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REVIEW OF SOME FLUID OSCILLATORS

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U.S. ARMY MATERIEL COMMAND
HARRY DIAMOND LABORATORIES
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by
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ABSTRACT

Fluid oscillators of various types have been developed and applied to fluidic systems for sensing or missile control. The operating characteristics of these oscillators, including the dependence of the frequency on the stagnation pressure and temperature, are a function of the type of return loop employed for maintaining oscillations.

This report discusses and summarizes the operating principles, design, frequency variation and applications of some of the most prominent oscillators such as: The sonic, lumped R-C-R and L-R, edgetone, ringtone, and vortex oscillators.

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ILLUSTRATIONS (Cont'd)

1. INTRODUCTION

Mechanical oscillators, such as the pendulum or balance wheel for clocks and windmills, have been extensively used in the past. Electronic oscillators of many kinds have contributed greatly to the advance of modern electronic communication. Recently, the invention of fluid amplification has generated interest in fluid oscillators and their application to sensing, timers, and fluidic control systems. All these oscillators utilize a direct-current energy source which they convert, with some losses, to an alternating output. In the case of the balance wheel in mechanical clocks, the energy is stored in a spring; for the electronic oscillator the energy is provided by a battery or a d-c power supply; for the fluid oscillator the energy is derived from compressed air, which is directed through an orifice or a power nozzle.

An oscillator can be regarded as an amplifier in which some of the output is returned by a feedback loop to the input in such a phase as to cause periodic alternations. In the pneumatic oscillator, the geometrical configuration of the feedback also determines the chief properties of the oscillator, e.g., its frequency and the dependence of the frequency upon stagnation conditions. Hence, oscillators are named according to the type of feedback loop used. A sonic oscillator is one in which the speed of propagation in the feedback loop is approximately equal to the speed of sound; an R-L oscillator uses a fluid resistance and a fluid inductance; an R-C-R uses a fluid resistance-capacitance-resistance. An edgetone oscillator is triggered into oscillations by a series of vortices, generated at the amplifier splitter, which feed back to the nozzle. A vortex oscillator employs the characteristics of vortex flow. The various kinds of oscillators respond differently to their input stagnation conditions. The frequency of a pneumatic oscillator generally is a function of these since the speed of sound in a gas depends on its temperature. The sonic oscillator's dependence on temperature can be used advantageously in a temperature sensor where thermocouples or similar devices are inapplicable. For pneumatic timers that require a time base whose frequency is independent of temperature and pressure, an R-C-R oscillator can be designed. An R-L oscillator can be designed as a pressure sensor since its frequency is pressure sensitive but temperature insensitive. The wedgetone and ringtone oscillators are capable of generating high intensity waves, which find wide applications in industrial processes.

2. EDGETONE AND RINGTONE OSCILLATORS

2.1 Edgetone or Wedgetone Oscillator with a Resonating Cavity

One of the pneumatic oscillators of considerable interest in fluidics is the edgetone-resonator type. Figure 1 shows a jet-edge

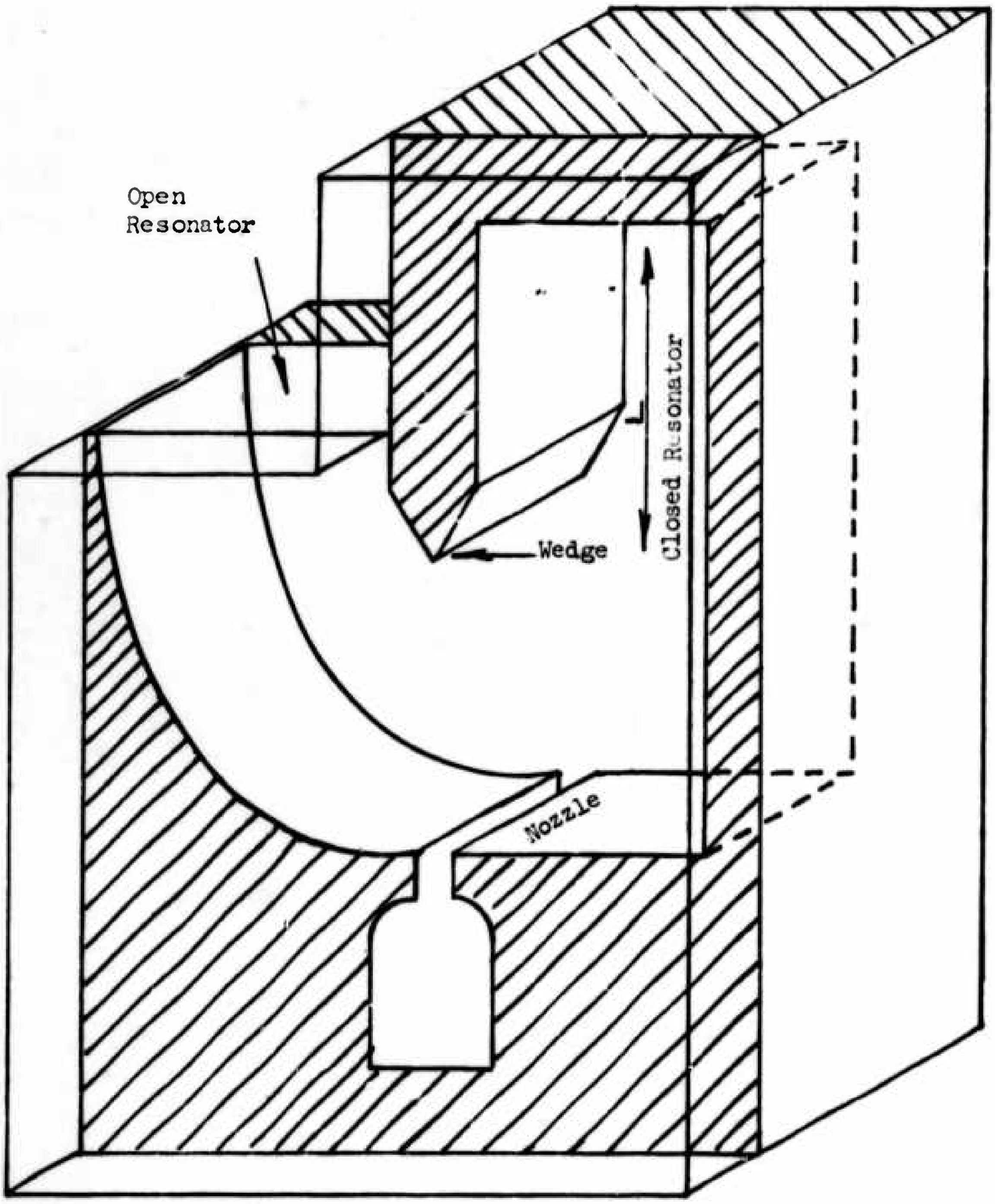


Figure 1. Jet-wedge-resonator oscillator.

system with a resonator in which a thin ribbon-like jet of air impinges upon a wedge situated a short distance from the input nozzle. A device of this sort produces definite tones. Soudhaus (ref 1) in 1954 and later Wachsmuth (ref 2) while studying the tones of a diapason organ stop, observed tones that were determined by the position of an edge and are therefore called edgetones. These are better known in acoustics as jet-tones or aeolian tones. The term wedgetone is used here rather than edgetone, since the jet impinges upon a wedge.

The oscillator under consideration is a compound and complex system in which the wedgetone is coupled to a closed column of air in a rectangular resonator on one side and to a smaller open resonator on the other. In general the oscillator has two frequencies: the wedgetone frequency and the cavity resonant frequency. The oscillator in figure 1 sounds or oscillates at the cavity resonant frequency by drawing the wedgetone out of its natural frequency. Only when the wedgetone frequency approaches one of the cavity eigenfrequencies do the two intersect. The result is the production of beats and mixing (ref 3). The frequency of the wedgetone is found to depend upon the velocity of the stream and the nozzle-to-wedge distance. G. Burniston Brown (ref 4) found that there exists four modes of oscillation for an edgetone system, and that the frequency can be expressed by

$$f = 0.466\ J\ (U_o - a)\left[\frac{1}{h} - b\right] \tag{1}$$

where a and b are experimental constants, U_o is the stream velocity, h is the orifice-to-wedge distance, and the value of J depends on the particular mode in which the jet is oscillating. J has values of 1, 2.3, 3.8, and 5.4 for the four modes. In Brown's work, which deals with laminar jets, a = 40 cm and b = 0.07 cm/sec.

The edgetone oscillator with a resonating cavity is a complex system having two principal sets of operational frequencies— the wedge-tone and the rectangular cavity resonant frequencies. However, in its simplest hydrodynamic form, it can be analyzed by considering that air from the nozzle flows through the open leg of the oscillator, as shown in figure 2. As the jet emerges from the nozzle, it generates turbulence along its boundary. Fluid particles are carried along or entrained by the jet, some of these particles being evacuated from cavity B. When the pressure in the cavity becomes lower than atmosphere, the jet moves into the closed cavity. When the pressure in the cavity becomes high enough, the jet returns to the open cavity and a new cycle is initiated. At the same time wedgetones are generated as the jet sweeps across the wedge.

Experimental studies indicated that the frequency output of the oscillator is a function of the closed cavity length L (fig. 3),

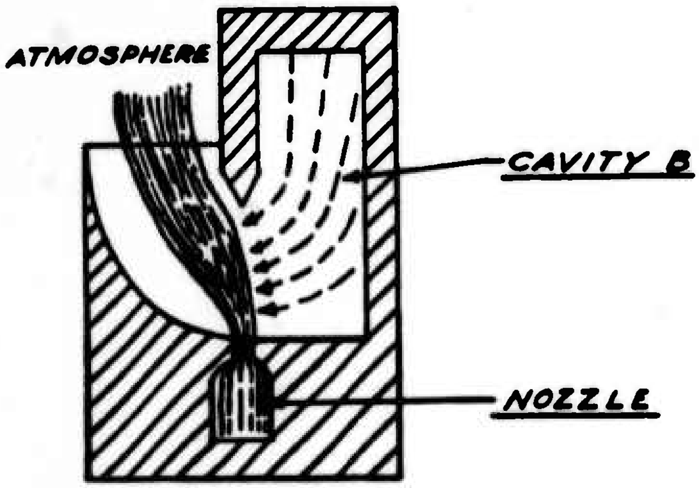


Figure 2. Wedge-tone oscillator operational characteristics.

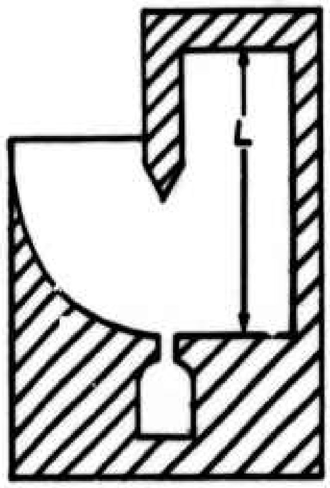


Figure 3. Fluid particle path length.

the capacitance of the cavity chambers, and the input pressure. Figure 4 shows the variation of frequency with input pressure with the greater variation of frequency in the lower pressure range.

2.2 Ringtone Oscillator

The ringtone oscillator is an axially symmetric structure with a cross section like that of a wedgetone oscillator. As shown in figure 5, it consists of an annular nozzle and a resonating cavity. The annular pattern is attained by placing a cylindrical centerbody in the nozzle. When air is introduced through the nozzle orifice, flow separation occurs over the centerbody surface. This induces the jet outer streamlines to converge at a circle beyond the centerbody; the result is a reduction of the effective annular jet diameter. The gas then impinges on the edge of the resonator cavity, producing a ringtone. The ringtone is the dominant frequency of the oscillator whenever the orifice is very close to the entrance of the resonator. The oscillator when used in this particular configuration serves to generate high-intensity oscillations in the sonic or ultrasonic regime (ref 5). When the orifice is set back from the resonant cavity, the frequency output is a function of the length and the volume of the cavity. As shown in figure 5, the frequency is pressure insensitive for this case. The ringtone oscillator can be used to generate high-intensity waves in the frequency range between 1 and 10 kHz. Litsios (ref 5) has shown that when this oscillator is used with a reflector, its efficiency (acoustic power input/pnemuatic input) is almost doubled. This oscillator or acoustic generator is used in industrial processes. For example, in the paper mill industry, it is used to deflate the foam recovered from the pulp washers. High-intensity sound generators (ref 6) can also be used in liquid or vapor degreasing and cleaning processes. Finally, a large ringtone oscillator, better known as an acoustic generator, operating in the frequency range between 2 and 4 kHz, at intensity greater than 150 dB, could be used to disperse a crowd during a riot.

3. SONIC OSCILLATORS

3.1 Sonic Oscillator with Interconnecting Channel

The sonic oscillator (ref 7) consists of a high-gain digital amplifier in which a feedback path is achieved by interconnecting the control ports (fig. 6). If the output has just shifted to the right outlet, entrainment reduces the pressure in the right control nozzle. An expansion wave propagates through the interconnection channel toward the left control nozzle. Simultaneously, atmospheric air coming through the left outlet starts a compression wave at the left control nozzle, which propagates through the same channel toward the right control nozzle. Both waves reach their destinations simultaneously and deflect the output to the left outlet. This starts a chain

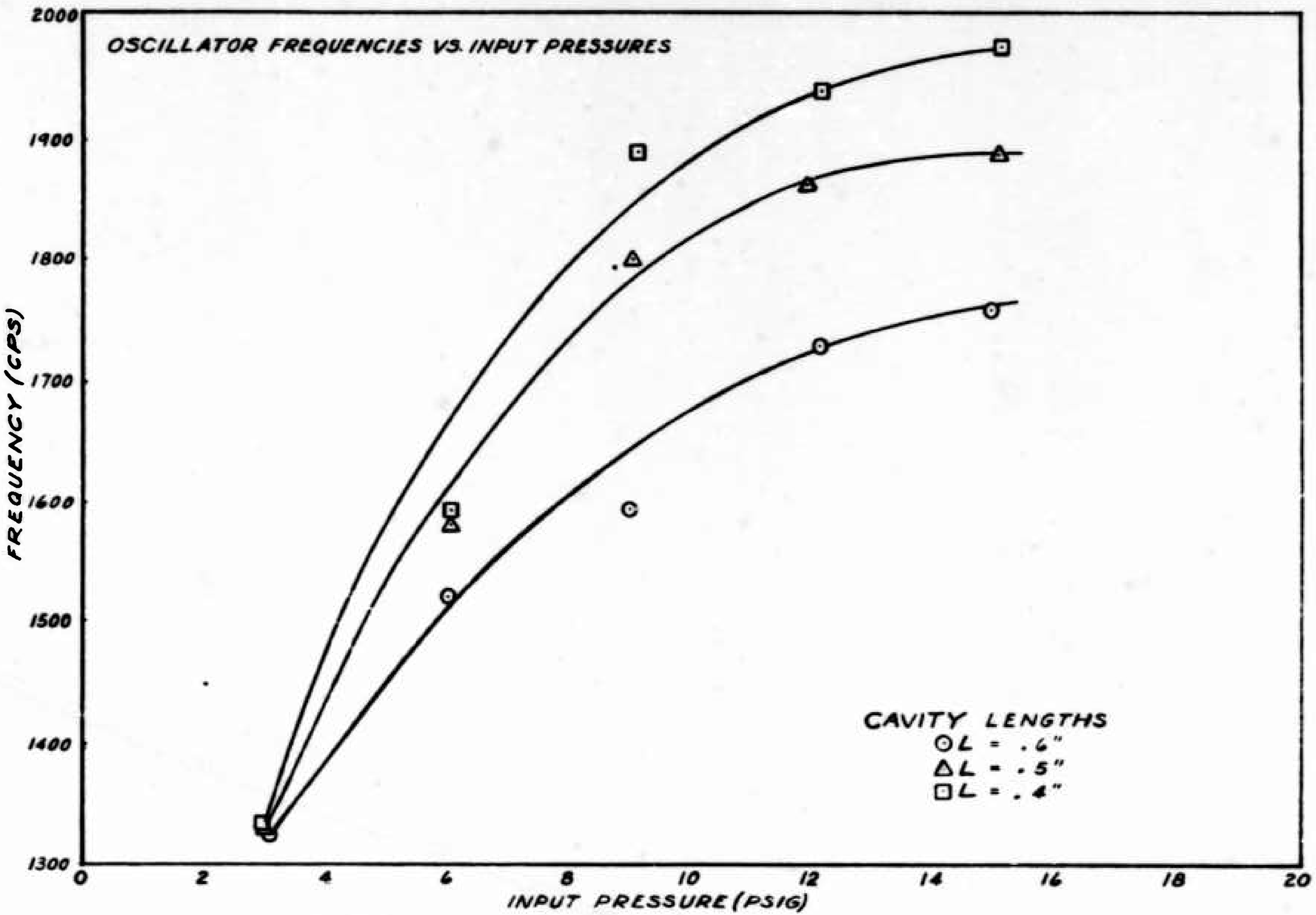


Figure 4. Wedgetone oscillator frequency characteristics.

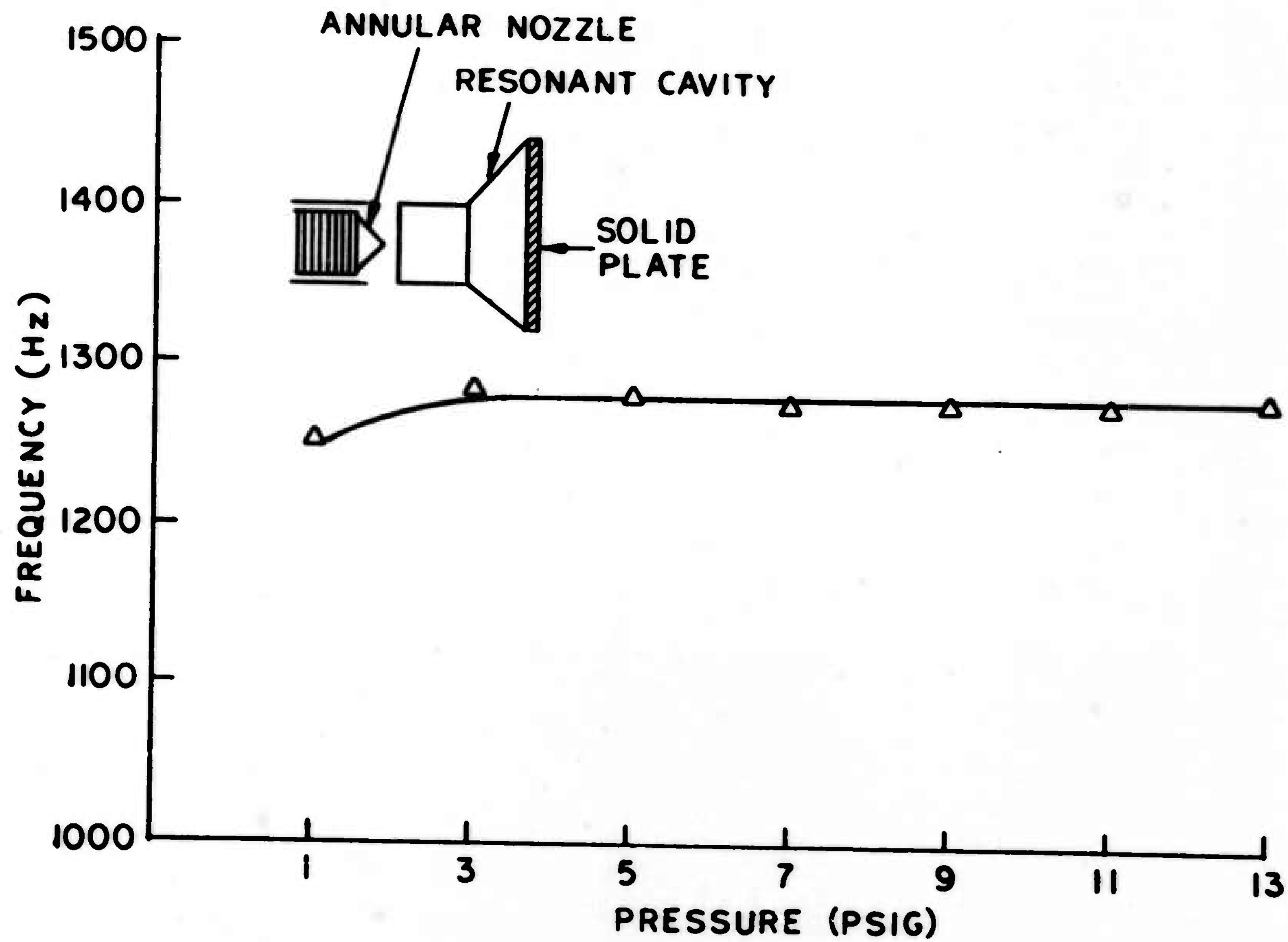


Figure 5. Ringtone oscillator-pressure versus frequency.

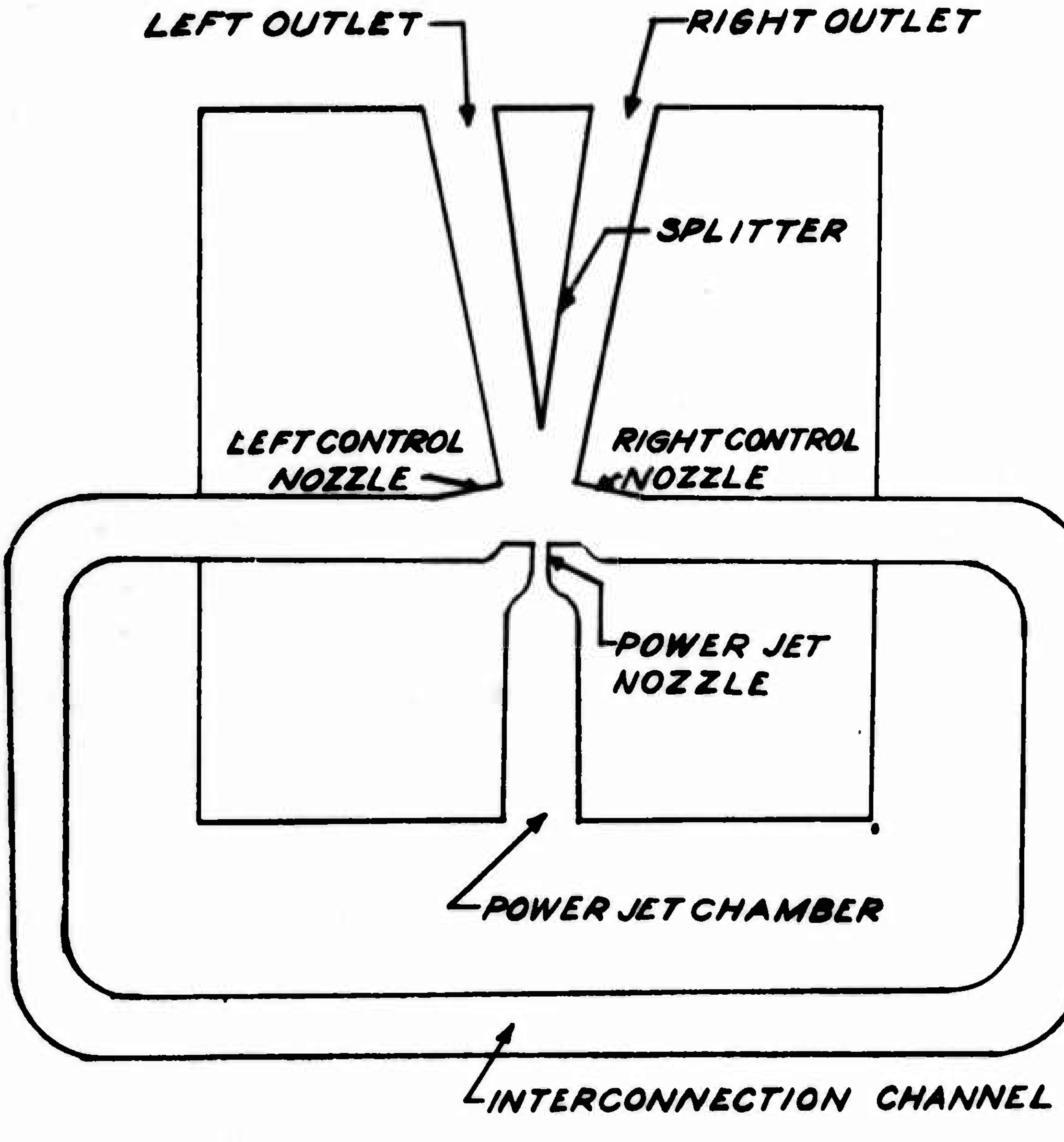


Figure 6. Schematic of sonic oscillator with interconnection channel.

of events which is similar but of opposite polarity, and a short time later the output is deflected to the right, completing one cycle and initiating the next. The period of oscillation is an inverse function of the speed of wave propagation of the fluid in the feedback loop. For small differential pressure across the jet and for an interconnection line whose cross section is not too small, the speed of wave propagation is nearly equal to the free speed of sound. Then the period of oscillations is

$$\tau = \frac{2L}{a_\infty} \tag{2}$$

where L = length of the interconnecting feedback path and a_∞ = free speed of sound. From equation (2) it follows that the frequency is

$$f = \frac{(\gamma R_g T)^{\frac{1}{2}}}{2L} \tag{3}$$

where γ is the specific heat constant, R_g is the gas constant, and T is the absolute temperature.

From equation (3) it is evident that the frequency is temperature dependent. The supply pressure and ambient pressure also affect the frequency. Figure 7 shows the dependence of the frequency on stagnation pressure for two lengths (2 and 4 ft) of interconnecting channel.

Figure 8 indicates the variation of frequency when the length L of the interconnecting channel is varied. Comparison between the experimental values and those obtained from equation (3) seems to show good agreement. The frequency in equation (3) is derived on the assumption that the switching time of the amplifier is negligible compared with the wave travel time in the interconnecting channel. Experiments (ref 7) indicate that the switching time t_s can be expressed as

$$t_s = \frac{1}{2}\left(\frac{1}{F} - \frac{1}{f}\right) \tag{4}$$

where F is the measured frequency and f is given by equation (3). The switching time appears to depend on the length and diameter of the interconnecting channel. For longer lengths and small diameters the switching time increases. The dependence of the switching time on the geometry of the interconnecting channel is caused by the attenuation of the waves (traveling in the channel), thus increasing the rise time of the pressure difference at the control ports necessary to deflect the jet. The sonic oscillator is a readily available, very versatile, and useful device. For laboratory use, one simply interconnects the control ports of a high-gain digital amplifier by a suitable length of tubing. However, its applications are thus far

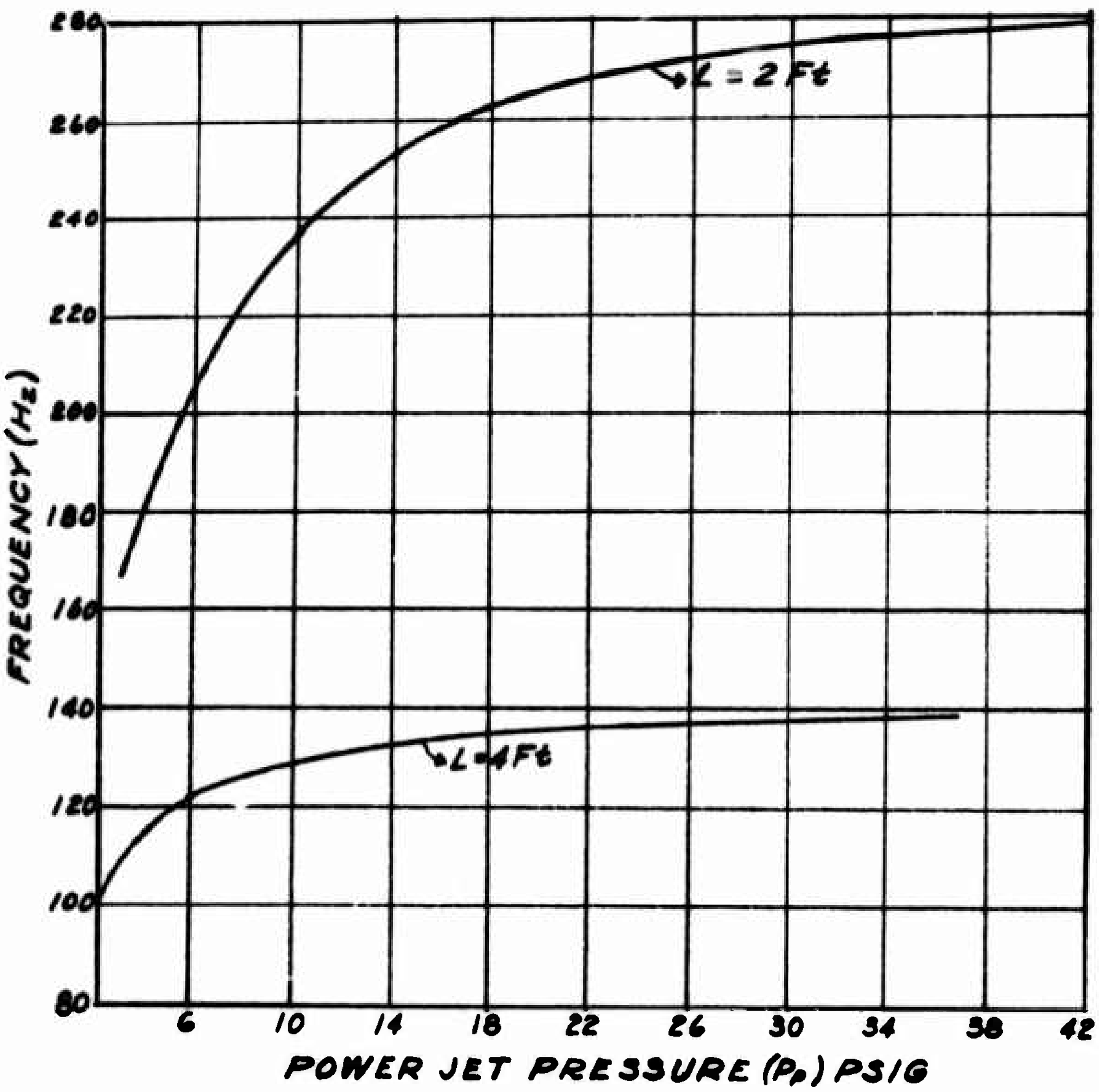


Figure 7. Sonic oscillator (with interconnecting channel) frequency versus power-jet supply pressure.

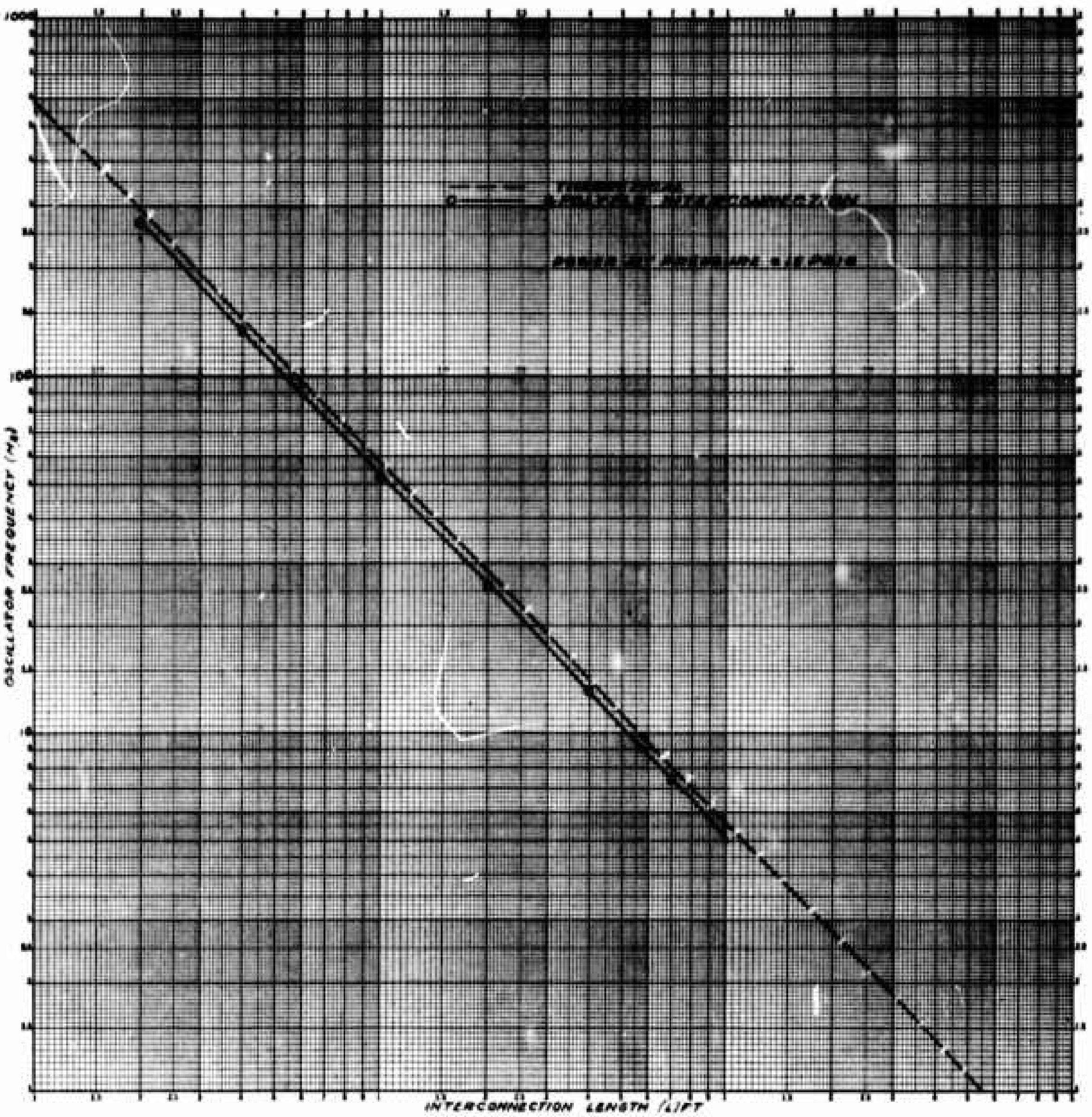


Figure 8. Sonic oscillator frequency versus interconnection channel length.

limited because its output frequency is dependent on both temperature and pressure.

3.2 Sonic Oscillator with Internal Feedback Loop or Temperature Sensor

The sonic oscillator with an internal feedback loop (fig. 9) operates by the coupling between a resonator and a jet edge (or splitter) and is similar to the wedgetone oscillator. When a stream issues from a nozzle and impinges on a wedge (splitter), it produces vortices at the wedge (ref 4). These vortices propagate back to the nozzle orifice forcing the jet to oscillate transverse to its direction of flow. These oscillations, referred to as edgetone or wedgetone oscillations, were discussed in conjunction with the wedgetone oscillator with resonator. The frequencies of the oscillations are given by equation (1).

If two symmetric cavities are placed on either side of the jet so that coupling occurs between the jet-edge frequency and the cavity resonant frequency continuous oscillations are maintained. The resonant frequency of the cavity depends on the acoustic velocity and on the cavity length, so

$$f = \frac{a_\infty}{4\ell}$$

ℓ = length of cavity

a_∞ = free speed of sound

Since the acoustic velocity is a function of temperature, the output frequency is

$$f = \frac{(\gamma R_g\ T)^{\frac{1}{2}}}{4\ell} \qquad (5)$$

where

γ = specific heat constant

ℓ = length of cavity

R_g = gas constant

T = temperature of gas

The pressure dependence of the oscillator is controlled by adjusting the size of the exhaust area. If the exhaust area is smaller than the power jet exit aperture, a choked flow condition can be achieved at the oscillator's exit and the pressure ratio across the

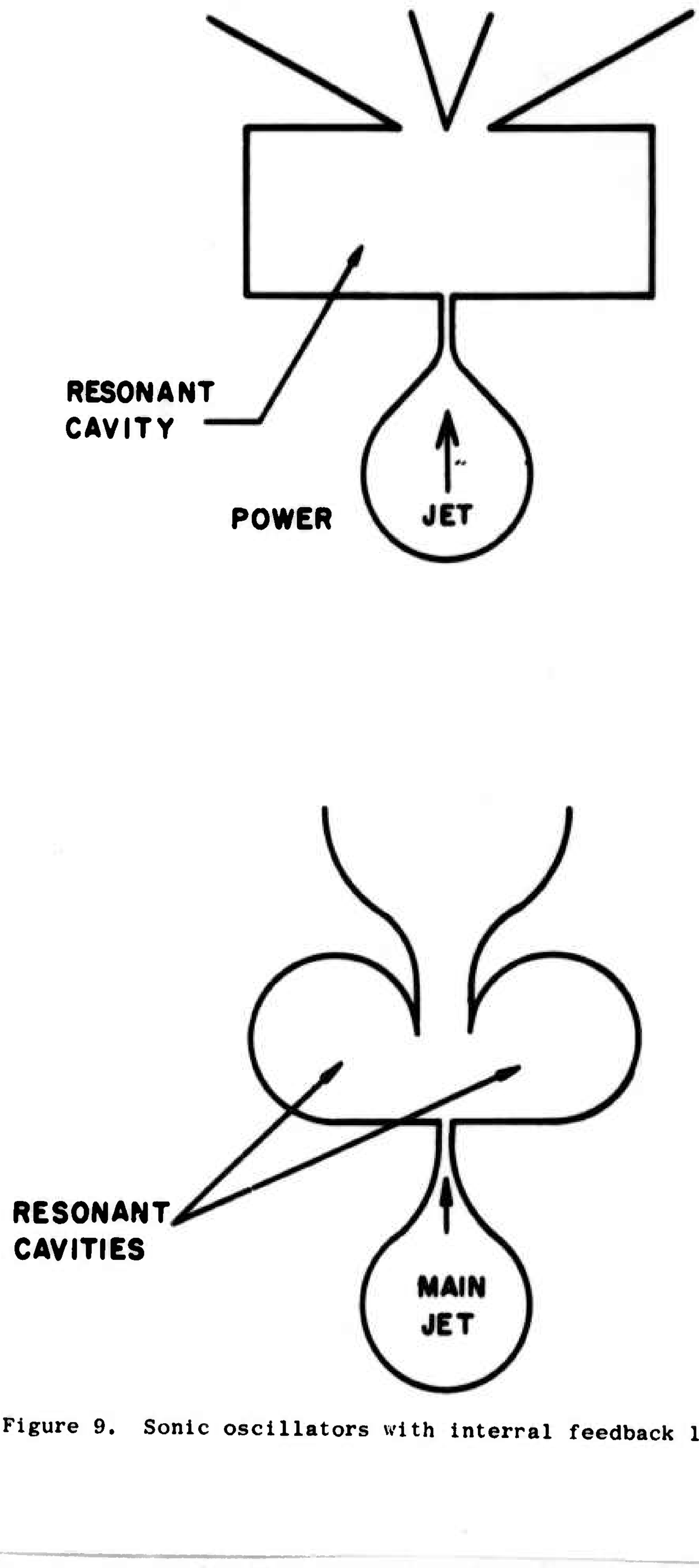


Figure 9. Sonic oscillators with interral feedback loop.

power nozzle is smaller than the critical pressure ratio. Equation (5) shows that frequency is a function of temperature and this characteristic allows the element to be used as a temperature sensor. Basically the main difference between the wedgetone oscillator with a resonant cavity and the temperature sensor is that, in the first case, the frequency of the wedgetone is higher than the cavity resonant frequency, and, in the second case, the two are the same.

The sensitivity of the temperature sensor, defined as the change in frequency per degree change in temperature, is

$$\frac{\Delta f}{\Delta T} = \frac{f-f_o}{T-T_o} = \frac{f_o}{T-T_o}\left[\left(\frac{T}{T_o}\right)^{\frac{1}{2}} -1\right] \qquad (6)$$

From equation (6) it appears that, if the frequency f_o taken at T_o is chosen very high, the oscillator will be more sensitive to temperature change. Obviously to operate at the high frequency the cavity must be small.

The basic advantage (ref 8) of this gas-temperature sensor is that it combines rugged construction with a response speed fast enough to measure temperature in a wide variety of applications ranging from blast furnaces to nuclear reactors. Recently the temperature sensor was installed in the leading edge of the vertical stabilizer of the X-15 experimental rocket plane to measure the jet stream temperature, which reaches values as high as 2800°F. This temperature sensor has also been used in gas turbines for automatic over-temperature control, automatic control of engine acceleration to avoid surging, and temperature indication in the cockpit (ref 8).

4. R-L OSCILLATOR

4.1 Temperature Insensitivity

Certain applications require the use of a pneumatic oscillator whose frequency is independent of changes in stagnation temperature but dependent on the pressure of the working gas. Such an oscillator could be designed using an inductance-resistance feedback loop (ref 9).

Figure 10 shows the configuration of an R-L oscillator. It consists of a high-gain digital amplifier and a feedback loop that returns a portion of the output to the control nozzle. The frequency of oscillation is then a function of the complex speed of wave propagation in the feedback network:

$$f = |C|/\ell \qquad (7)$$

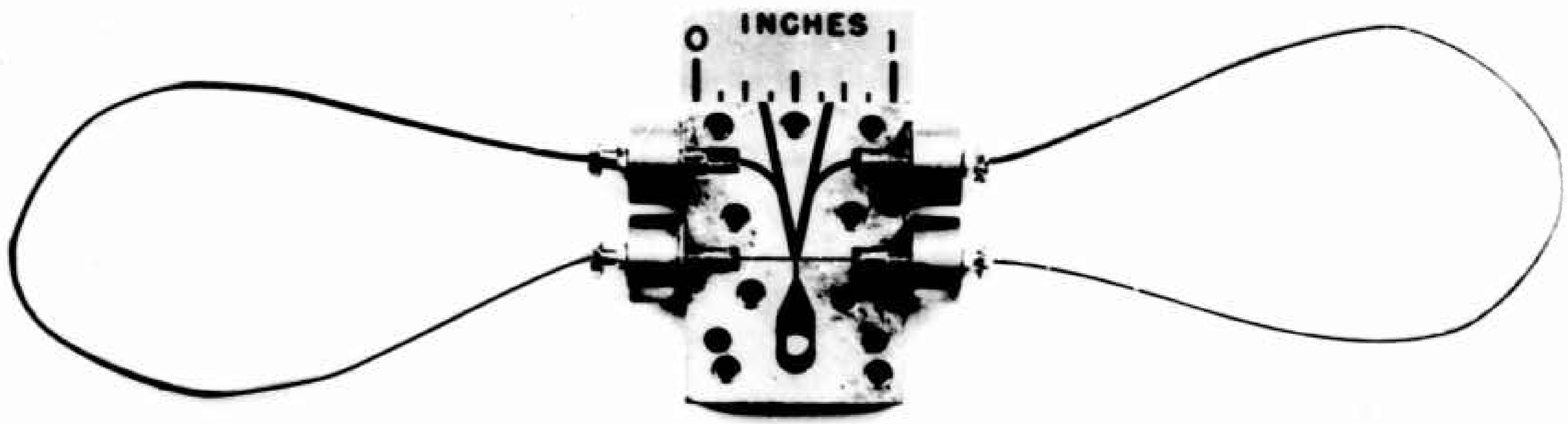


Figure 10. Resistance-Inductance (R-L) feedback oscillator.

where $|C|$ = complex speed of wave propagation, ℓ = length of the feedback path. The magnitude of the complex speed of wave propagation in an R-L network of constant cross-section area can be expressed approximately for small amplitude waves (ref 10) by

$$|C|^4 = \frac{a_\infty^4}{1 + \dfrac{R^2}{\omega^2 L^2}} \tag{8}$$

where a_∞ = free speed of sound, R = resistance per unit length, L = inertance per unit length, and ω = angular frequency. For a duct with circular cross section

$$R = \frac{8\pi\mu}{A^2} \quad \text{and} \quad L = \frac{\rho}{A}$$

where μ = viscosity of the working gas (for air it is approximately proportional to $T^{3/4}$), A = cross-sectional area of duct, and ρ = density of the working gas. For an ideal gas

$$\rho = \frac{P}{R_g\ T}$$

where P = pressure in the feedback loop, T = absolute temperature of the gas, and R_g = gas constant. Substituting the values of R, L, and ρ for air in equation (8),

$$|C|^4 = \frac{K_1}{\dfrac{1}{T^2} + \dfrac{K_2\ T^{3/2}}{\omega^2 A^2 P^2}} \tag{9}$$

where K_1 and K_2 are constants.

From equation (8) it follows that $|C| = 0$ for T = 0 and T = ∞; consequently $|C|$ has a maximum value at some temperature, and it should be least sensitive to temperature changes in the vicinity of the maximum. Hence, it follows that, if the maximum value of $|C|$ could be expanded over a required temperature range, then from equation (7), for an oscillator with a uniform duct in the feedback path, the frequency would be temperature insensitive. $|C|$ is maximum when the denominator in equation (9) is a minimum. Setting the derivative of the denominator with respect to temperature equal to zero, yields

$$T_M = \left[\frac{4\ \omega^2\ A^2\ P^2}{3K_2}\right]^{2/7} \tag{10}$$

where T_M is the temperature at which the magnitude of the complex speed of wave propagation is maximum for a given angular frequency ω, static pressure P, and cross-sectional area A.

To design an oscillator that is temperature insensitive in the vicinity of a required temperature T_1, the following procedure is necessary:

(a) Let $T_1 = T_M$ in equation (10).

(b) Solve for ω AP in equation (10).

(c) For the desired ω, select A and P to be compatible with the computed ωAP.

(d) Substitute ωAP in equation (9) to determine $|C|$.

(e) Substitute $|C|$ in equation (7) and determine the frequency f_1 and $\omega_1 = 2\pi f_1$.

(f) If $\omega_1 \neq \omega$, modify A and P and iterate steps (c) through (e) until $\omega_1 = \omega$.

The result of the above theory is shown in figure 11 where the value of the frequency obtained at $|C|$ maximum is displayed. Figure 12 shows the experimental results. It is evident that the maximum frequency in figure 11 has approximately the same value as the measured frequency in figure 12. In the use of the equations the Mach number was assumed to be unity at the entrance of the feedback network. In reality the Mach number varies with position along the duct and reaches unity only at the exit. This assumption is responsible for the difference between the temperature at which the computed curve peaks and the range of temperature over which the frequency is constant.

4.2 Pressure-Controlled Oscillator

The above analysis indicates that temperature insensitivity is obtained by compensating the wave speed along the R-L feedback loop, and that the insensitivity to temperature is obtained at the expense of an increase in sensitivity to pressure. This can be observed from equation (9), where for ducts of small cross-sectional area in the feedback loop $|C|$, the speed of wave propagation becomes pressure sensitive. This property, under certain conditions, can be used to design a pressure-controlled oscillator whose frequency is approximately proportional to the input pressure. From equation (7)

$$|C| = \frac{\omega \ell}{2\pi}$$

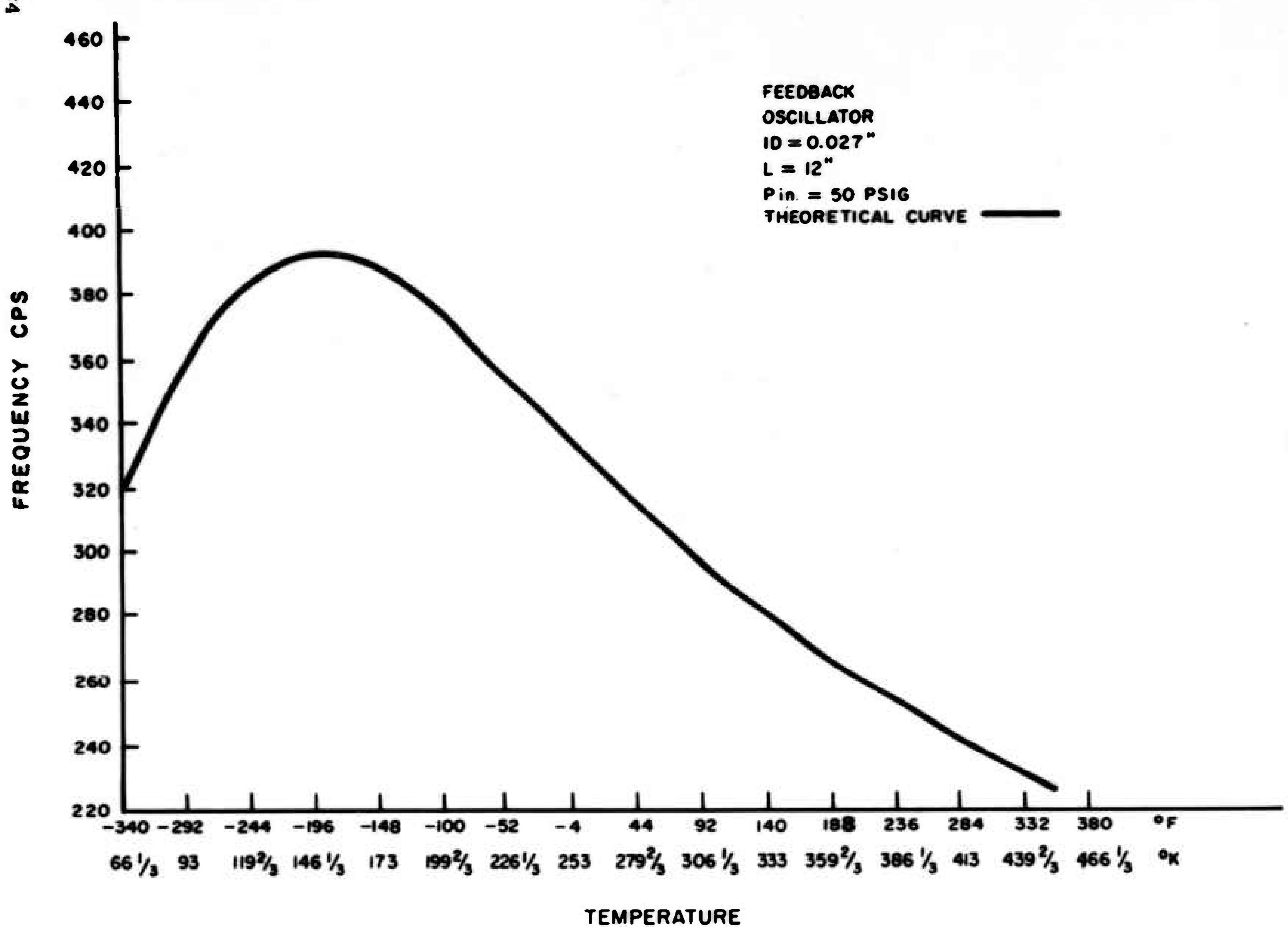


Figure 11. R-L oscillator computed frequency versus temperature.

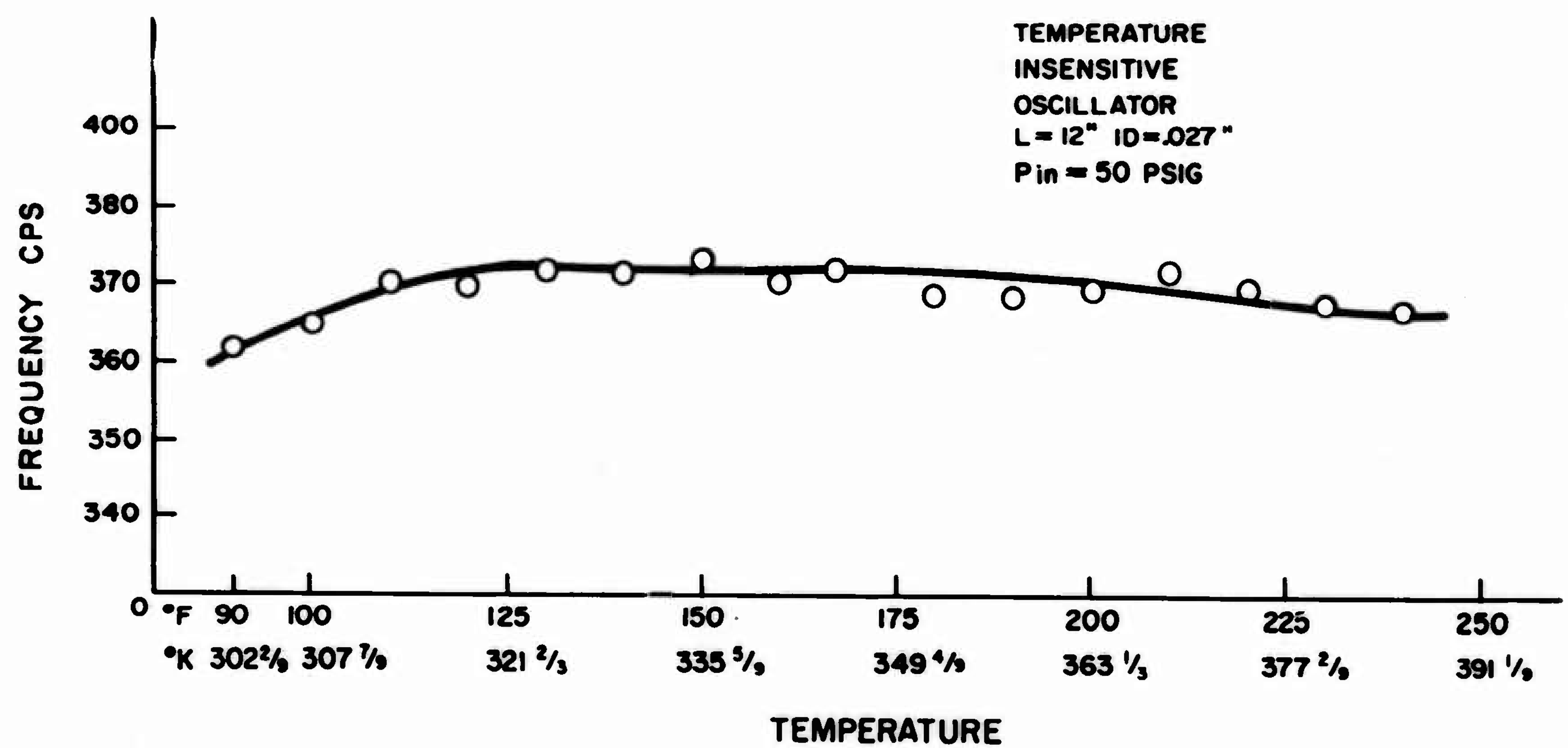


Figure 12. R-L oscillator temperature versus frequency (experiment).

Substituting into equation (9) and solving for ω^2, we get

$$\omega^2 = \frac{K_2 T^{7/2}}{A^2 P^2} + \frac{1}{2}\left[\frac{K_2^2 T^7}{A^4 P^4} + \frac{4K_1 (2\pi)^4 T^2}{\ell^4}\right]^{\frac{1}{2}} . \qquad (11)$$

Rearranging terms in (11) yields

$$\omega^2 = \frac{K_2 T^{7/2}}{A^2 P^2}\left[-\frac{1}{2} + \frac{1}{2}\left(1 + \frac{4(2\pi)^4 K_1 T^2}{\ell^4} \cdot \frac{A^4 P^4}{K_2^2 T^7}\right)^{\frac{1}{2}}\right] \qquad (11a)$$

If A, P and L are chosen properly

$$\frac{4(2\pi)^4 K_1 T^2}{\ell^4} \cdot \frac{A^4 P^4}{K_2^2 T^7} << 1 .$$

Then the radical can be approximated by

$$1 + \frac{1}{2}\left(\frac{4(2\pi)^4 K_1 T^2}{\ell^4} \cdot \frac{A^4 P^4}{K_2^2 T^7}\right)$$

and (11a) becomes

$$\omega^2 \approx \frac{K_2 T^{7/2}}{A^2 P^2}\left[\frac{(2\pi)^4 \; K_1 A^4 P^4}{\ell^4 \; K_2^2 \; T^5}\right]$$

from which

$$\omega \approx (2\pi)^2 \left(\frac{K_1}{K_2}\right)^{\frac{1}{2}} \frac{A}{\ell^2 \; T^{3/4}} P \qquad (12)$$

Equation (12) is the relation desired for a pressure-controlled R-L oscillator. Figure 13 compares the computed and measured dependence of the frequency.

The R-L oscillator can be used to measure pressure inside jet engines or like systems where changes in frequency occur primarily from pressure variations. The pressure-controlled oscillator can be adapted to timing devices to measure the distance traveled by projectiles or missiles in which velocity changes occur along the flight path; in this case the oscillator frequency will vary with changes in velocity along the path traveled because the pressure at the missile nose is velocity dependent. Counters integrate the number of cycles generated and provide a measure of distance.

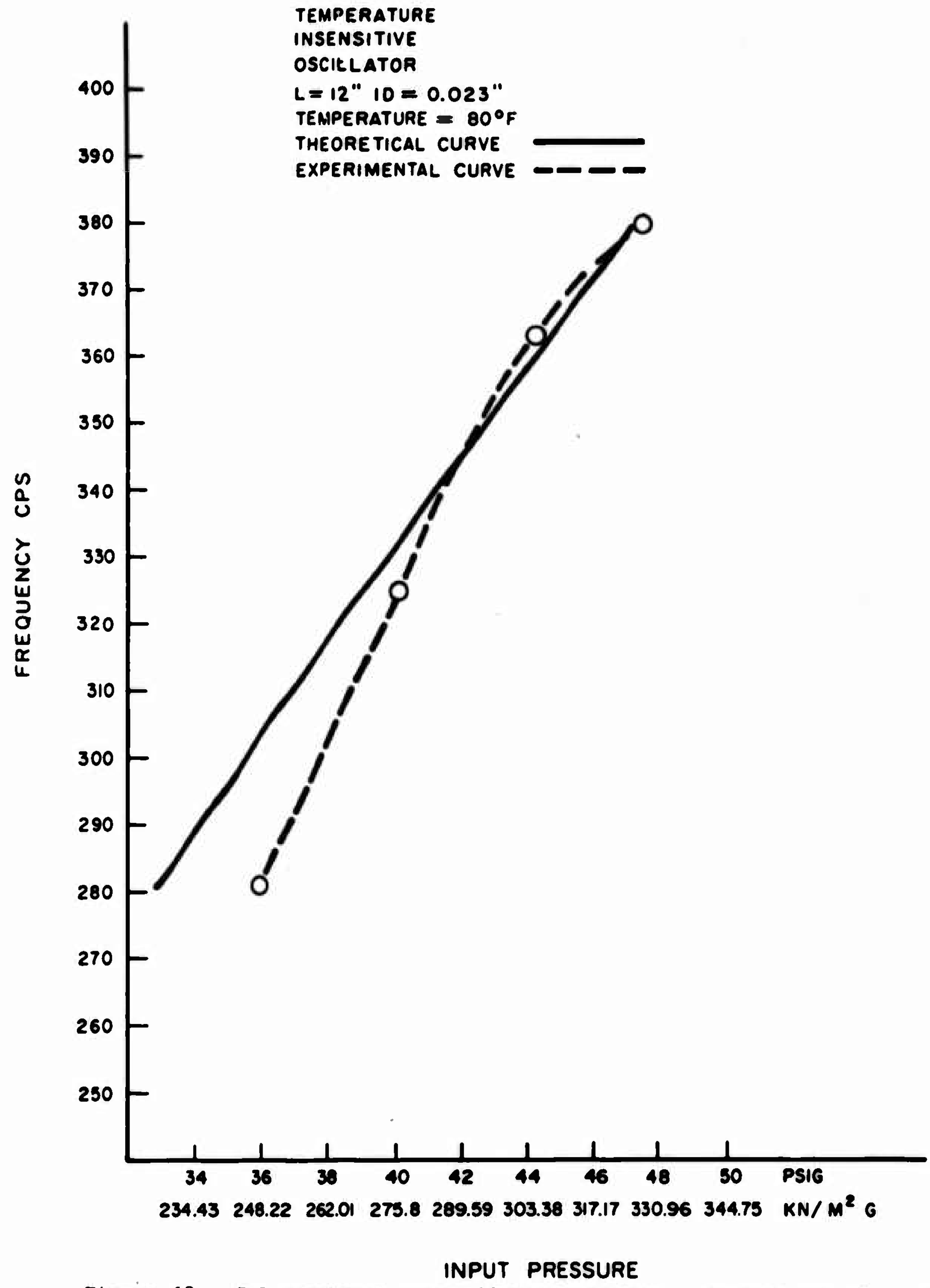


Figure 13. R-L pressure controlled oscillator. Comparison of experiment and theory.

5. RELAXATION OSCILLATOR

A relaxation oscillator (fig. 14) consists of a high-gain digital amplifier in which part of each output is fed back to its own control jet through a series R-C-R circuit. When the output is switched to either side, a pressure pulse propagates through this feedback path. When it reaches the control nozzle, it causes the output to switch to the other side. There the same kind of action occurs, completing one cycle and starting the next. The amount of fluid entering the capacitor is determined by the resistor R_1 connected to the output of the capacitor and the fluid leaving it by the resistor R_2 located at the control end of the capacitor. Hence, R_1, R_2, and the capacitor volume determine the filling time of the capacitor, which in turn determines the frequency of the oscillator.

The oscillatory mode is excited only for pressure ratios for which the jet spreads to occupy the full width of the output channel, for only then is a feedback achieved that will induce oscillation. In one particular case (fig. 15) the oscillator exhausts into a binary device that has a pressure below ambient in its interaction region. The amplifier control area sets a fixed load on the oscillator output, which causes a back pressure. The back pressure induces the oscillator power jet to spread and forces a portion to feed back into the R-C-R network initiating oscillations.

The binary amplifier and the oscillator have a common supply so that a change in one is accompanied by a change in the other. This action is needed because some of the increase in flow through the oscillator nozzle is conveyed to the lower pressure region in the interaction region of the binary amplifier control ports. In addition, the binary amplifier is provided with a set of bleeds located in the separation region. These bleeds exhaust any increase in back pressure that arises when the amplifier is loaded.

In the R-L oscillator discussed, temperature insensitivity is achieved by continuously compensating the speed of wave propagation uniformly along the R-L feedback path, even though pressure insensitivity is sacrificed. To obtain an oscillator insensitive to both temperature and pressure, we can use the lumped R-C feedback network. The compensation for temperature insensitivity in the network is achieved as follows: As the temperature rises, the resistance in the network increases, which causes a reduction in flow through the feedback loop, tending to lower the oscillation frequency. However, simultaneously, the effective tank capacitance decreases with higher temperatures, tending to increase the frequency. Hence, by adjusting the resistance of the resistors and the volume of the capacitor so that one compensates the other exactly, temperature insensitivity can be achieved. A similar arrangement is proposed for pressure

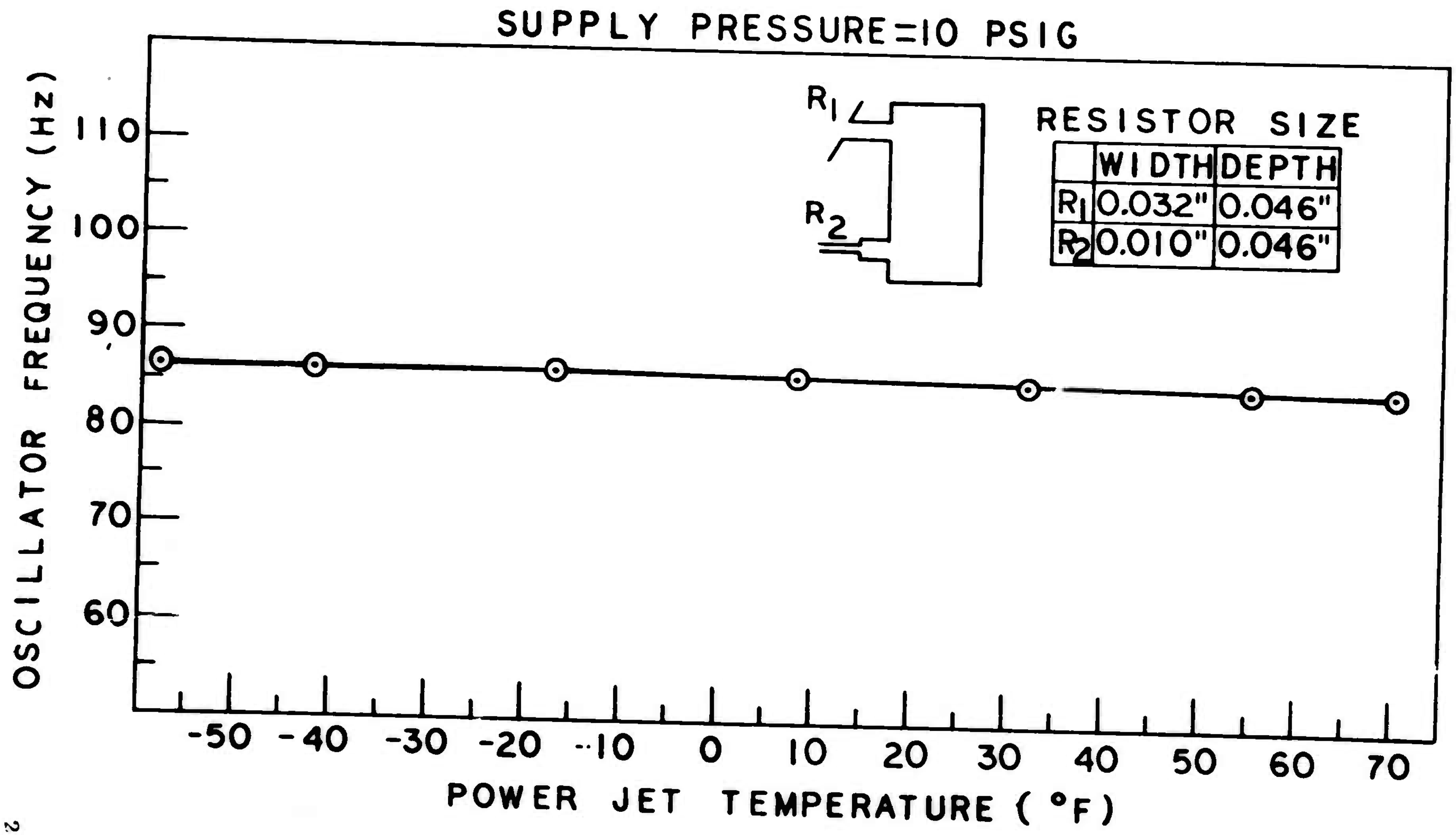


Figure 14. Oscillator frequency versus stagnation temperature.

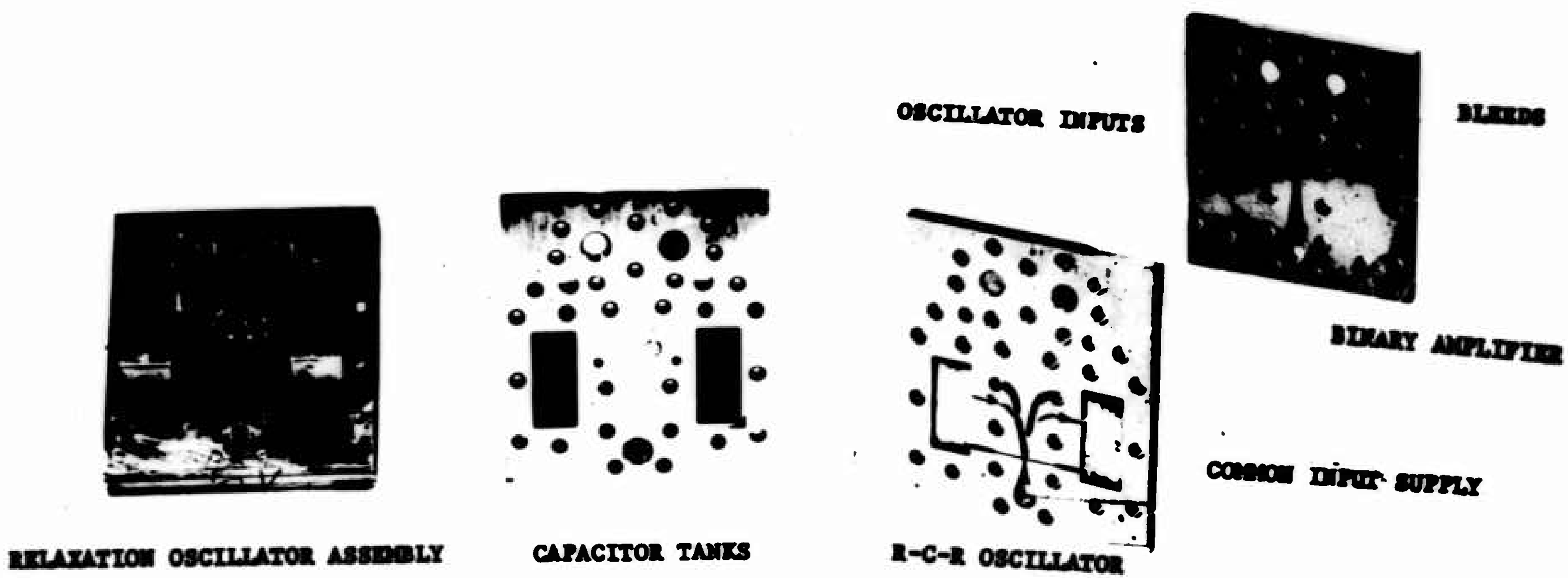


Figure 15. Relaxation oscillator and digital amplifier.

insensitivity. Reference 11 discusses a mathematical analysis that establishes the criteria for temperature and pressure insensitivity by considering the flow conditions in the components of the network.

An R-C-R oscillator was built according to the design criteria established in reference 11. The width of the resistors in the feedback network were 0.032 in. for R_1 and 0.010 in. for R_2, and the capacitor volume was 0.306 in.^{3} The aspect ratio of the unit was 3:1. A binary buffer amplifier was used in testing this unit. The oscillator exhibited a frequency variation smaller than $\pm$ 1 percent for a pressure range from 6 to 30 psig (fig. 16). Frequency changed less than 1 percent over a temperature range from 77° to 175°F at a pressure input of 10 psig (fig. 17). A similar oscillator was tested to determine the sensitivity characteristics at the low gas temperature. For the test, dried air at -70°F was used to prevent ice formation in the oscillator channels. The templets on which the oscillation was engraved were diffusion bonded to eliminate leakages at low temperature. The measured frequency changes at a pressure input of 10 psig did not exceed 1.5 percent for a temperature range from -58° to 70°F (fig. 18).

The development of an R-C-R oscillator insensitive to both pressure and temperature is essential for timers that must operate under a wide range of environmental conditions. The oscillator supplies a train of constant frequency pressure pulses, which are counted by cascaded frequency diveders (fig. 19). In addition the oscillator is used as a modulator in a missile control system (fig. 20). For the control system the oscillator sets into oscillation a series of cascaded digital amplifiers feeding opposed lateral jets (ref 12). Normally, these amplifiers oscillate symmetrically and the net force output of the jets is zero. When a corrective proportional signal is introduced by a gyroscope, the balance of oscillation of the system shifts more into one output jet than into the other, resulting in a net increase in thrust in the desired direction. This is known as the pulse duration modulation system. It provides a proportional output from a digital system.

6. VORTEX OSCILLATOR

An oscillator whose operating principle and physical characteristics are distinctly different from the feedback types previously discussed is the vortex oscillator—in particular, the countervortex oscillator (ref 13).

A typical countervortex oscillator consists of a straight tube with two circular chambers located at the open ends of the tube (fig. 21a). The oscillations in the unit are induced by the vortical motion of the working fluid. Specifically, the oscillations are

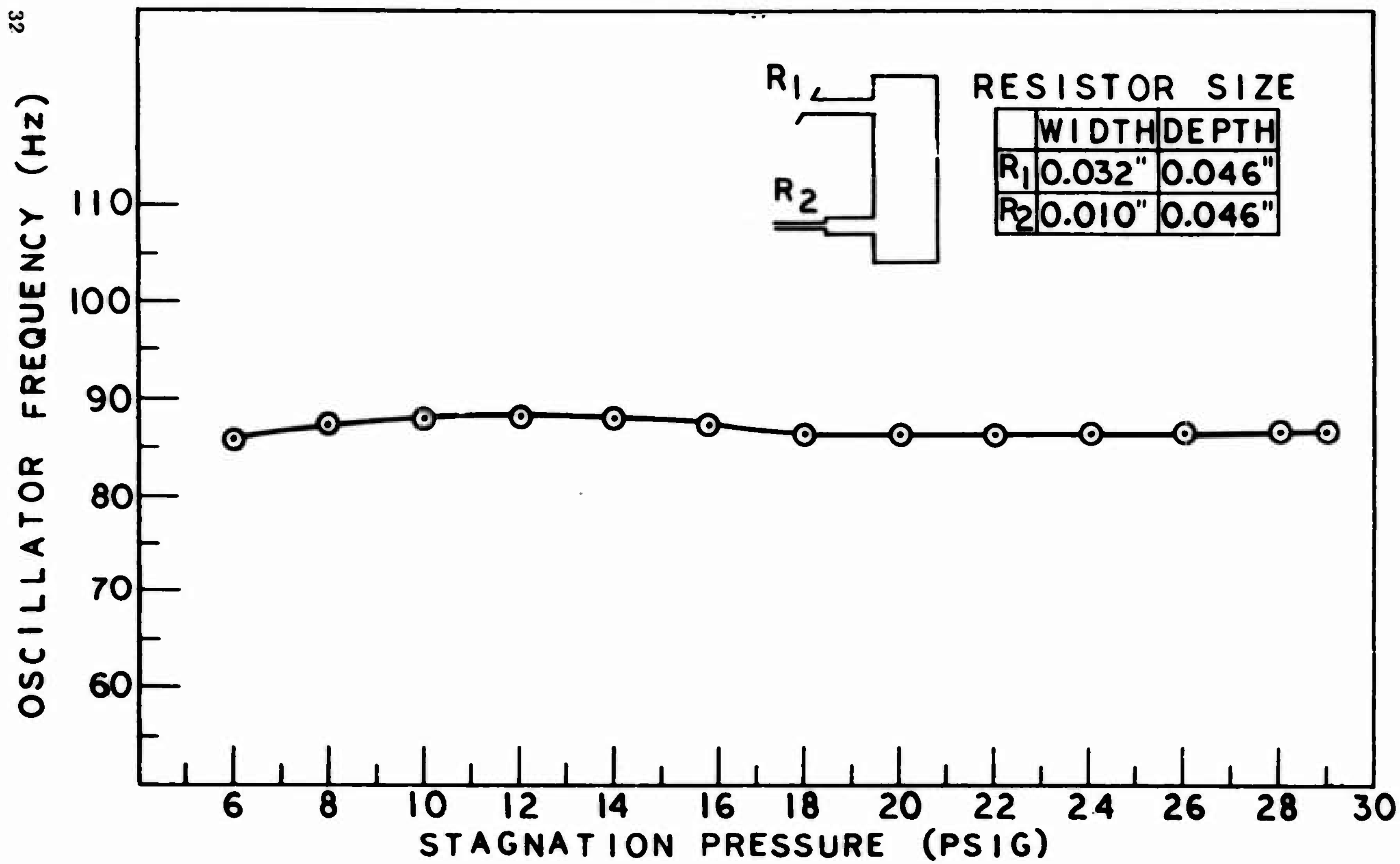


Figure 16. Oscillator frequency versus stagnation pressure.

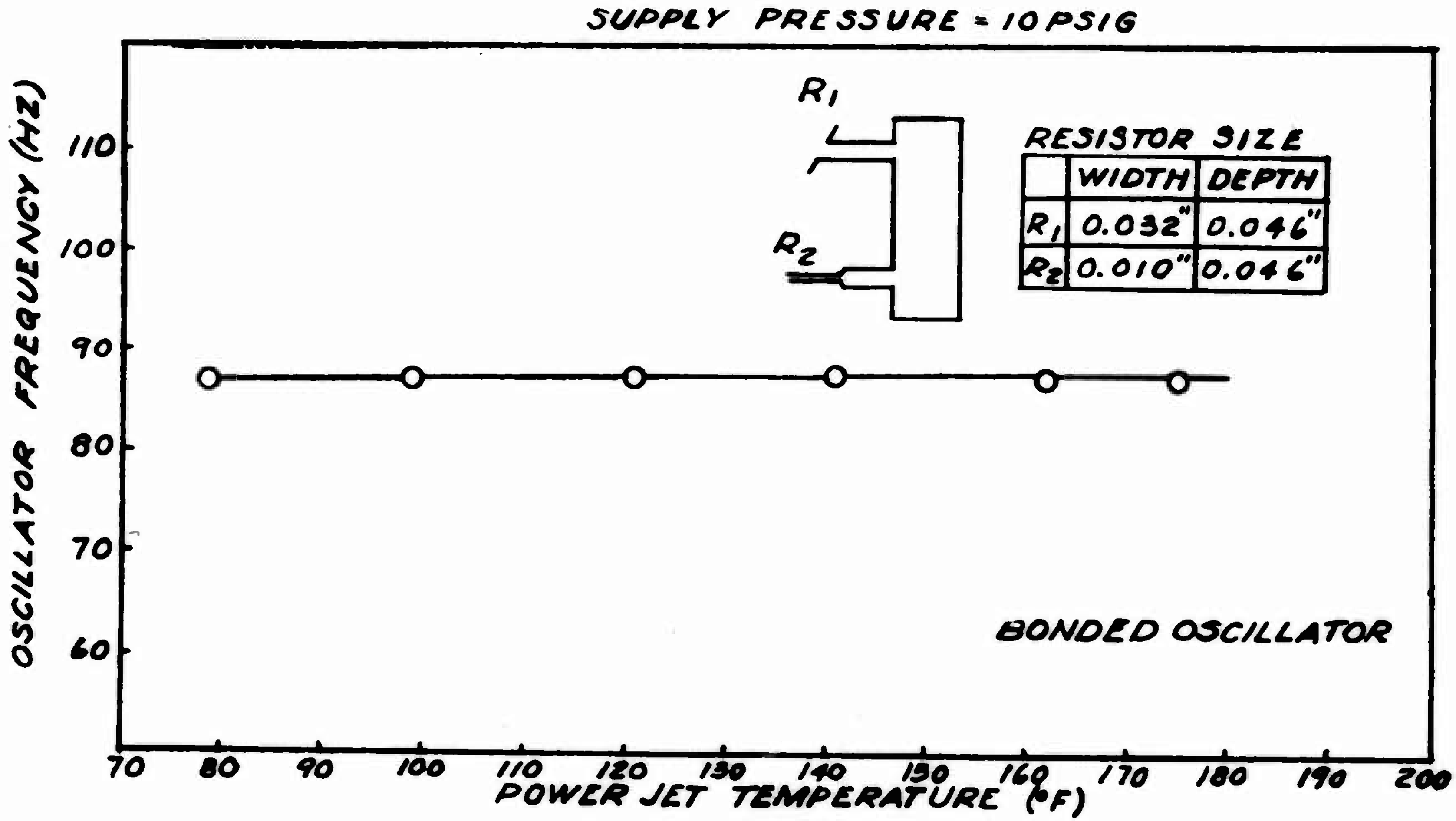
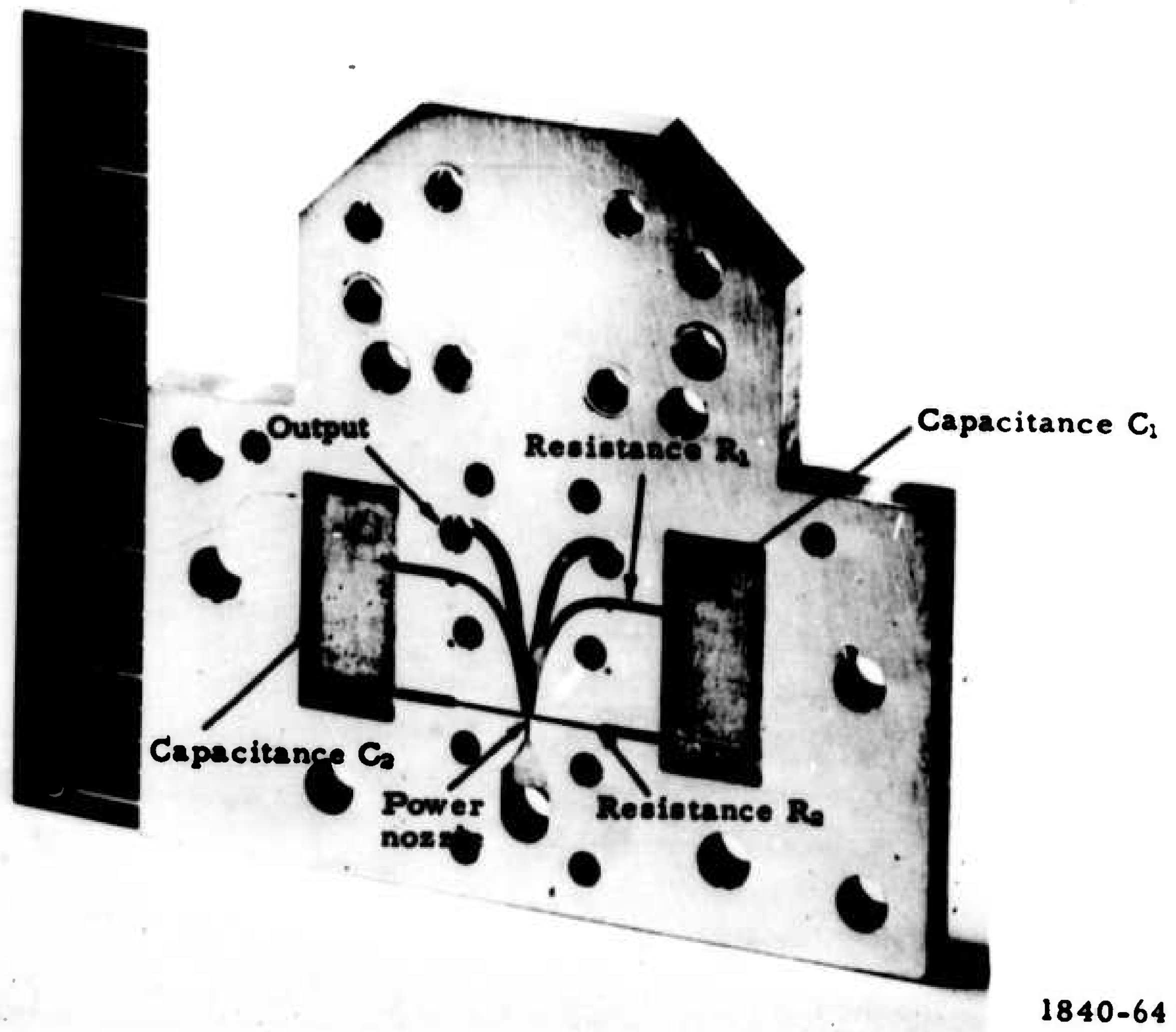


Figure 17. Oscillator frequency versus stagnation temperature.



1840-64

Figure 18. Relaxation oscillator.

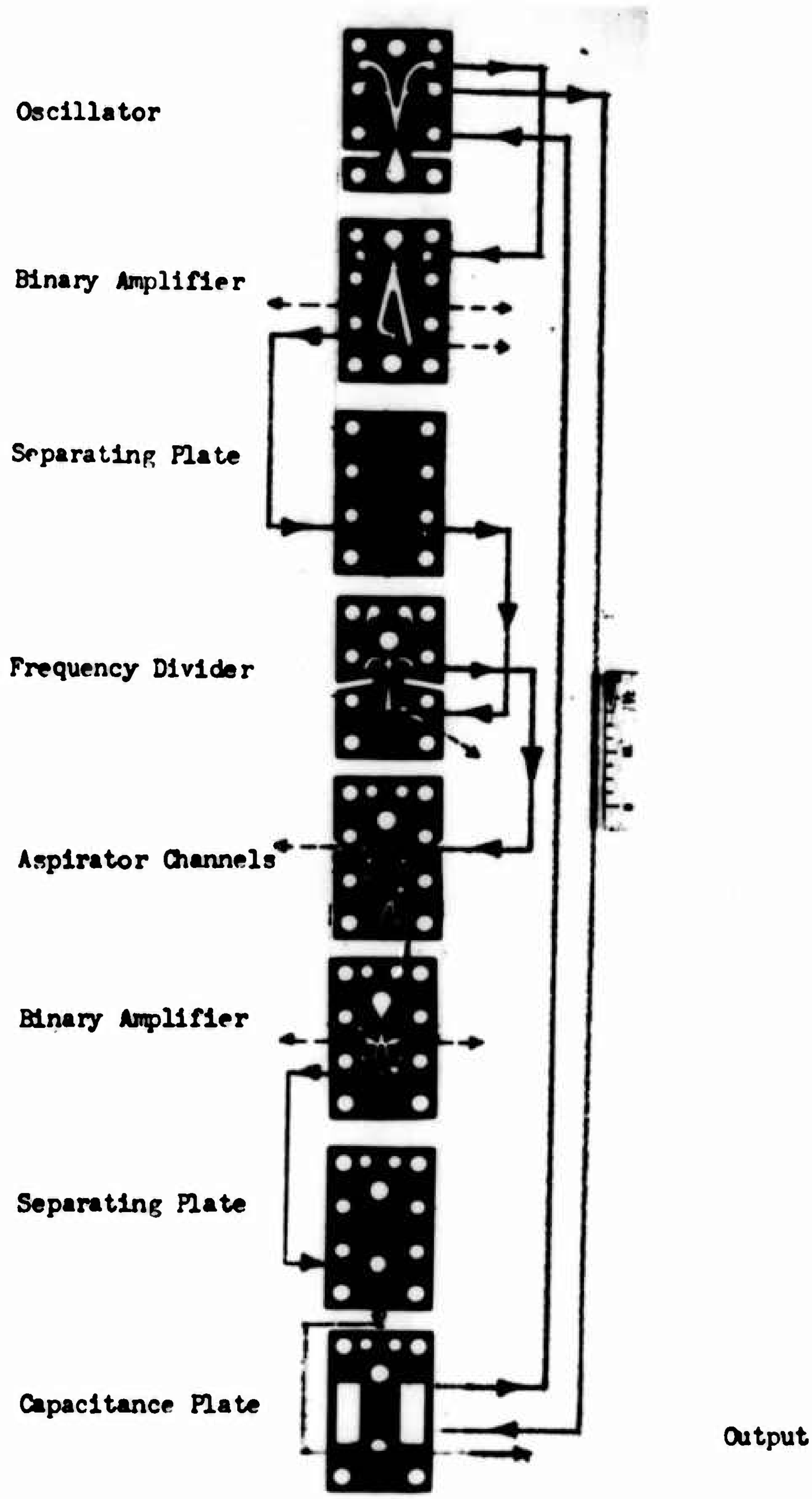


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Figure 19. R-C-R oscillator as time base for a timer.

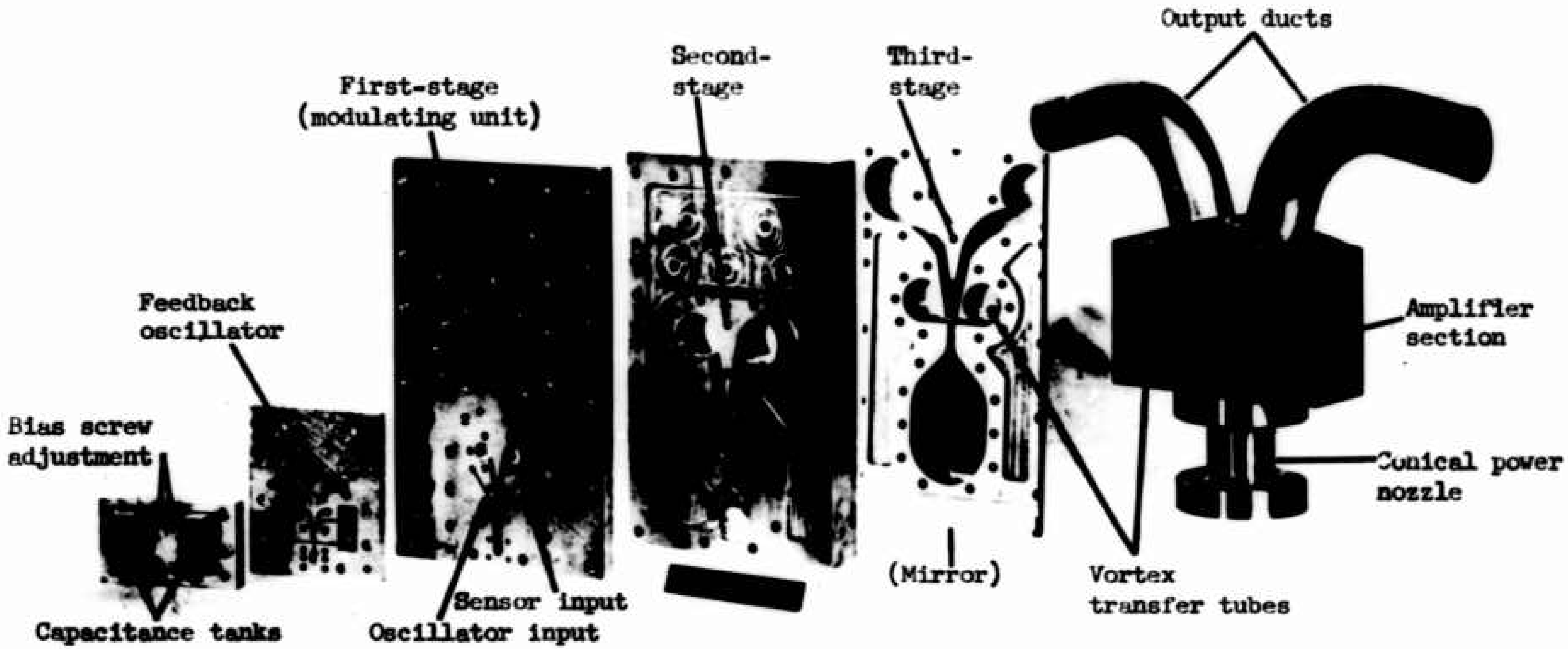

Figure 20. Four-stage fluid amplifier assembly for missile control system.

generated by the interaction of two vortices moving in opposite directions originating in the tube side chambers. The vortices are produced by jet streams introduced tangentially into the two chambers (fig. 21b). The vortex of the upstream chamber is initially irrotational and of uniform strength. However, upon entering the connecting tube, whose cross section is smaller than that of the circular chamber, the tangential velocity of the vortex increases. This velocity increase imparts a high kinetic energy to the inner flow layers, which in turn is transferred to the outer layers. This energy transfer causes the vortex to become rotational at the tube exit before entering the down-stream vortex chamber. Upon emerging from the connecting tube, the rotational vortex interacts with the vortex produced in the downstream chamber. At a distance approximately equal to the radius of the connecting tube, the radial velocity of the upstream vortex approaches that of the vortex from the downstream chamber. When the vortical velocities of the interacting vortices are identical, the rotation at the core of the downstream vortex tends to become unstable. The instability at the core arises from viscous forces generated by the upstream rotational vortex, which constantly reverses the direction of rotation of the core of the downstream vortex. The inner core alternates between its preferred direction and its forced direction. The process of velocity reversal is periodic and causes the core to exhaust through the downstream chamber with an oscillating motion. The oscillating output contines as new sections of the core are subjected to the same periodic velocity reversal process.

Experimental studies conducted by Sarpkaya (ref 13) indicate that the frequency and amplitude of oscillation depend on the dimensions of the connecting tube. Figure 22 shows the frequency of oscillation as a function of the upstream vortex pressure for various connecting tube lengths. Although no particular application of such a counter-vortex oscillator has been developed, the simplicity of its design and the stability of the oscillation over a wide range of upstream pressure makes it extremely attractive.

7. POSTSCRIPT

This report describes some of the most prominent fluid oscillators and discusses their basic application to fluidic systems. This material has been gathered together from many sources (see references). However, the low temperature results for the R-C-R oscillator are reported here for the first time. Other types of oscillators are being studied for possible application to fluidic systems. Some have moving members, whereas others utilize the characteristics of the oscillators mentioned but with added features.

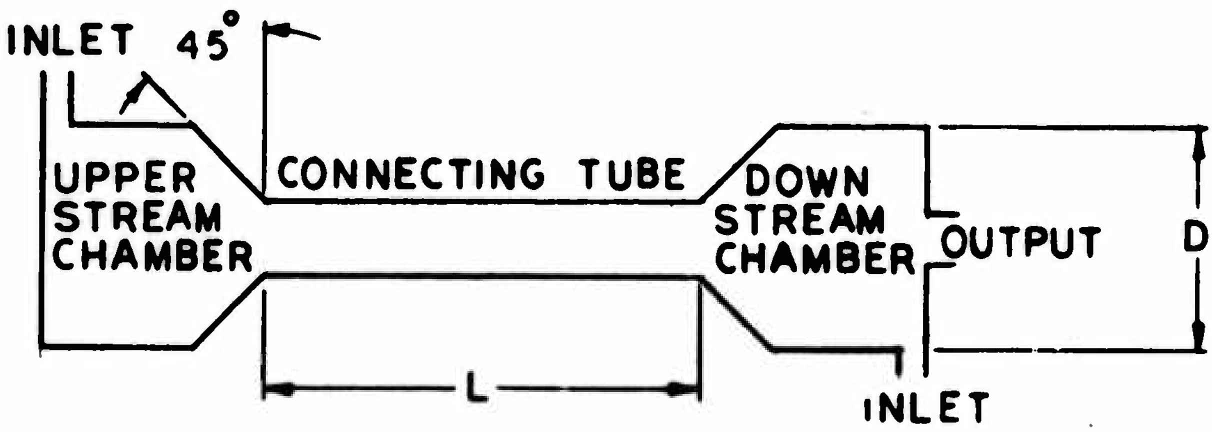

Figure 21a. Vortex oscillator schematic.

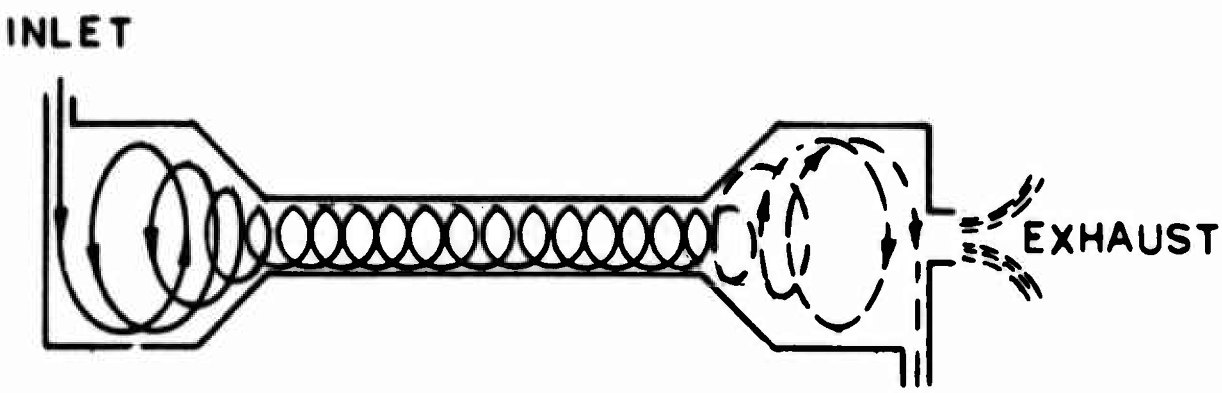

Figure 21b. Vortex oscillator flow model.

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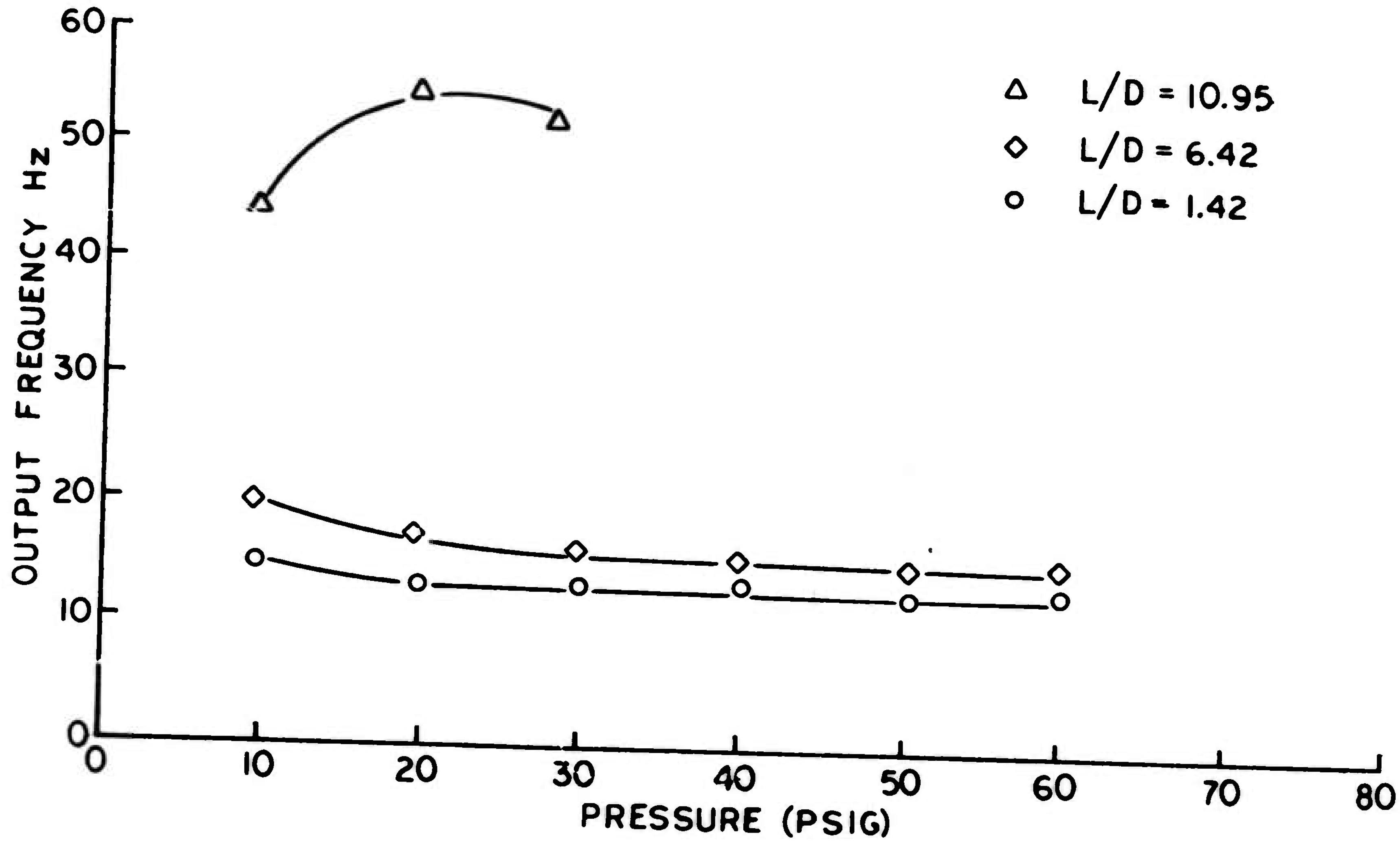

Figure 22. Pressure in upstream vortex chamber versus frequency (Hz).

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SYMBOLS

A	cross-section area
a	constant
a_{∞}	free speed of sound
b	constant
C	capacitance
C'	complex speed of wave propagation
F	measured frequency
f	frequency
f_o	reference frequency
Δf	change in frequency
h	orifice to wedge distance
J	mode of oscillation
K_1	constant
K_2	constant
L	inductance
ℓ	feedback length
P	pressure
R	resistance
R_1	feedback resistor
R_2	feedback resistor
R_g	gas constant
T	temperature
ΔT	change in temperature

SYMBOLS (Cont'd)

T_o	reference temperature
t_s	switching time
U_o	stream velocity
γ	specific heat constant
ρ	density of the gas
μ	viscosity of the gas
τ	period of oscillation
ω	angular frequency

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13. ABSTRACT

Fluid oscillators of various types have been developed and applied to fluidic systems for sensing or missile control. The operating characteristics of these oscillators, including the dependence of the frequency on the stagnation pressure and temperature, are a function of the type of return loop employed for maintaining oscillations.

This report discusses and summarizes the operating principles, design, frequency variation, and applications of some of the most prominent oscillators such as: The sonic, lumped R-C-R and L-R, edgetone, ringtone, and vortex oscillators. ( )

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Fluerics	8	1				
Sonic oscillator	8	3				
Lumped R-C-R oscillator	8	3				
Lumped L-R oscillator	8	3				
Edgetone oscillator	8	3				
Ringtone oscillator	8	3				
Vortex oscillator	8	3				
Stagnation pressure	6	3				
Fluid temperature	6	3				
Frequency	7	3				