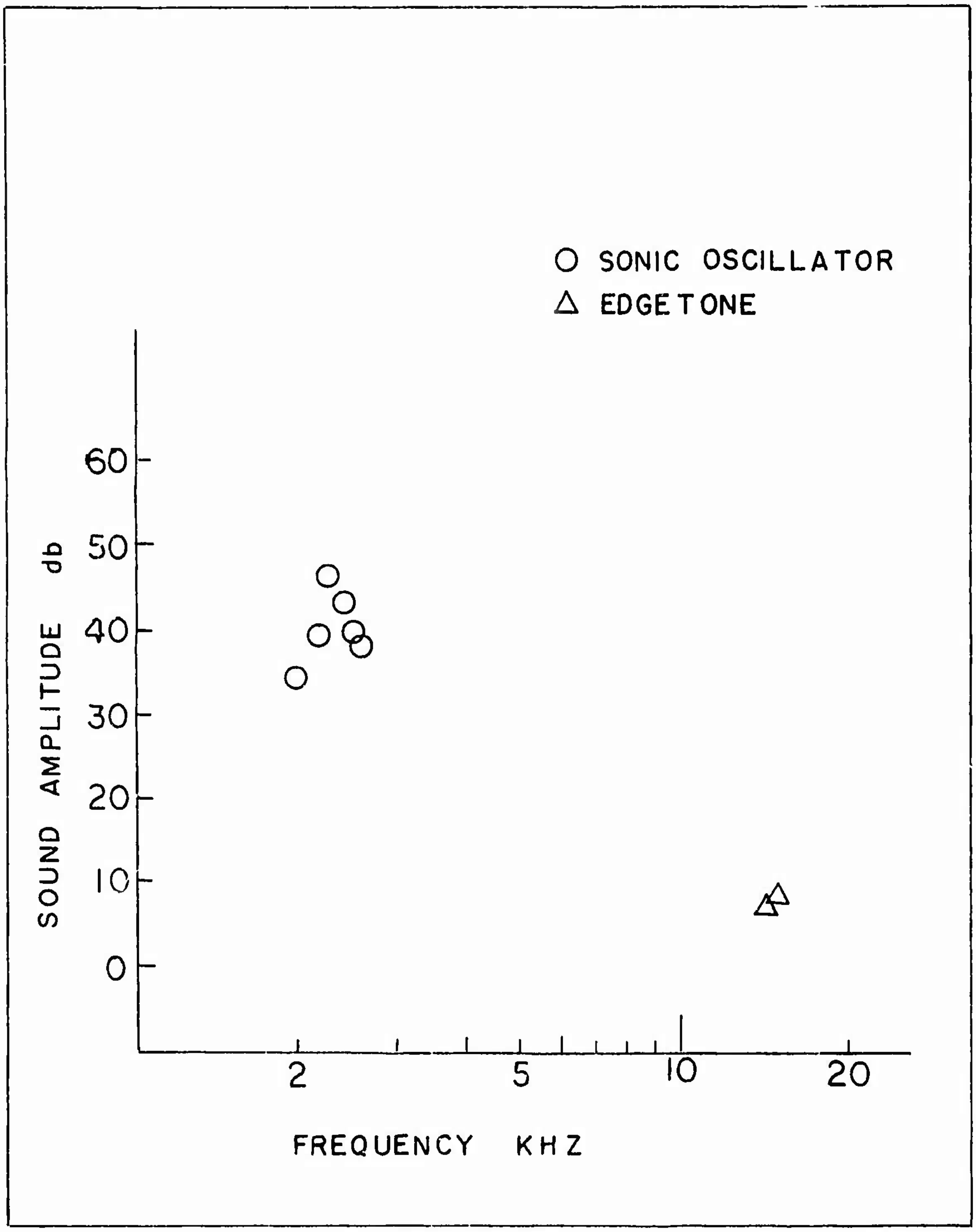


FIGURE 22 OSCILLATOR OPERATING FREQUENCY RANGES

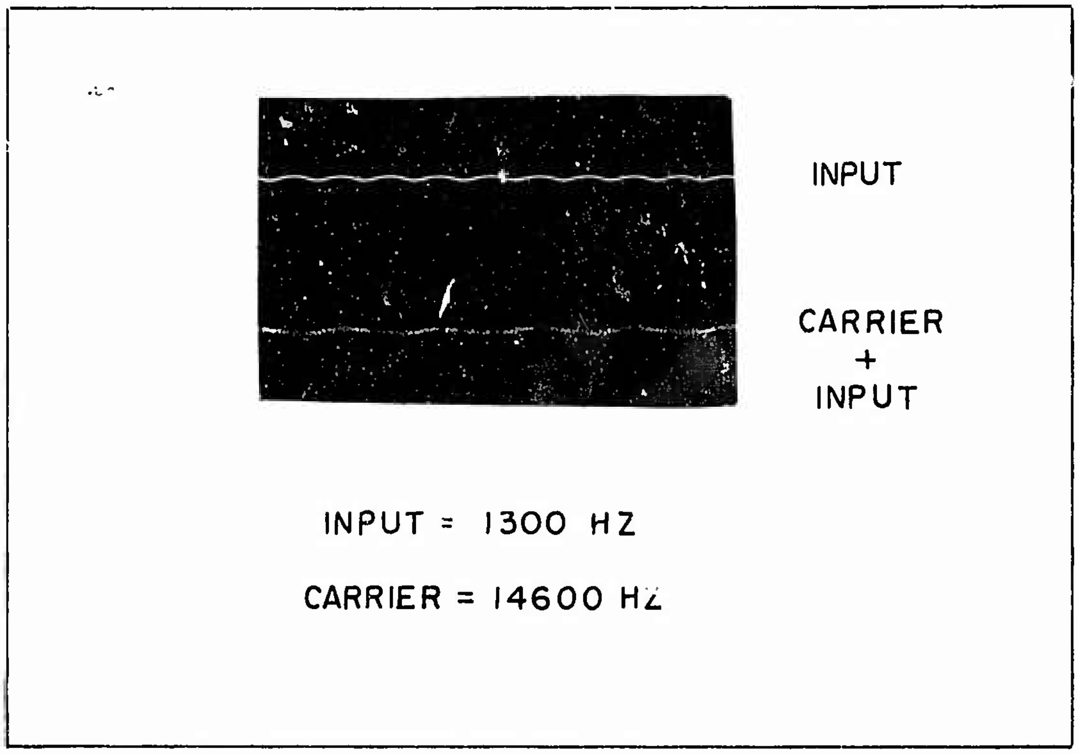


FIGURE 23 MODULATION OF EDGETONE FREQUENCY

only those pressures which provided sinusoidal carrier waves were used.

Summary. Comparison of the results obtained from the two oscillators reveal that there existed two distinct regions of oscillation. Fig. 22 compares the operating frequencies and the sound amplitudes of the two oscillators. The edgetone produced lower amplitude sinusoidal tones but of higher frequency. The sonic oscillator used higher flow rates to produce high amplitude outputs but of low frequency.

Modulation of the Carrier Frequency

The main purpose of modulation is to serve as a means of transmitting the input signal. However an important secondary characteristic inherent in modulation is the ability to amplify input signals over a wide range of frequencies. This aspect of modulation systems enables the transmission of weak signals which would otherwise be attenuated before reaching the receiver. The amplification characteristics of the two modulation systems designed for this study were used as the chief means of comparison.

Edgetone Configuration. A series of signals covering an important segment of the speech range (200-3000Hz) were used to modulate the carrier frequency. Fig. 23 shows a 14600 Hz carrier signal modulated by a 1300 Hz input signal.

The gain produced by the modulation section was determined by the equation

$$\text{Gain} = 10 \log_{10} \frac{V_{out}}{V_{in}} \text{ (db)} \tag{10}$$

where V is the rms voltage recorded by the pressure transducers.

Fig. 24 reveals the amplification characteristics of the oscillator over the range tested. It can be seen that significant amplification occurred at input frequencies of 900, 1000, and 2000 Hz. At other frequencies the signal was attenuated rather than amplified.

Sonic Oscillator Configuration. This oscillator offered generally higher gain characteristics than the edgetone oscillator in the same range. Fig. 25 shows the amplification characteristics of this oscillator when it was operating at 2552 Hz.

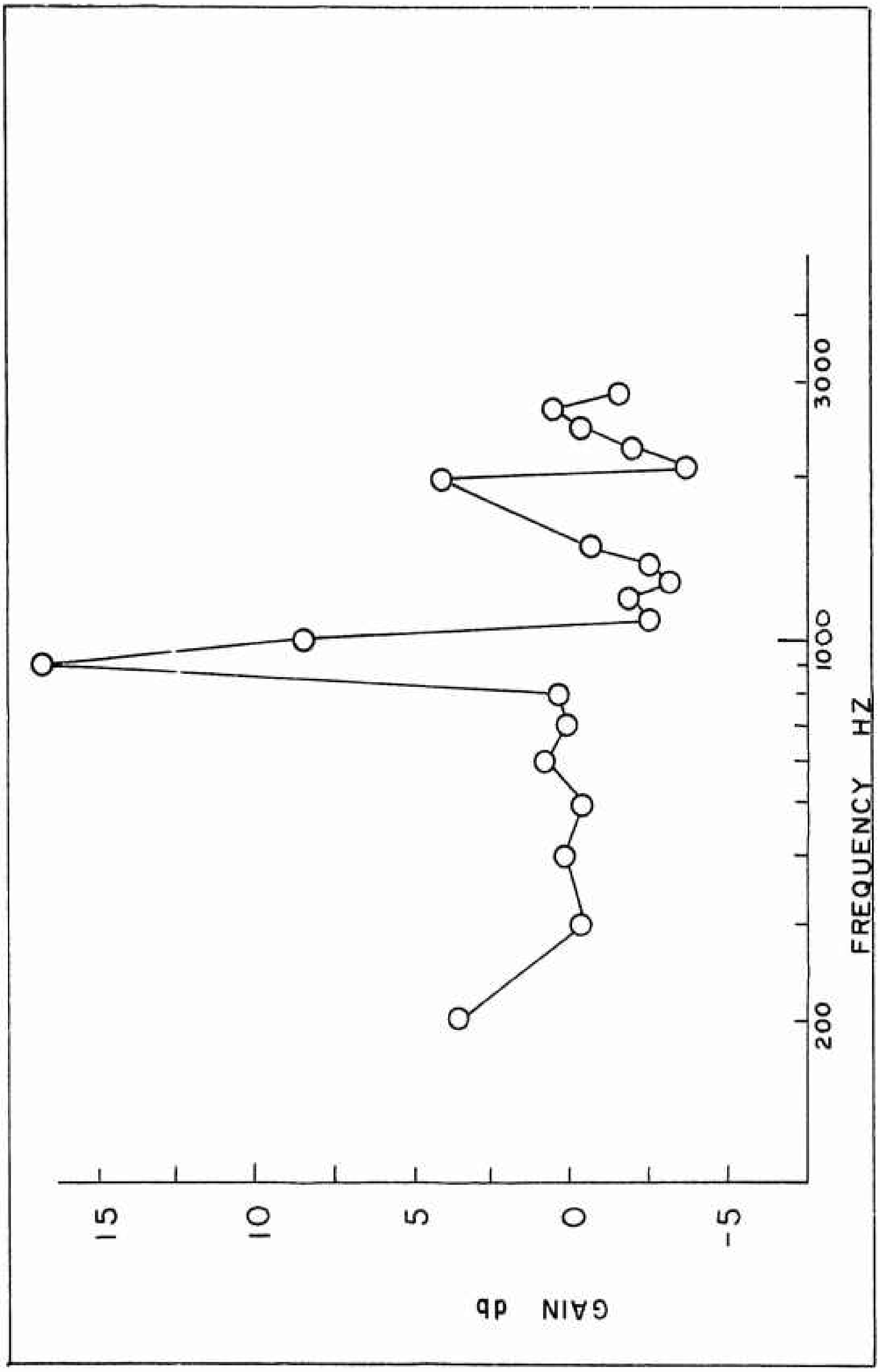


FIGURE 24 SIGNAL RESPONSE - EDGETONE OSCILLATOR

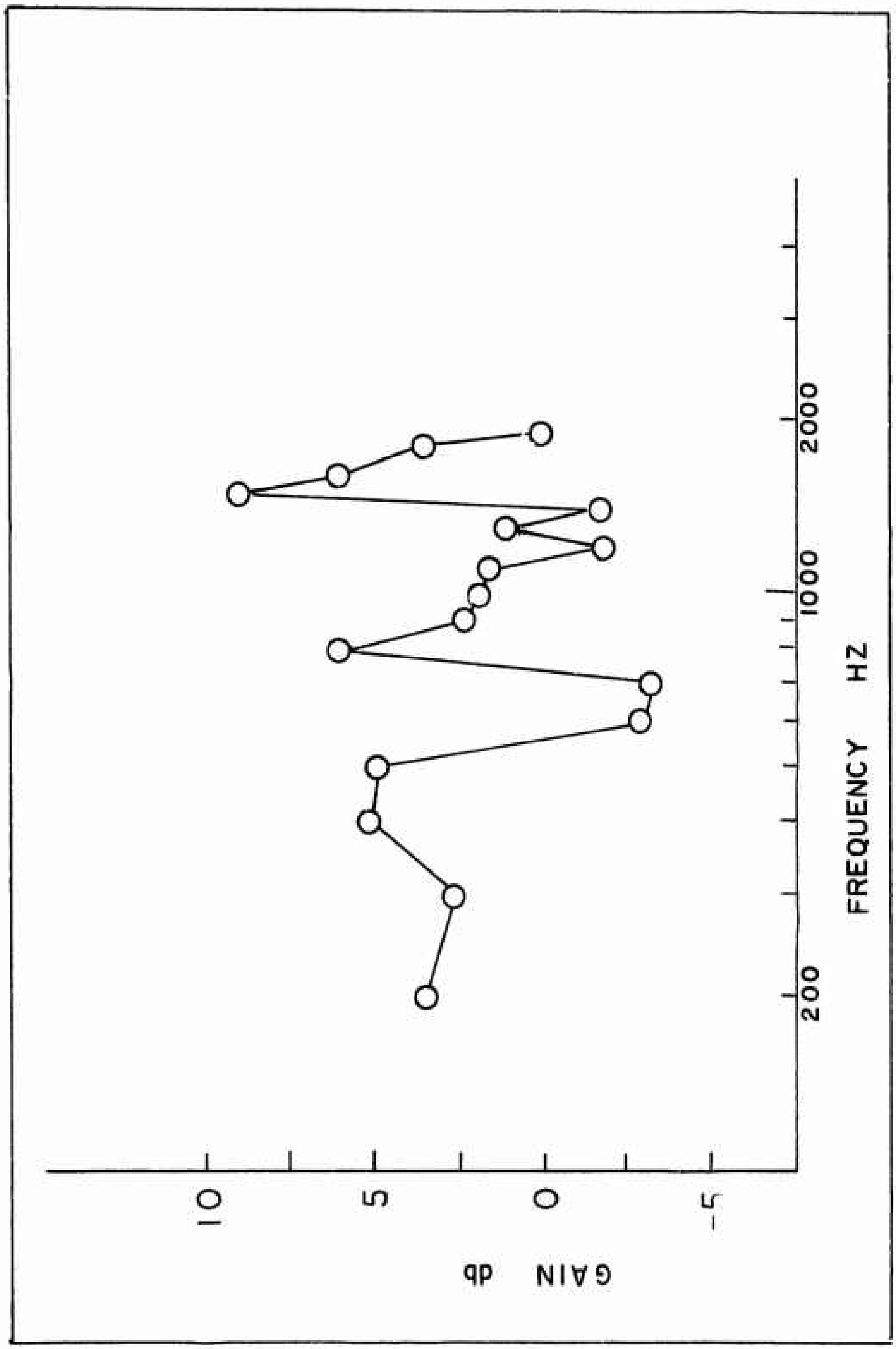


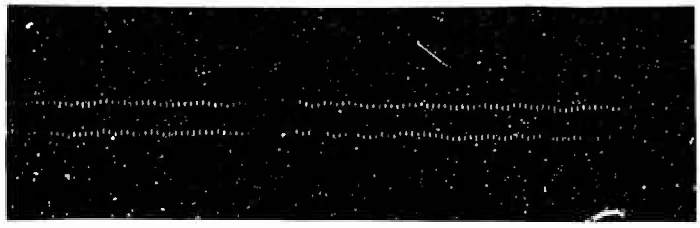
FIGURE 25 SIGNAL RESPONSE - SONIC OSCILLATOR

Because of the greater sound amplitudes created by this oscillator it was easier to observe the actual process of amplification involved. Fig. 26 shows a series of pictures showing a 2240 Hz carrier being modulated by a 467 Hz signal. The magnitude of the input signal was varied until a minimum voltage output was reached at which visible modulation occurred. It was seen that a minimum value existed which depended on the frequency and strength of the carrier. In the case of the 2240 Hz carrier the minimum size of disturbance was about 12% of the rms voltage carrier strengths. At other carrier frequencies this minimum ranged as high as 20% of the rms voltage of the carrier frequency. This minimum voltage for disturbance was a function of the carrier frequency being produced by the oscillator.

Demodulator Characteristics

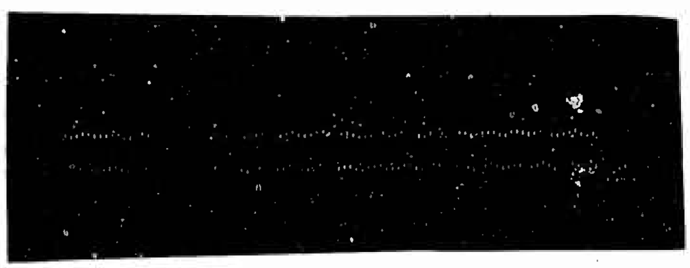
The theory developed for the demodulator stated that by the use of properly positioned flow splitters sound could be produced by splitting an acoustically disturbed jet at the predicted vortex centers. The sound produced by the subsequent changes in mass flow rate would be that of the input signal. Unfortunately this did not occur.

The operation of the demodulator depended on the availability of a jet flow which would be sensitive to the carrier frequency. Using the dimensions of the demodulator and again making the approximation that the velocity of the jet could



2240 HZ CARRIER $V_c = 7.6$ mv

CARRIER + INPUT $\frac{V_I}{V_c} = .37$



CARRIER + INPUT $\frac{V_I}{V_c} = .12$

FIGURE 26 MODULATION OF SONIC OSCILLATOR FREQUENCY be given by the flow rate Q divided by the cross-sectional area of the channel, a graph of Reynolds Number ($R_e = tQ/\nu A$) versus flow rate was plotted (Fig. 27). In addition a graph of the Strouhal number ($St = ftA/Q$) versus flow rate was plotted (Fig. 28) for various carrier frequencies.

With these two graphs and knowing the region of sound sensitive jets (Fig. 5) it was possible to determine a flow rate into the demodulator which would theoretically be sensitive to the carrier frequency. Having determined the flow rate it was then possible to position the splitters at the theoretical center of the vortices as predicted by Savic (Ref 16:245) in equations 6 and 7.

The response of the demodulator was disappointing. Signals were obtained in only a portion of the band (200-2000) of input signals. Those points which were demodulated are shown in Fig. 29. Other signals could not be detected over the "noise" produced by the jet flow running the system.

To try to remedy this lack of response various attempts were made to obtain a signal. Splitter separation was varied to the maximum limit. No improvement in sound output from the demodulator was noted. Investigations into previous studies on sound sensitive jets were made to determine if vortex formation could occur in the distance provided by the demodulator. Upon comparison with previous studies (Ref 18:1165) the length designed into the demodulator should have been enough to develop the jet form as predicted by Savic.

Since the demodulator would not respond satisfactorily to any carrier frequency it must be assumed that the problem

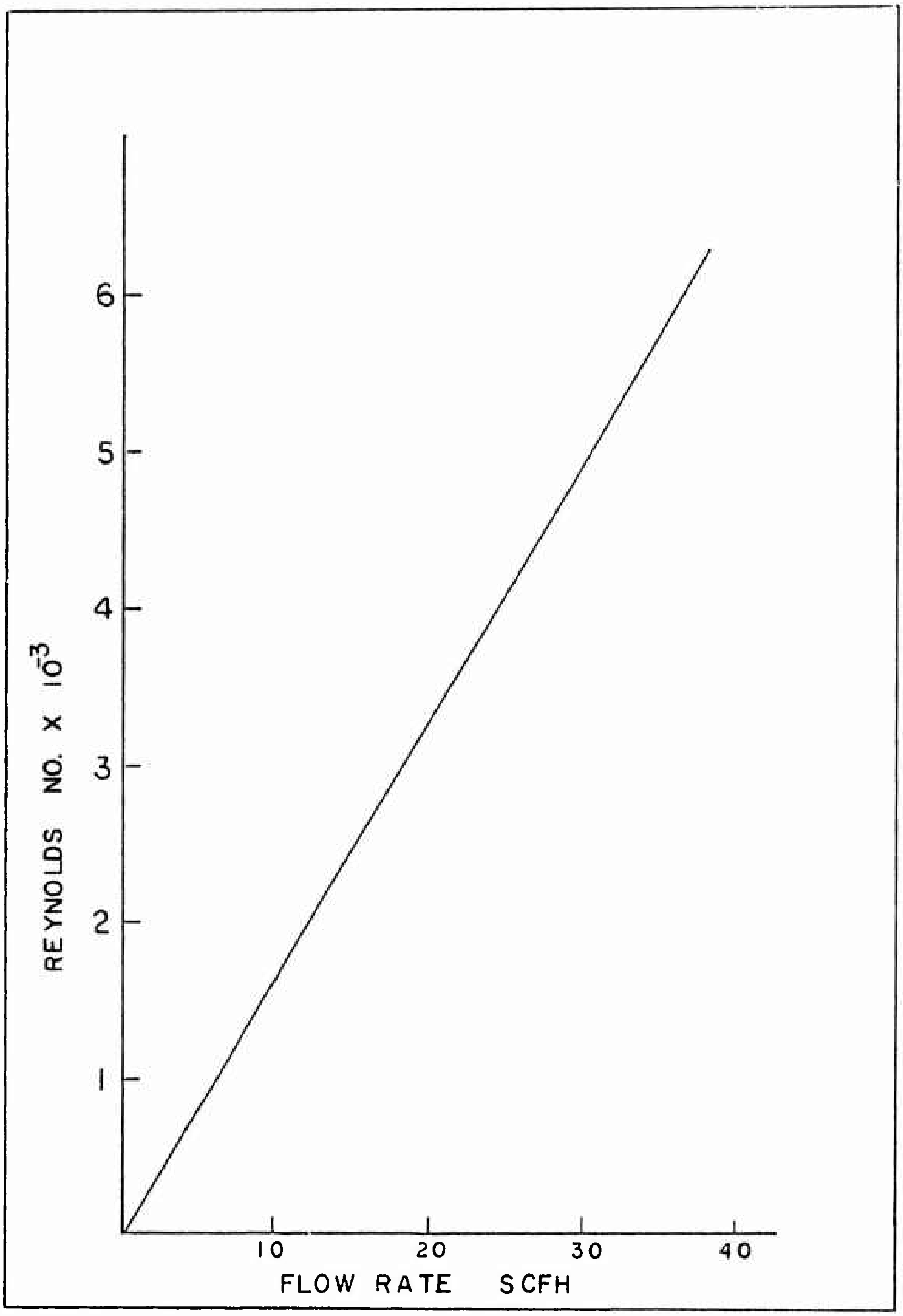


FIGURE 27 REYNOLDS NUMBER VS FLOW RATE - DEMODULATOR

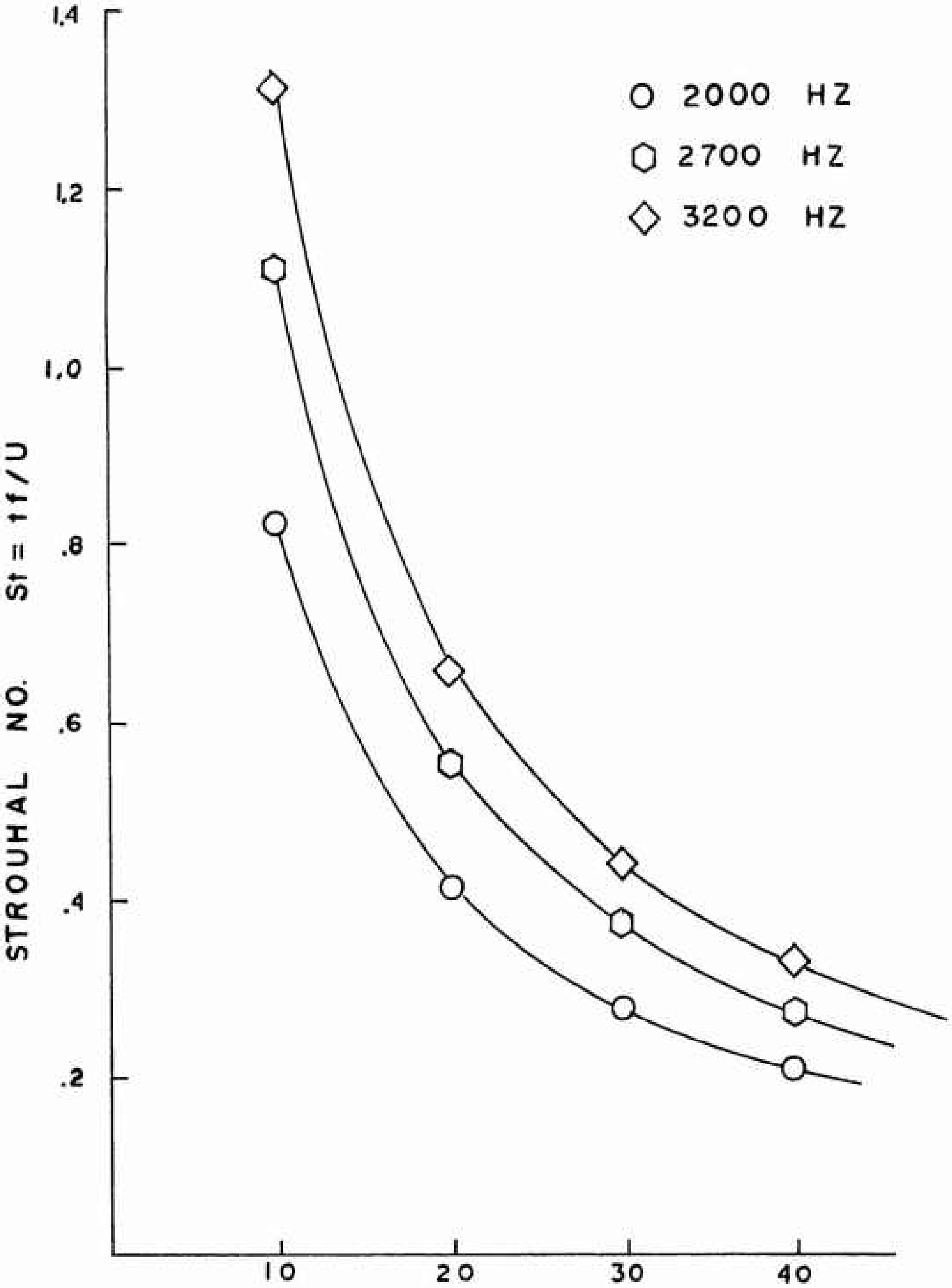


FIGURE 28 STROUHAL NUMBER VS REYNOLDS NUMBER - DEMODULATOR

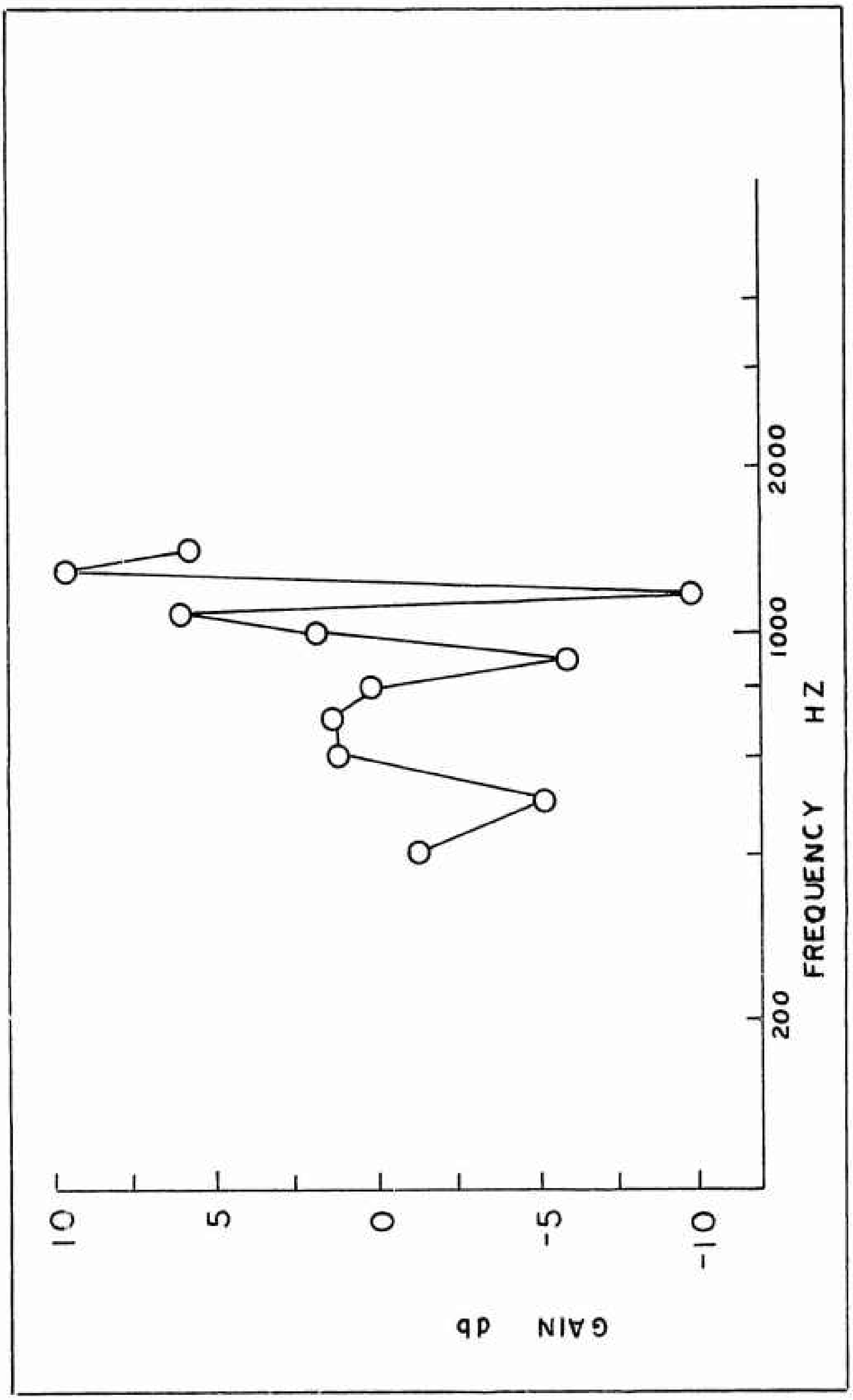


FIGURE 29 SIGNAL RESPONSE DEMODULATOR

lies either in the design of the demodulator or in the positioning of the splitters. Because of the small distances predicted for the spread of an acoustically disturbed jet (Fig. 30 in appendix A) the problem probably lies in the positioning of the splitters.

VI. Conclusions

The following conclusions can be drawn from this study:

1. From theory it is possible to design a fluidic oscillator. Two separate oscillators were designed for two different ranges of frequencies and two different flow rates.

2. The superimposing of the input signal onto the DC flow which drove the oscillator allowed the oscillator to act as an amplifier as well as a modulator. Gains as high as 16.7 db were attained in this manner.

3. The exact reason for the failure of the demodulator is not clear. The chief reason seemed to be that the calculated spread rates of the induced vortices were too small to be picked off by the splitters. The splitters could not be positioned with enough accuracy to split the flow at the predicted center of the induced vortices.

VII. Recommendations

1. Additional study on the spreading of jet flow due to an acoustical signal. Previous studies have predicted that there is an effect on the jet flow. However the minimum power of the acoustic signal to produce the spreading of the jet has not been found. In addition the lateral spread of the center of vortices has not been solved to a point where design can be accomplished satisfactorily.

2. Study of the effect of high frequency signals on the line characteristics. This would allow line diameters and lengths to be determined which would allow the optimum transmission of signals in the system.

3. Redesign of demodulator so as to allow axial as well as lateral displacement of the splitters. This would allow study into a possible position for the splitters.

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Appendix A

Calculation of Vortex Center Spread

Savic (Ref 16:248) in his studies on the effective vortex motion in an acoustically disturbed two-dimensional jet, discovered that the position of the centers of induced vortices of the flow downstream of the disturbance area was predicted by the equation

$$\tanh by = \frac{1}{2bk}$$

where y is the lateral spread, k is an arbitrary constant and b is given by the equation

$$b = 0.2751\ (K/\nu^2)^{\frac{1}{3}}\ x^{-\frac{2}{3}}$$

in which ν is kinematic viscosity, x is the downstream distance and K is the momentum of the fluid per unit time and unit length.

In calculating the spread of the jet the following assumptions are made:

1. The momentum term can be approximated by

$$K = t\ \left(\frac{Q}{A}\right)^2$$

where t is the width of the inlet channel, A is the cross-sectional area of the channel and Q is the volume rate of flow.

2. The arbitrary constant k is taken to be 0.1 as was done by Savic.

Assuming an ambient temperature of $70^{\circ}F$:

$$= 1.7 \cdot 10^{-4} \quad ft^2/sec$$

Other parameters based on demodulator design

$$t = 0.0104 \text{ ft}$$

$$A = 0.00011 \text{ ft}^2$$

$$Q = 10 \text{ SCFH}$$

Solution of Savics equation:

$$K = (.0104) \left(\frac{10}{1.1 \cdot 10^{-4} \cdot .3600}\right)^2$$

$$= 6.631 \quad ft^3/sec^2$$

Therefore:

$$\frac{1}{2bk} = \frac{x^{2/3}}{2(0.1)(0.2751)(6.63/2.89 \cdot 10^{-8})^{1/3}}$$

$$= \frac{x^{2/3}}{33.66}$$

$$b = 168.3 \; x^{-2/3}$$

The location of the center of vortices is therefore given by the equation

$$\tanh \left(168.3 \; x^{-2/3} \; y\right) = \frac{x^{2/3}}{33.66}$$

The results of the solution are given in Fig. 30.

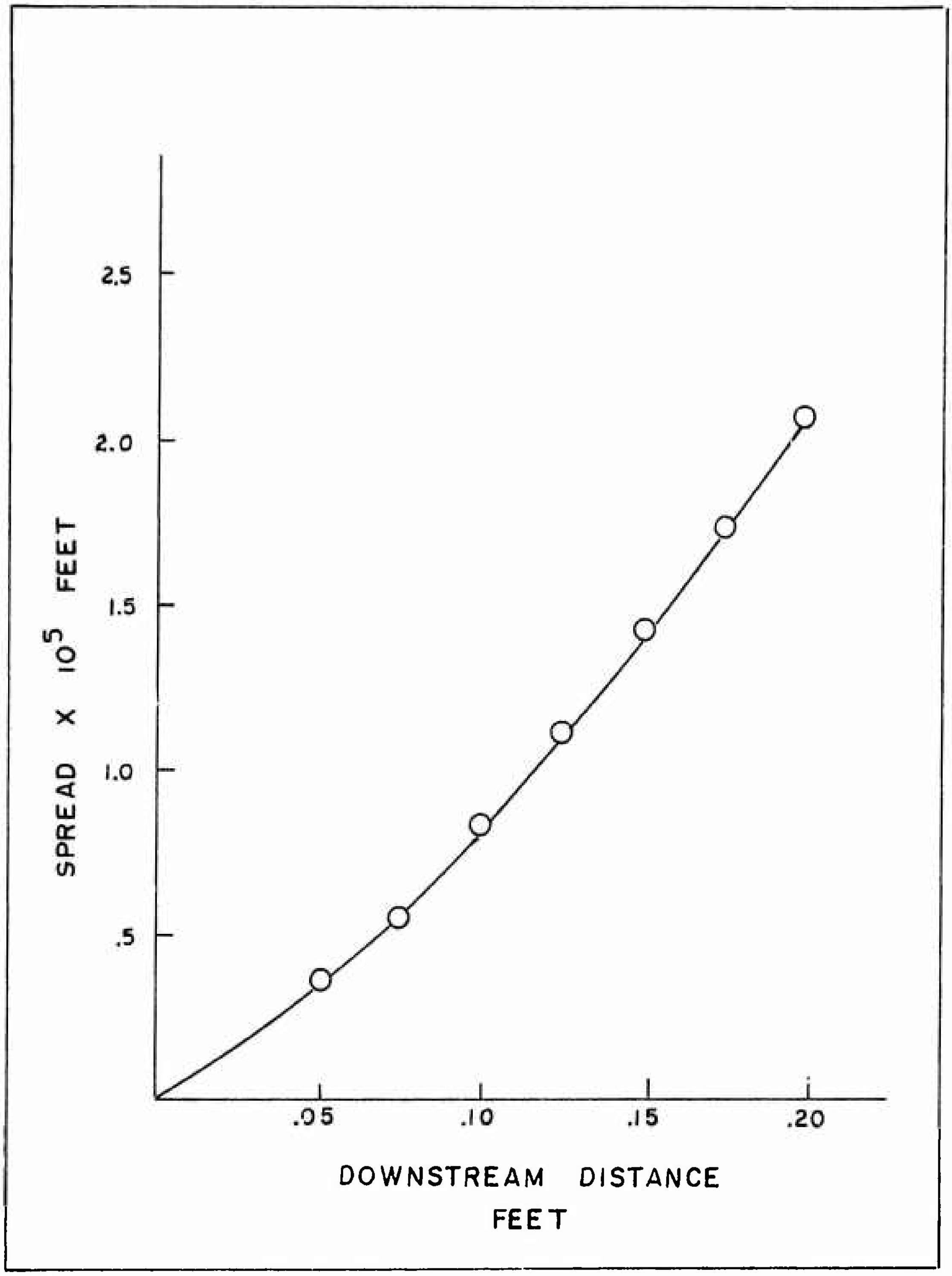

FIGURE 30 LOCATION OF CENTER OF VORTEX REGION

Appendix B

Monitoring Equipment Specifications

Detailed specifications of the monitoring and measurement apparatus mentioned in Section III are listed. These are given in the following manner: name of the instrument, manufacturer, model or type number, range, and additional information such as accuracy, linearity, resolution, etc.

Pressure transducers, Kistler Instrument Corp., Model 701A, range = 0-100 psi, resolution = 0.05 psi, linearity = 0.5%, pizeoelectric type.

Charge amplifier, Kistler Instrument Corp., Model 504, accuracy = ± 1.5%, frequency response DC to 100 khz.

Wave Analyzer, Hewlett-Packard, Model 302A, voltage range = 0-3 volts, voltage accuracy = 5%, frequency range 20 hz - 50 khz, frequency accuracy = 1% + 5 hz.

Oscilloscope, Tektronix Model 551, sweep = .000001 - 5 sec/cm dual trace vertical amplifier, vertical sensitivity = .05-20 volts/cm accuracy = 3%.

Electronic counter, Beckman Model 7360, range = 0 - 100 khz accuracy = 1 hz.

Flowmeter, Brooks Sho-Rate Rotameter, Model 1241-1355 accuracy = ± 5% of maximum scale from 100% to 10% of scale reading.

AC Signal generator driver, Hewlett Packard Model 201C audio oscillator, frequency range 20-20 khz, frequency accuracy = ± 1%, frequency stability = ± 2% or 0.2 hz.

Pressure manometer, 30 inch U-tube Hg manometer Meriam Model 10AA25.

Appendix C

Oscillator Sound Pressure Level Comparison

The normal method of relating sound level measurements is by the use of the sound pressure level. The sound pressure level (SPL) is given in decibels by the equation

$$SPL = 20 \log_{10} \frac{P_{rms}}{P_{ref}} \qquad (C-1)$$

where P_{rms} is the measure of the effective sound pressure of the sound and P_{ref} = 0.0002 microbar.

Substituting into the equation for P_{ref} and converting into f-p-s units you obtain the equation

$$SPL = 20 \log_{10} (3.45 \times 10^8) P_{rms} \qquad (C-2)$$

To make this equation useful for data from the pressure transducers, the pressure reading P_{rms} was converted to an electrical reading by the equation

$$P_{rms} = V S \qquad (C-3)$$

where V is the voltage reading of the rms sound pressure recorded by the pressure transducer and S is the setting on the charge amplifier. Equation (C-2) was then reduced to

$$SPL = 20 \log_{10} (3.45 \times 10^5 S V) \qquad (C-4)$$

where V is now measured in millivolts and S is measured in psig/volts.

Table I. Edgetone Oscillator SPL Measurements

Frequency (Hz)	V (mv)	S(psig/volt)	SPL (db)
12790	.014	2	80
14300	.30	2	106
14400	.41	2	109
14600	.24	2	104
15000	.38	2	108

Table II. Sonic Oscillator SPL Measurements

Frequency (Hz)	V (mv)	S(psig/volt)	SPL (db)
1802	.3	2	105
1981	7.2	2	133
2149	13.0	2	139
2220	22	2	143
2251	29	2	146
2279	34	2	147
2307	33	2	147
2400	20	2	143
2512	13.5	2	139
2614	11	2	138

For comparison purposes 100 db SPL was taken as the reference value on Fig.22.

Appendix D

Experimental Data

Table III.
Modulator Gain - Sonic Oscillator

$f_{carr} = 2552$

Frequency (Hz)	V_{in} (mv)	V_{out} (mv)	Gain (db)
200	.14	.21	3.5
300	.11	.15	2.7
400	.22	.40	5.1
500	.12	.21	4.9
600	.17	.12	-3.0
700	.44	.30	-3.3
800	.05	.1	6.0
900	.28	.36	2.3
1000	.24	.30	1.9
1100	.32	.38	1.5
1200	.69	.55	-1.9
1300	1.3	1.5	1.2
1400	.88	.71	-1.8
1500	.05	.14	9.0
1600	.04	.08	6.1
1800	.04	.06	3.5
1900	.03	.03	0

Table IV.
Modulator Gain - Edgetone Oscillator

$f_{carr} = 14700$

Frequency (Hz)	V_{in} (mv)	V_{out} (mv)	Gain (db)
200	.12	.18	3.5
300	.18	.17	-0.5
400	.36	.38	0.2
500	.82	.78	-0.5
600	1.1	1.2	0.8
700	1.9	1.9	0.0
800	.72	.74	0.3
900	.07	.48	16.7
1000	.08	.21	8.3
1100	.65	.48	-2.6
1200	.60	.48	-1.9
1300	.68	.46	-3.3
1400	.66	.49	-2.6
1500	.84	.76	-0.9
2000	.05	.08	4.1
2200	.17	.11	-3.9
2400	1.2	.95	-2.0
2600	.92	.89	-0.3
2800	.68	.72	0.5
3000	.06	.05	-1.6

Table V.
Demodulator Gain

f_{carr} = 2545   Prob 0.3" from inlet

Frequency (Hz)	V_{in} (mv)	V_{out} (mv)	Gain (db)
200	.004	.004	-
300	.02	.014	-
400	.04	.034	-1.2
500	.36	.20	-5
600	.007	.008	+1.2
700	.31	.36	+1.5
800	.024	.024	0
900	.012	.006	-5.8
1000	.005	.006	2.0
1100	.002	.004	6.2
1200	.01	.002	-9.7
1300	.02	.06	+9.7
1400	.04	.076	6.0
1500	.014	-	-
1600	.002	-	-
1700	.002	-	-
1800	.002	-	-
1900	.002	-	-
2000	.002	-	-

VITA

Robert J. Knowles Jr. was born [redacted] He graduated from [redacted] in 1966. In July 1969 he graduated from Parks College of Aeronautical Engineering, a division of St. Louis University, with the degree of Bachelor of Science in Aerospace Engineering and was commissioned as a Reserve Officer in the United States Air Force. His initial assignment in the Air Force was to the Air Force Institute of Technology beginning September 1969.

Permanent address: [redacted]

This thesis was typed by Mrs. Mary E. Batman