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Exploratory Experiments on Acoustic Oscillations Driven by Periodic Vortex Shedding

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Nomenclature

- a = sound speed
- f = frequency
- ℓ = characteristic dimension
- L = cavity length
- $\bar{M}$ = average Mach number
- n = acoustic mode number
- S = Strouhal number
- u = average chamber velocity

Subscripts

- a = acoustic
- c = critical
- s = value associated with vortex shedding

ANALYSIS of pressure data from a number of segmented solid propellant rocket motors has shown the presence of low-amplitude pressure oscillations. However, when the acoustic stability analyses of Culick[1] and Cantrell and Hart[2] are applied to motors, they are all predicted to be stable. At first one might suspect the accuracy of the propellant combustion response values used in these analyses. Review of these data, however, shows they are relatively repeatable. Furthermore, their values are often less than unity and, hence, are well below the values required to overcome the nozzle and flow turning losses. Inclusion of particle damping only increases the response required to generate pressure oscillations spontaneously. Thus there is little reason to suspect that errors in the propellant properties can account for the observed oscillations. Hence, it appears that a significant source of acoustic energy has been omitted from these analyses.

Several years ago, Flandro and Jacobs[3] suggested that periodic vortex shedding could interact with the chamber acoustics to generate pressure oscillations. A review of this coupling has been prepared recently by Flandro.[4] Also, Culick and Magiawala[5] have described experimental results on acoustic interactions with vortices using a blower-driven tube with no flow restrictions at the downstream end.

The experiments reported in this paper studied this mechanism under conditions which simulate segmented rocket motor acoustics more closely. In particular, the objectives were to study the effect of flow across protruding inhibitors which often exist in this type of rocket motor chamber, and to determine the conditions which produced significant coupling between the flow and the acoustics.

The essential features of the apparatus are shown in Fig. 1. The flow cavity consisted of carbon steel tubing with an internal diameter of 3.8 cm and a length of approximately 106 cm. Nitrogen entered the chamber through a sonic choke and exhausted through a second sonic choke. Thus the chamber was acoustically isolated from the surrounding environment. Strain gage-type transducers monitored the pressure upstream of both chokes. In addition, a Kistler transducer was located at the head end of the simulated chamber to monitor the acoustic pressure.

The tubing was sectioned at the midpoint so that the spacing between the two restrictors could be varied. These restrictors had a port of 1.9 cm. Provision was made for inserting a hot wire anemometer midway between the two restrictors.

The shedding frequency of periodic vortex flows can be characterized by the Strouhal number

$$S = f_s \ell / u \qquad (1)$$

where ℓ is a characteristic length and f_s is the shedding frequency. If the shedding frequency equals the frequency of one of the acoustic modes, one suspects significant driving of acoustic oscillations could be generated. Since the acoustic mode frequency is

$$f_a = na/2L \qquad (2)$$

one would expect conditions of high acoustic level to be characterized by

$$S_c = n\ell / 2\bar{M}L \qquad (3)$$

This simple concept was tested by varying the restrictor spacing ℓ and determining the conditions required for maximum acoustic pressure.

Initial experiments were run with all restrictors removed. The amplitude spectrum showed dominant peaks corresponding to the first six axial modes of the apparatus. Next, a series of tests was conducted with two restrictors located at the $L/2$ position. The hot wire anemometer was located approximately midway between the two restrictors, and at the diameter of the restrictor orifice. The initial spacing between the two restrictors was 1.42 cm. Figure 2 shows the frequency spectra obtained from the Kistler transducer and the hot wire anemometer for a Mach number of 0.042 through the restrictor orifices. These data show no amplification of any of the acoustic frequencies. In fact, there appeared to be some damping of the first few modes. Next, the spacing between the restrictors was increased in small increments to a maximum value of 2.54 cm. The results obtained at 2.0 cm,

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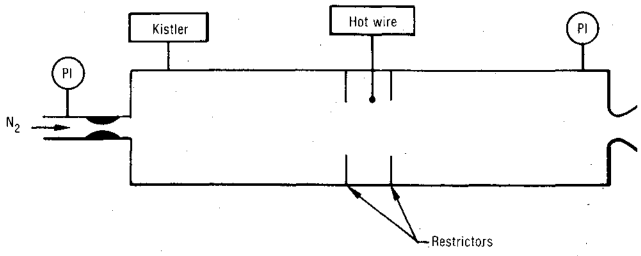

Fig. 1 Experimental apparatus.

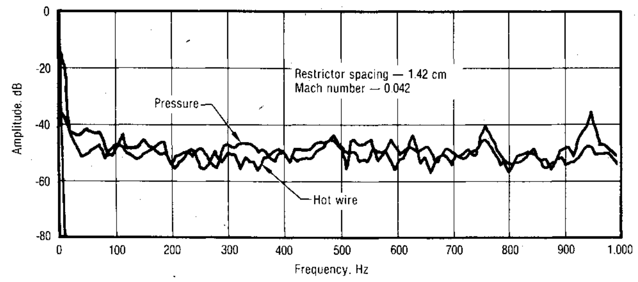

Fig. 2 Acoustic response with restrictors.

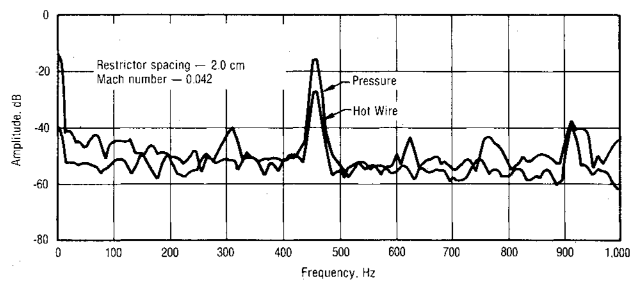

Fig. 3 Acoustic response with restrictors.

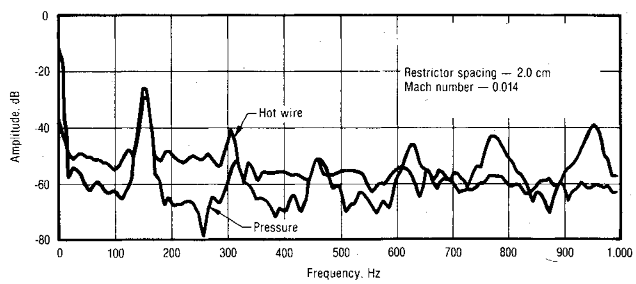

Fig. 4 Acoustic response with restrictors.

which provided the maximum acoustic response, are shown in Fig. 3. Note that both the acoustic pressure and the hot wire show a marked increase in amplitude at approximately 460 Hz, which represents the third acoustic mode of this chamber.

If the Mach number in the chamber were reduced by a factor of 3, Eq. (3) indicates that the fundamental acoustic mode of the chamber should be excited. The area of both the upstream and the exhaust sonic chokes were decreased by 3, which maintained constant pressure but reduced the Mach number of the gas flow through the restrictors. Again, incremental increases in restrictor spacing were made and the effects on the hot wire anemometer and pressure data observed.

Figure 4 shows the results for a restrictor spacing of 2.0 cm, which again represents the maximum acoustic pressure generated. Under these conditions of reduced Mach number, it is apparent that now the first longitudinal mode of the chamber was favored for excitation. Analysis of these data shows a phase angle of approximately 90 deg between the anemometer and the pressure oscillations.

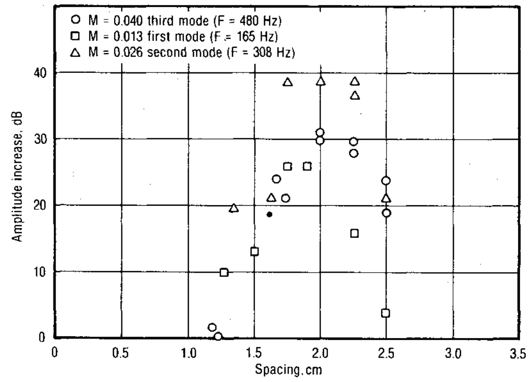

Fig. 5 Tuning of orifice spacing.

Next, the area of both chokes was adjusted to produce a Mach number of 0.026 through the restrictor pair. In principle, this would favor tuning of the second axial mode. The data, however, showed no particular increase of any mode, regardless of restrictor spacing. Thus, the first and third axial modes of the chamber could be amplified by adjusting the restrictor spacing, but the second axial mode could not be amplified.

The result suggests that, in addition to a critical Strouhal number, the position of the restrictor pair relative to the acoustic mode structure is an important parameter. The first and third modes were amplified by placing the restrictor pair at a pressure node or velocity antinode. However, the experiments which attempted to amplify the second mode were conducted with the restrictor pair at a pressure antinode and velocity node. The restrictor pair was then moved to the $L/4$ position and tests were run with a Mach number of 0.026 through the restrictors. Amplification of the second axial mode was now produced.

Figure 5 shows a plot of relative pressure amplitude vs restrictor spacing for the three conditions for which significant amplitude was obtained. The data are similar for all three sets of conditions and indicate that a spacing of 2.0 cm provides maximum acoustic driving in these experiments. Substituting these data into Eq. (3) shows that the critical Strouhal number for all three configurations is 0.8, which is consistent with the results by Flandro.[4]

These simple experiments have demonstrated that significant increases in acoustic pressure amplitude can be generated by coupling from periodic vortex shedding. Based on the results, a 5-10% pressure oscillation can be generated under the proper flow conditions. Thus, an insignificant oscillation can become very troublesome. These tests have also shown that there are locations relative to the mode shape which are preferred for amplification, in addition to the matching of the shedding and acoustic frequencies.

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