Experimental Investigation of a Cylindrical Resonator

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Similar to a conventional resonance tube, a cylindrical resonator is investigated experimentally for producing high pressure and temperature gases. A quartz pressure transducer was used to determine pressure at the center of the resonator disk and a schlieren system to observe internal and external shock waves. A peak pressure nearly 3 times the jet stagnation pressure is observed and the internal shock waves are shown to be somewhat nonsymmetric and eccentric.

Introduction

STUDY of fluid oscillations associated with the operation of a simple resonance tube was initiated by Hartmann.[1] This device consists of a closed-end tube mounted with its open end facing an underexpanded fluid jet. Spark schlieren[2] and shadow photography[3,4] has shown that the resonant cycle is characterized by alternate periods of inflow and outflow from the tube which correspond to the appearance of an internal travelling shock wave and expansion waves. Thompson[4,5] has introduced a wave diagram analysis based on appropriate boundary conditions at the tube mouth. A more recent investigation[6] has improved Thompson's theory and used streak schlieren photographs to demonstrate that the traveling shock wave is internally generated.

It is well-known that the structure of the exciting jet strongly affects the performance of a simple resonance tube.[3] At a pressure ratio less than 4, underexpanded choked jets have a repetitive cellular appearance and resonance occurs only if the tube mouth is placed in the downstream half of each jet cell. This half cell is termed "the intervals of instability". Smith and Powell[3] have shown that higher harmonic resonant frequencies are obtained with the cavity mouth located near the midpoint of a jet cell and that the fundamental frequency is obtained at the downstream end.

Current interest[7,8] in aerodynamic resonators is focused on their use as a high-temperature device or igniter by taking advantage of the repeated irreversible shock heating of the indigenous fluid which remains permanently trapped inside a straight or tapered tube. It is noted that end wall temperatures of the order of 400°C can be achieved with gaseous nitrogen[7] and 1200°C with helium.[8]

The present investigation demonstrates a working device based on a combination of principles given by Hartmann[1] and Guderley.[9] Amplification of the internal shock wave can be accomplished by employing a cylindrical resonator cavity excited by a circumferential fluid jet. The resonant cycle is then characterized by a cylindrical implosion-explosion process which has a significantly greater potential for generation of high temperature and pressure than the conventional plane shock wave. Since all significant shock amplification occurs in a comparatively small region surrounding the implosion center, the cylindrical symmetry of the imploding wave is crucial to the successful operation of this device. Accordingly, the aim of this investigation is to examine the operating characteristics of such a cylindrical configuration. To this end, spark schlieren and shadow photography is employed to observe the nature of the external flowfield (exciting jets) as well as the internal flowfield (traveling shock wave). The resonant frequency and pressure amplitude are measured with a pressure transducer located at the geometric center of one resonator disk. Acoustic theory is used for a rough estimate of the resonant frequency.

Acoustic Theory

Despite the fact that strong traveling shocks may appear inside the resonator cavity, acoustic theory may be employed to give an estimate of the resonant frequency. Essentially, the internal waves are taken to be acoustic in nature so that the wave motion is then described by the linear wave equation. In cylindrical coordinates this procedure yields the well-known solution for the perturbation velocity potential,[10] which is written in terms of the familiar Bessel functions. Application of the boundary conditions (the particle velocity at the center must be zero and the perturbation pressure is zero at the resonator mouth i.e., $r = r_o$) yields the condition $Jo(2\pi f r_o/c) = 0$ where f is the frequency and c the local sound speed. The first root of the Bessel function then gives the fundamental frequency of acoustic vibration: $f = c/2.615 r_o$.

Experiments

A cross-sectional view of the cylindrical resonator is presented in Fig. 1. Two circular disks 2.65 in. in diameter with a lip chamfer of 45° are separated by a gap to form the resonator cavity. These disks are supported by a hollow (for schlieren viewing) threaded rod which is held in place by a threaded tightening ring so that the disk gap is adjustable. The resonator cavity is surrounded by a cylindrical plenum chamber 7.5 in. in

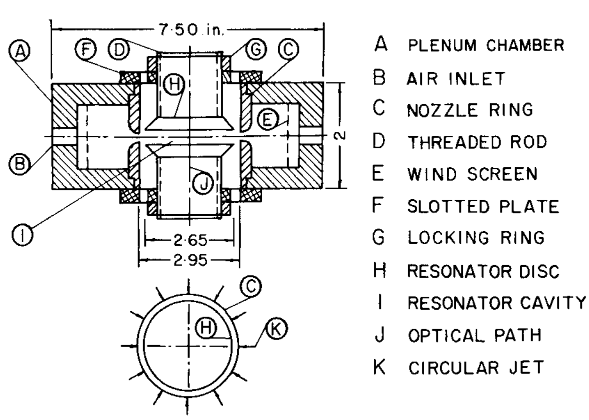

Fig. 1 Schematic of the cylindrical resonator.

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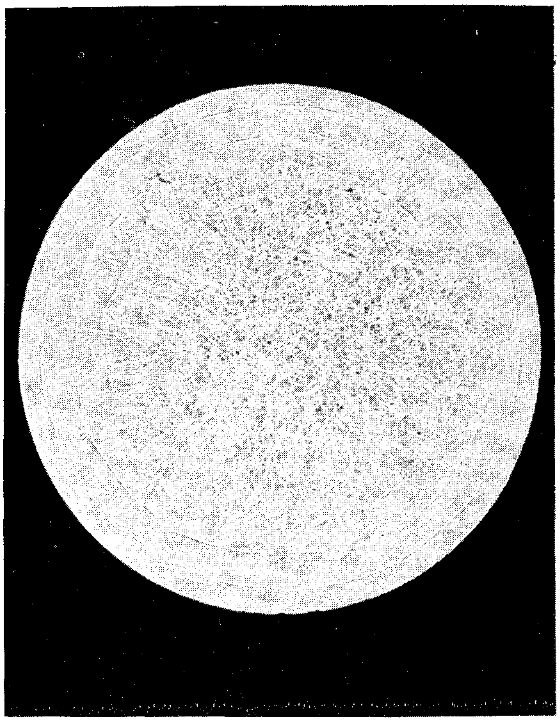

Fig. 2 A typical spark shadowgraph showing jet cells (pressure ratio = 3.94).

diameter fitted with five compressed air inlets connected to a common supply. A narrow slit 0.030 in. wide with a $\frac{1}{4}$ in. rounded entrance in the inner wall of the plenum serves as a nozzle for the exciting jet which is directed radially towards the resonator cavity. The device is constructed entirely of aluminum except for the central portion of the resonator disks which are fitted with Plexiglas windows for schlieren viewing.

The most important physical parameters which affect the acoustic or thermal output of the resonator are the nozzle width and diameter, jet stagnation pressure, resonator disk gap and diameter, and the resonator material. The present study is largely a qualitative one and an extensive parametric program to maximize the resonator output has not been undertaken. Instead, a nozzle diameter of 2.95 in. and nozzle width of 0.030 in. were arbitrarily chosen and resonator disks of 2.75 and 2.65 in. were tested separately. The latter were found to yield a consistently higher resonant pressure amplitude for all jet pressures. Similarly, a resonator disk gap of 0.068 in. was also found to be superior to any other value in this regard. These values were then held fixed for the balance of the tests despite the fact that they were not determined from an exhaustive parametric study.

With the resonator geometry thus fixed, the test procedure was largely concerned with adjusting the jet stagnation pressure. As the pressure is increased, each jet cell is lengthened and the effective location of the resonator mouth is then altered. For the present investigation, three series of tests were performed. First, flash shadowgraphy was employed to examine the jet cell dimensions with the resonator disks removed. Second, a $\frac{3}{8}$ in. quartz pressure transducer (pcb Piezotronics Inc., Model 101A) was mounted in the center of one resonator disk so that the pressure history could be recorded on an oscilloscope (Tektronix Model 555). Finally, the resonator disks were fitted with Plexiglas windows and the resonant cycle was examined via spark schlieren photography. The windows gave a 1.5-in.-diam field of view at the geometric center of the resonator cavity and the optical axis was normal to the resonator disks.

Results and Discussion

The structure of the exciting jet alone (resonator disks removed) is shown in Fig. 2 for a stagnation pressure ratio of 3.94. In this view, three jet cells are visible with the first exhibiting the highest degree of circular symmetry. Since cell symmetry is crucial to the operation of this device, it appears to be best to design the resonator to operate on the first or outermost cell of the exciting jet.

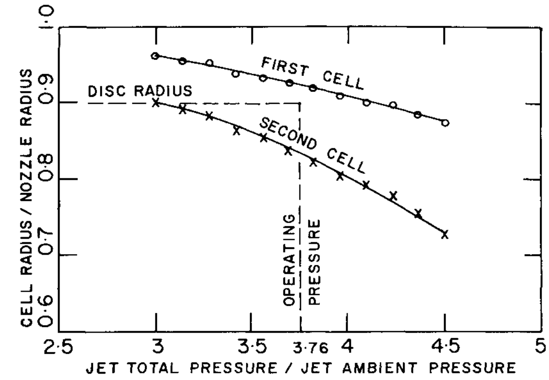

Fig. 3 Jet cell radius vs jet pressure ratio (nozzle radius = 1.475 in. and nozzle width = 0.03 in.).

Figure 3 shows the jet cell measurements taken from several shadowgraphs similar to that of Fig. 2 for jet pressure ratios between 3.0 and 4.5. It can be seen that cell length increases for higher pressure ratios and the second cell is longer than the first. Now, with the resonator disk in place, resonance is observed to commence at a pressure ratio of 3.76. When this operating point is superimposed on the figure, it surprisingly falls into the first half of the second jet cell which is theoretically outside the "intervals of instability." Yet resonance persists. The possible reason for this is that the jet structure is altered when the resonator disks are in place, as the disks are chamfered with some bluntness. This type of behavior has been observed for simple resonance tubes as well.[3]

The pressure history at the center of one resonator disk is presented in Fig. 4 for jet pressure ratios between 3.69 and 5.19. Resonance begins very abruptly at a pressure ratio of 3.76 and thereafter the pressure amplitude ($P_{max}-P_{min}$) falls rapidly and becomes only about one fourth its initial level at a pressure ratio of 5.19, as in Fig. 5. At the onset of resonance, the pressure trace is seen to exhibit periodically a very steep rise which implies the existence of a strong internal imploding-exploding shock wave. The peak pressure of approximately 163 psia is nearly three times the jet stagnation pressure of 55 psia. In addition, the subsequent expansion phase of the resonant cycle is seen to take place in three distinct stages because of wave

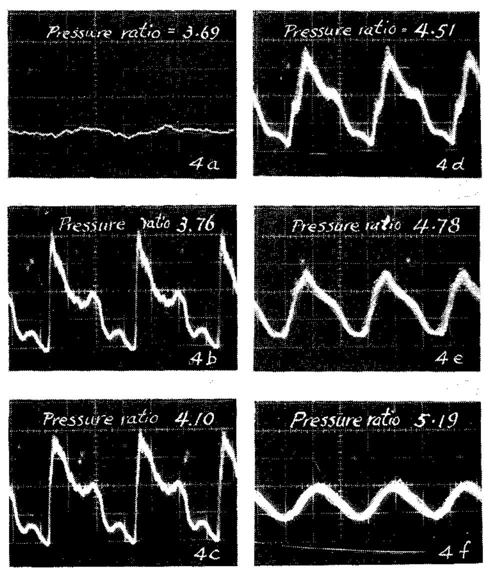

Fig. 4 Pressure measurements at the disk center.

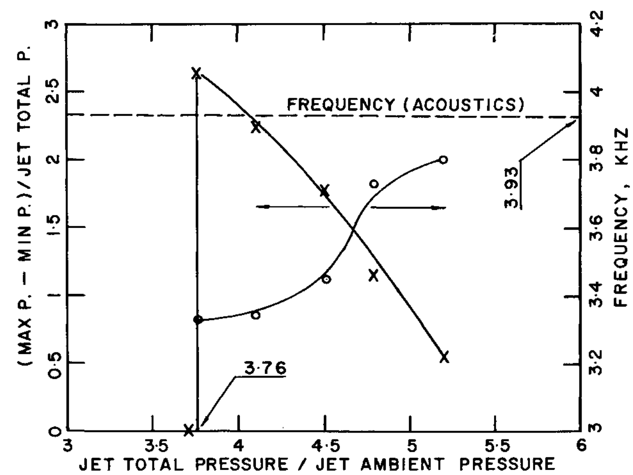

Fig. 5 Pressure amplitude vs jet pressure ratio (3.76 is a minimum value for resonance).

interaction within the confined diverging region. As the jet pressure ratio is increased, the waveform gradually becomes distorted until eventually the motion appears to be entirely acoustic. It is implied from Fig. 3 that this behavior is due to lengthening of the jet cell structure so that eventually the resonator mouth is effectively located in the upstream half of the cell and resonance cannot be maintained in this stable interval.

According to the oscilloscope traces, the resonant frequency is 3.33 kcps, which is about 15% lower than the acoustic frequency of 3.93 kcps with $c = 1135$ fps and $r_o = 1.325$ in. Attempting to account for shock heating effects by raising c above its ambient value makes the discrepancy even larger. Thus it appears that the shock-wave speeds with respect to the disk are subsonic over a considerable segment of the resonant cycle. Not surprisingly, the frequency measured from Fig. 4f is only 4% lower than the theoretical acoustic value (see Fig. 5).

Schlieren photographs, taken randomly but arranged in time sequence to illustrate pertinent features of the resonant cycle for a jet pressure ratio of 3.76, are presented in Fig. 6. These clearly show a nearly circular internal shock wave. Although whether this wave is imploding or exploding has not been determined experimentally, Figs. 6b and 6c are assumed to show the imploding wave as the enclosed flowfield appears quiescent, while Figs. 6d and 6e are thought to show the exploding shock for the opposite reason. Figures 6a and 6d show in- and outflow of the resonant cycle as the external shock is pushed far upstream against the impulse of the exciting jet, respectively.

Figure 6 also yields some qualitative information regarding the resonator performance. The internal shock, although nearly circular, is not perfectly so and is characterized by the appearance of several Mach reflections[11] around its periphery. The shock wave does not appear to collapse to the geometric center of the disks, therefore it seems likely that the resonator performance (i.e., pressure amplitude or temperature) can be increased by refining the design. It is noted that the appearance of a burn close to the center of the Plexiglas windows (small dark area in the photographs) indicates that the internal shock creates high temperature and collapses into a fairly small region.

Conclusions

A cylindrical resonator operating on an imploding-exploding cycle has been demonstrated experimentally. To achieve resonant conditions, the resonator disks must be precisely aligned relative to the exciting jet nozzle and the disk gap must be adjusted until the pressure amplitude is maximized. This type of "tuning" is required because a systematic experimental program to define the effect of various geometric parameters such as nozzle width and radius, disk gap and radius, etc., has not been completed.

The higher acoustic potential of the present device over conventional resonance tubes is demonstrated as a pressure rise of nearly 3 times the jet stagnation pressure has been measured at the center of the resonator cavity. Acoustic theory yields a fair estimate of the resonant frequency as the measured value is about 15% lower.

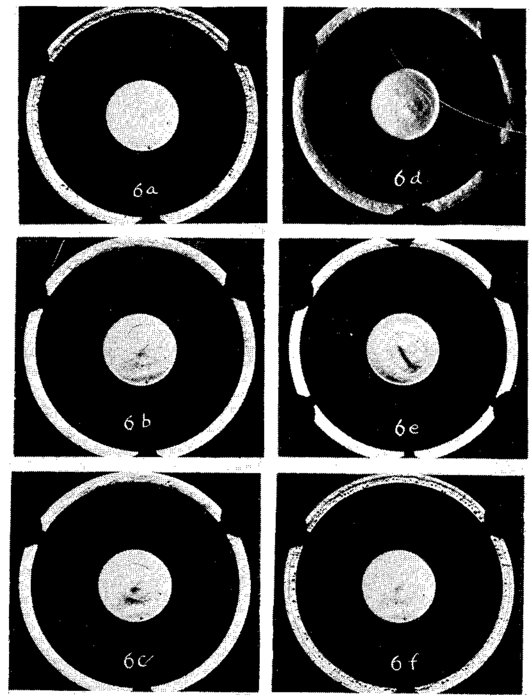

Fig. 6 Schlieren photographs showing shock waves (jet pressure ratio = 3.76 and total pressure = 55 psia).

Shadow and schlieren photographs show that 1) without the resonator disks, the jet from the circular nozzle has clearly defined jet cells of nearly circular shape, and 2) with the disks in place, the imploding and exploding shock waves in the central region of the disks are somewhat eccentric and characterized by the appearance of Mach reflections along the main shock profile. Although the cylindrical resonator is ultimately intended for high temperature generation, temperature measurements have been delayed until the shock wave eccentricity is improved.

References

[1] Hartmann, J., "On the Production of Acoustic Waves by Means of an Air Jet of a Velocity Exceeding that of Sound," *Philosophical Magazine*, Vol. 11, 1931, pp. 329–334.

[2] Vrebalovich, T., "Resonance Tubes in a Supersonic Flow Field," TR 32-378, 1962, Jet Propulsion Lab., Pasadena, Calif.

[3] Smith, T. J. B. and Powell, A., "Experiments Concerning the Hartmann Whistle," Rept. 64-62, 1964, Univ. of California, Berkeley, Calif.

[4] Thompson, P. A., "Resonance Tubes," Sc.D. thesis, 1960, MIT, Cambridge, Mass.

[5] Thompson, P. A., "Jet-Driven Resonance Tube," *AIAA Journal*, Vol. 2, No. 7, July 1964, pp. 1230–1233.

[6] Wu, J. H. T., Neemah, R. A., and Ostrowski, P. P., "Resonance Tubes in Underexpanded Sonic Jets," *CASI Transactions*, Vol. 6, No. 1, 1973, pp. 26–35.

[7] Phillips, B. R. and Pavli, A. J., "Resonance Tube Ignition of Hydrogen-Oxygen Mixtures," TN D-6354, 1971, NASA.

[8] Corrado, A. P., Rakowsky, E. L., and Marchese, V. P., "Resonance Tube Heating," private communication based on Abstract for American Physics Society Fluid Dynamics meeting, Nov. 1972, Boulder, Colo.

[9] Guderley, G., "Powerful Spherical and Cylindrical Compression Shocks in the Neighbourhood of the Centre of the Sphere and of the Cylinder Axis," *Luftfahrtforschung*, Vol. 19, 1942.

[10] Morse, P. M. and Ingard, K. U., *Theoretical Acoustics*, McGraw-Hill, New York, 1968.

[11] Whitham, G. B., "A New Approach to Problems of Shock Dynamics, Part I, Two-Dimensional Problems," *Journal of Fluid Mechanics*, Vol. 4, 1958, pp. 145–171.