ACOUSTIC FIELD IN A DUCT RESULTING FROM VORTEX SHEDDING FROM MULTIPLE RESTRICTORS

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Abstract

This paper reports an experimental investigation of the acoustic field in a duct due to vortex shedding from multiple restrictors. The spacing between two restrictors was varied very closely in these experiments. It was observed that high amplitude acoustic field was established in the duct when the restrictors were closely spaced and that the highest amplitude of acoustic oscillations occurred for a certain specific spacing of the restrictors depending upon other conditions. It was also observed that the dominant frequencies locked on to the different possible natural acoustic modes that could be established in the duct.

Introduction

The objective of this investigation is to perform cold flow simulations of vortex shedding in segmented solid rocket motors (SRMs). In segmented solid rocket motors, the space between the segments is filled with an inert material, a type of epoxy resin, to prevent the propellant from burning from the gaps between segments. The inert material burns at a slower rate than the propellant. This cause the inert material to protrude into the flow in the form of annular rings (Fig.1). The flow through these rings may cause periodic vortex shedding over a broad range of conditions. Periodic vortex shedding is one of the principal mechanisms for the excitation of the natural acoustic modes of the combustion chamber [1]. This has been confirmed in the cold flow simulation of flow past protruding restrictors, performed by Culick and Magiawala [2]. They have demonstrated the coupling between the flow and the longitudinal acoustic modes of the duct. They conclude that simple arguments based on resonance are not sufficient to explain the effects of restrictor location on the acoustics-vortex interaction. They also observed that a single restrictor was not likely to excite strong oscillations.

A later study [3] also discusses similar experiments with a choked nozzle at the exit. The possibility of generation of 5-10% pressure oscillations was demonstrated "under proper flow conditions". The location of the restrictors with respect to the acoustic mode shapes was varied, and its effect on the acoustic amplification was studied. In a more elaborate study, Brown et al. [4], with a cold flow model of the Titan SRM, critically examined and confirmed periodic vortex shedding as a driving mechanism for acoustic oscillations. In this study, the mass addition to the port flow due to solid propellant combustion was simulated by flow of nitrogen through a choked porous pipe. Pure acoustic tones corresponding to longitudinal resonant modes of the duct were produced under certain flow and geometrical conditions for flow past two closely spaced baffles [5]. The conditions were to ensure close coincidence between the frequency of vortex shedding from the forward baffle and the natural frequency of the duct. Flow visualization studies demonstrated a stable vortex structure between the baffles, containing an integral number of vortices at all times. In a recent work [6], active control of vortex shedding due to circular orifices in the middle of a rectangular duct at a mean pressure of 65 Torr has been attempted. Stubos et al. [7] investigated aerodynamically generated acoustic resonance in a pipe with annular flow restrictors. They reported that as long as the distance between the restrictors remained smaller than the length of the flow recovery region behind the upstream restrictor, the fluid flow could amplify the acoustic perturbations at the frequencies of the acoustic modes, leading to strong resonance for specific flow ranges. They investigated the lock-on of the vortex shedding frequency with the duct modes. A few adaptive control algorithms have been applied to control the aero acoustic instabilities caused due to vortex shedding [8]. The results indicate the feasibility of such an approach.

Although many of the past investigators, following Culick and Magiawala [2] have employed a pair of closely-spaced restrictors in order to obtain reasonably

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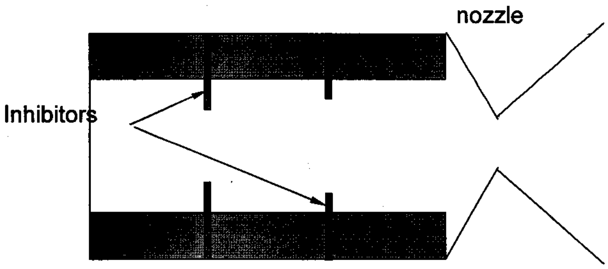

Fig. 1 Schematic of a segmented solid rocket motor

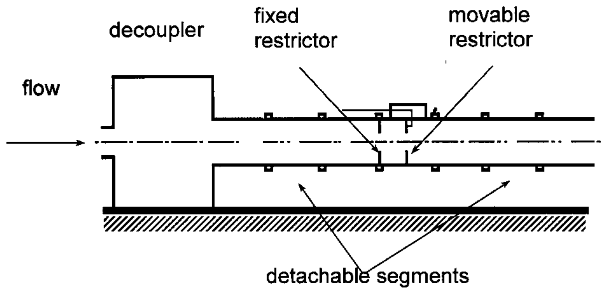

Fig. 2 Schematic of the experimental setup

high acoustic amplitudes in the duct, recently Karthik et al. [9] have shown that high acoustic amplitudes can indeed be excited by a single restrictor if it is of appropriate thickness depending upon other prevailing conditions. This is significant because, in realistic segmented solid rocket motor geometry, the restrictors are placed quite far apart, and the governing flow-acoustic interactive processes are expected to occur in the vicinity of a single restrictor.

Similarly, the work by Venkateswarlu, et al. [10] also involves the use of a single restrictor, although in relatively long ducts. Here, high acoustic amplitudes are not excited, but the acoustic oscillations do correspond to the duct modes. Further, they present some results that indicate that the vortex shedding may be influenced by a pressure-coupled feedback mechanism prevailing in the region between the restrictor and the downstream end of the duct. The vortex shedding is deducted to occur at more than one frequency level that are multiples of each other.

The present study focuses on the situation when two restrictors are present, and a close variation of the spacing between the restrictors is attempted. It is found, as expected, that discrete tones of high amplitude are excited in a manner representative of a flow-acoustic 'lock-on' under conditions corresponding to close spacing of the restrictors, as observed by past investigators, but the results are less coherent as the spacing is increased.

Experimental Setup

An experimental setup in which the interaction of the vortices shed from the restrictors with the chamber acoustic modes was developed (Fig.2). The thickness of all the restrictors used in these experiments was approximately 2.5mm. A circular duct made of mild steel of internal diameter 51mm was used to simulate the flow and acoustic environment in the solid rocket motor. In all the experiments reported in this paper. The length of the test section was 1050mm. One end of the duct was connected to a de-coupler of length 270mm and diameter 280mm, and the other end was open to the atmosphere. Experiments were performed by fixing one restrictor (stationary) at 450 mm from the de-coupler, and moving the second restrictor downstream to select locations between 3mm and 104mm.

Experimental Procedure

Air from a compressor was allowed into the test section after passing through a rotameter. Once the flow stabilized, a data acquisition program was run on the computer to record acoustic signal from the duct. The sampling frequency was 15,000 Hz and the number of samples were 15,000, which gave a resolution of ±1 Hz. The speed of sound for the working conditions was approximately 350 m/s.

Experiments were performed with restrictors of inner diameters 15, 16, 17, 18, 19 and 20 mm. For each position of the movable restrictor, the air flow rate was varied from 50 lpm to 500 lpm (corresponding to an average velocity at the duct entrance in the range of 0.41 - 4.1 m/s) and the acoustic measurement using the transducer was obtained. There was an uncertainty of 2% in the rotameter measurement. From the frequency domain plots, the variation of dominant frequency with respect to the spacing between the restrictors was obtained under each condition.

The acoustic field in the duct was measured using a piezo-electric transducer (PCB 103A12) that had a sensitivity of 539.8 mV/psi. The transducer was located at a distance of 150mm from the stationary restrictor in all the experiments. The acoustic signals sensed by the transducer were in the analog form. These signals were digitized using an analog-to-digital converter card connected to a computer. The data thus obtained in the digital format was inputted to a program that used a discrete fast Fourier transformation (FFT) algorithm to convert time domain data to frequency domain data.

Results and Discussion

Effect of Restrictor Spacing

Broadly speaking, there is a marked difference in the quality of the acoustic data obtained when the restrictors are closely spaced as opposed to when they are located far apart. Fig.3 shows typical acoustic pressure amplitude spectra obtained when the restrictors are closely spaced and when they are far apart. Although the sampling frequency was as high as 15000 Hz, frequencies only up to 3500 Hz are shown in the figures for better clarity. When the restrictors are closely spaced (Fig. 3(a)), a discrete frequency is observed, and it is characterized by a pure audible tone of high amplitude. On the other hand, when the restrictors are spaced far apart, the acoustic pressure amplitude spectrum does not contain a discrete frequency (Fig. 3b). The amplitudes are also significantly lower than in this case. The amplitude peaks around a frequency of 2000 Hz are attributed to spurious cavity oscillations at the transducer mount in some tests, and these predominate over the acoustic oscillations excited in the duct due to the vortex shedding at the restrictors.

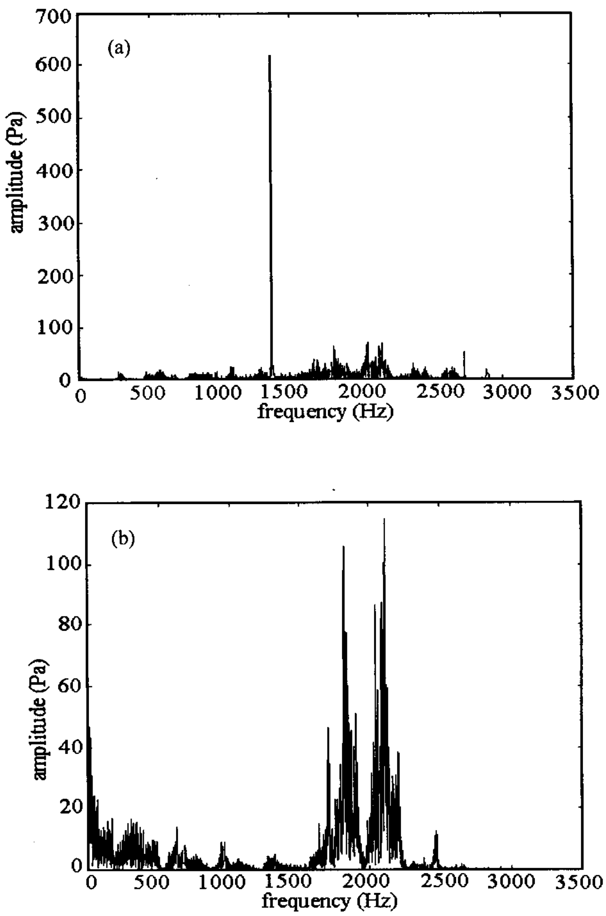

Fig. 3 Typical acoustic pressure amplitude spectrum for a mean velocity of 1.60 m/s and restrictor inner diameter of 16 mm for different restrictor spacings: (a) 15 mm, (b) 104 mm

Figure 4(a) - (e) shows the acoustic pressure amplitude spectra for a velocity range stacked together for different spacings between restrictors of 15mm inner diameter. The following features are observed on the whole :

a) As the spacing between the restrictors is increased, it takes high velocity levels to excite high amplitude acoustic oscillations.

b) Whenever dominant frequency variations with velocity are clearly discernible, it can be seen that the frequencies increase gradually over narrow ranges of velocities, and then jump to a different value with mild changes in velocity between two such ranges

c) During the transition from a frequency corresponding to one mode to another corresponding to a different mode, the acoustic pressure amplitudes are generally lower. The transition to the frequency corresponding to the next mode is not abrupt but very gradual. During the transition, both the frequencies exist simultaneously and the acoustic pressure amplitudes of both modes are of comparable magnitude. It can actually be seen that the amplitude corresponding to the first frequency diminishes and the amplitude corresponding to that of the next mode gradually increases with increasing flow velocity until it becomes the only dominant frequency.

d) During transitions from one mode to the other, higher harmonics could also be observed at significant amplitudes.

e) The observed dominant frequencies and their shifts between different modes can be identified in many cases with possible natural acoustic modes of the duct.

Figure 5 shows the dominant frequency and amplitude as a function of average flow velocity at duct inlet with a restrictor of 17 mm inner diameter, for different restrictor spacings starting from the farthest spacing corresponding

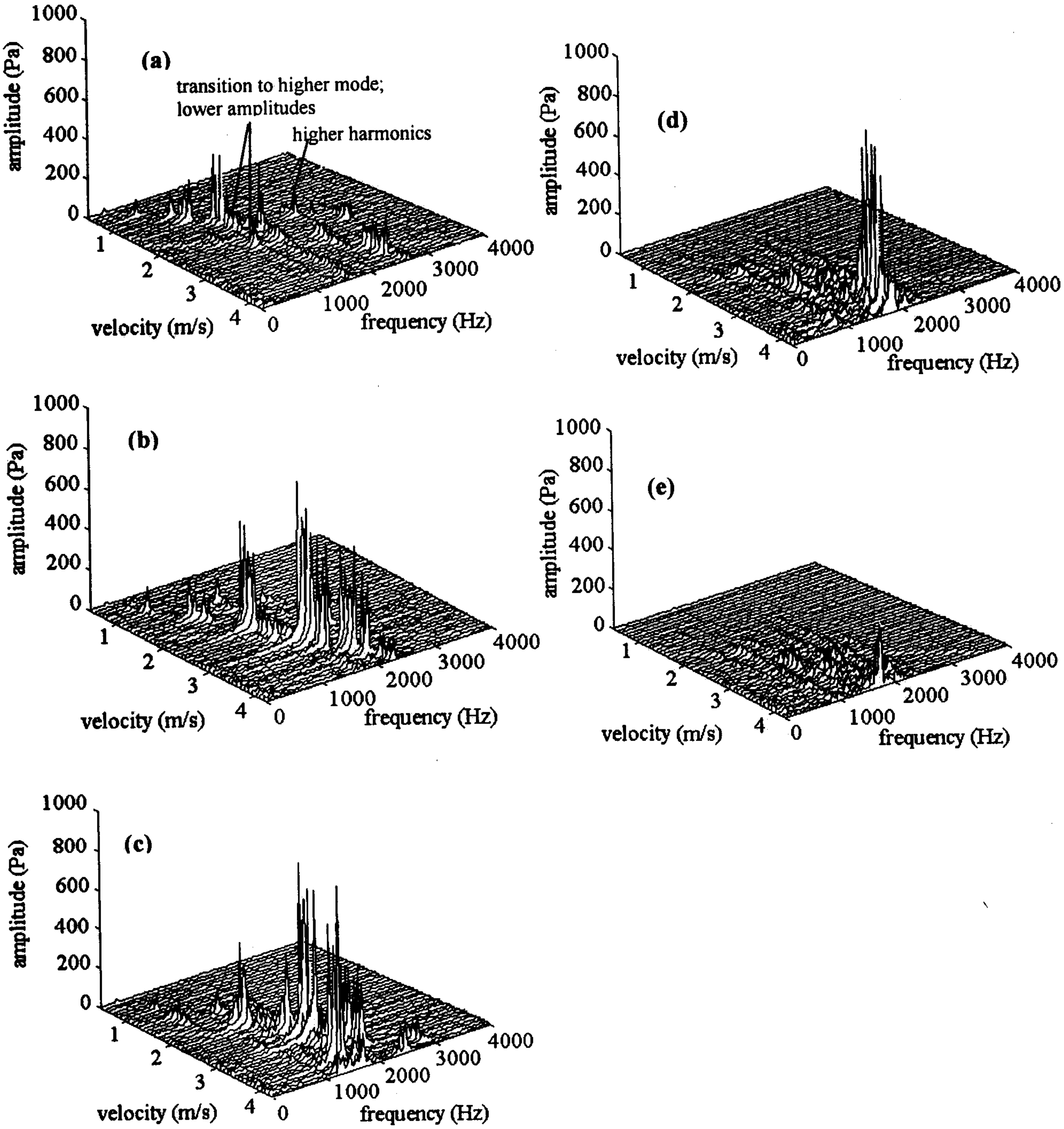

Fig. 4 Acoustic pressure amplitude spectra as function of mean velocity for a restrictor with an inner diameter of 15 mm and different restrictor spacings: (a) 12 mm, (b) 18 mm, (c) 33 mm, (d) 48 mm, (e) 54 mm

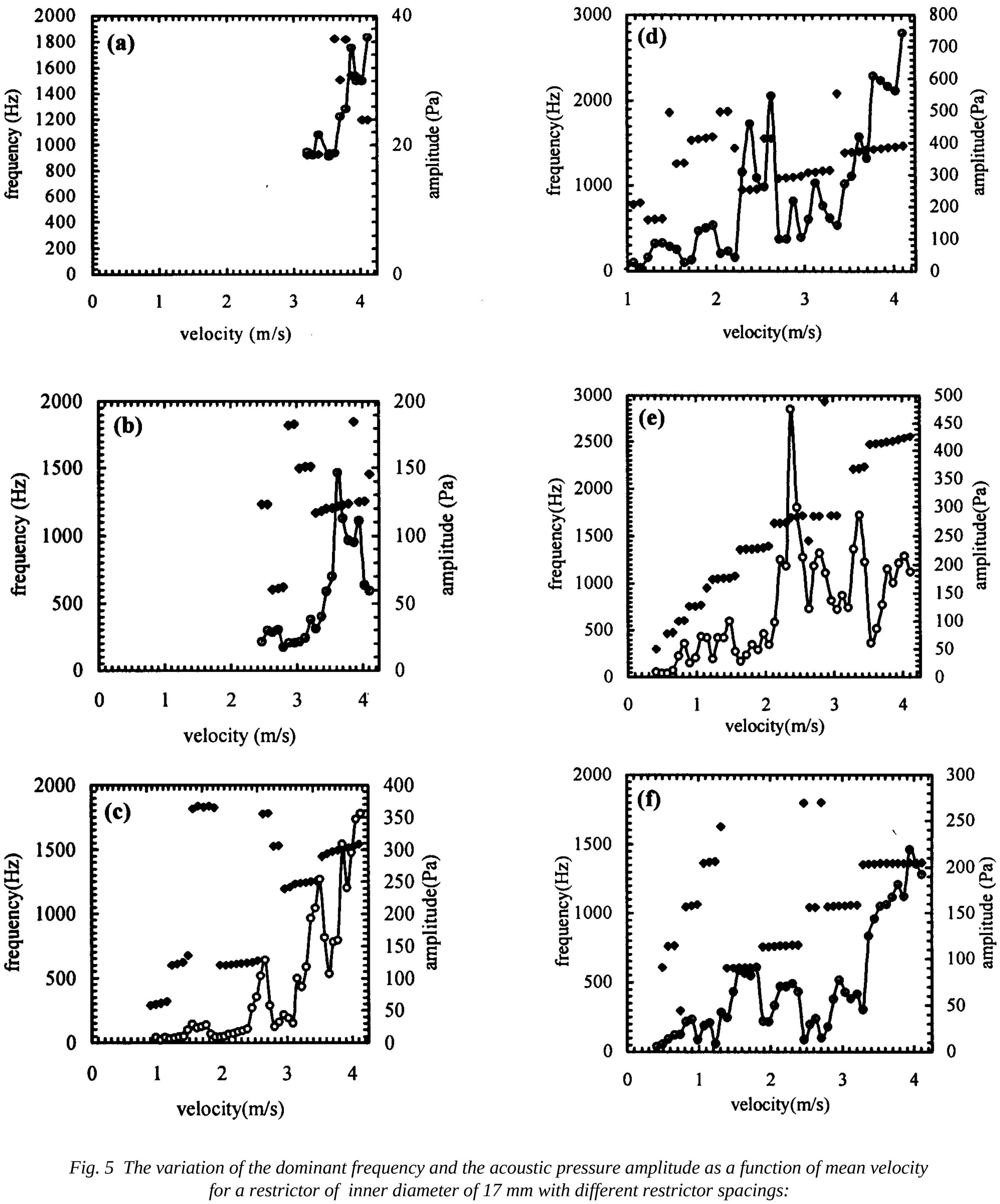

Fig. 5 The variation of the dominant frequency and the acoustic pressure amplitude as a function of mean velocity for a restrictor of inner diameter of 17 mm with different restrictor spacings: (a) 66 mm, (b) 54 mm, (c) 45 mm, (d) 27 mm, (e) 12 mm, (f) 3 mm;
◆ *frequency,* ❍ amplitude

to audible pure tones to the closed spacing tested. In all these cases, it can be seen that for the farthest spacing the acoustic mode shifts do not occur prominently with increase in flow rate, and the amplitudes are at rather low levels. For intermediate spacing, the frequency jumps discretely at select mean flow velocity conditions, but increases mildly with velocity between such conditions, indicating a lock-on type of behaviour [9]. In the limit of very close spacing, the behaviour approaches excitation of nearly continuous variation of frequency with increase in flow velocity - too short steps in the frequency jumps.

Effect of Restrictor Inner Diameter

Restrictors with larger inner diameters excite lower frequencies for the same mean flow velocity and spacing as shown in Fig.6. However, the frequencies match the natural frequency corresponding to the duct acoustic modes. Although lower frequencies are excited with larger inner diameters of the restrictors as a rule, in some cases in appears violated because of the possibility that the higher modes are excited with the larger orifices and the lower modes with the smaller orifices at a given flow velocity.

The amplitude levels and the robustness of the pattern of frequency jumps decrease with increase in the size of the orifices. This is significant when it is realized that the orifice sizes differ only by 1 mm in the different sets of experiments. Also, the range of flow rates over which the frequency jumps are excited extend over the entire velocity range tested, unlike in the case with single thick restrictors with small openings [9].

Table-1 shows the restrictor spacing for which maximum acoustic pressure amplitudes are excited. The restrictor spacing appears to be an important parameter in the excitation of maximum acoustic pressure amplitudes. The 'optimum' spacing is larger for restrictors of larger inner diameter. The maximum acoustic pressure ampli-

Table-1 : Maximum acoustic pressure amplitude

Restrictor inner diameter (mm)	Restrictor spacing (mm)	Mean velocity (m/s)	Dominant frequency (Hz)	Maximum acoustic pressure amplitude (Pa)
15	27	3.9	1693	1929
16	30	4.0	1714	1316
17	33	3.5	1769	1087
18	33	3.8	1564	98

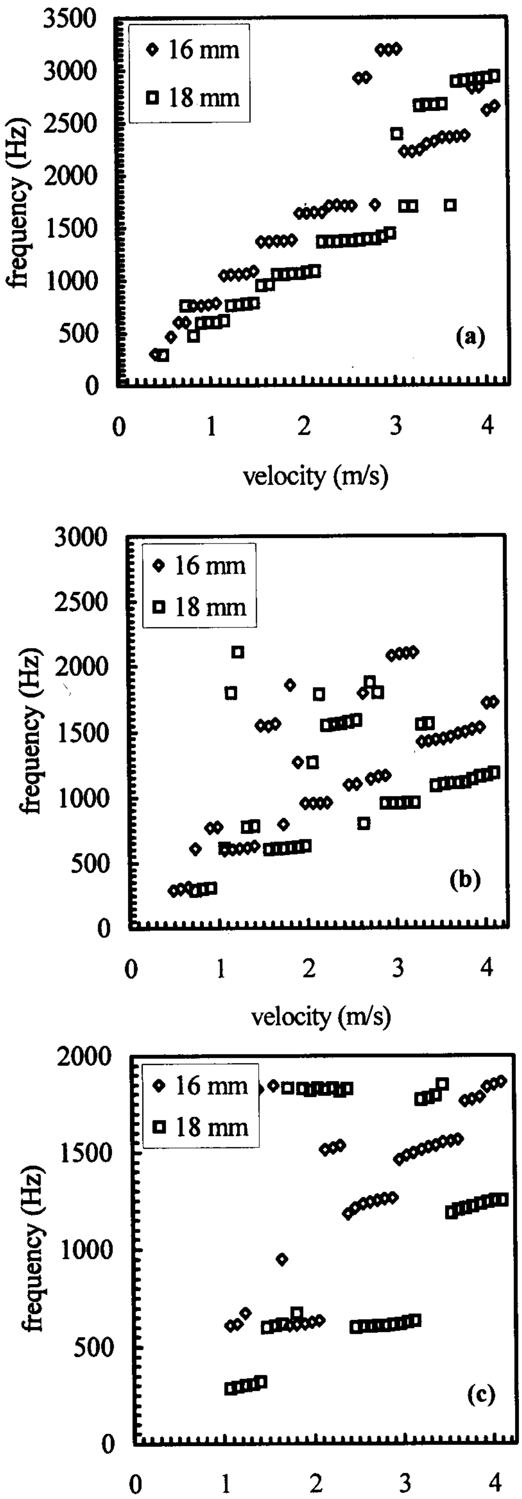

Fig. 6 Comparison of the variation of the dominant frequency with mean velocity for restrictors of various inner diameter for restrictor spacings: (a) 15 mm, (b) 30 mm, (c) 45 mm

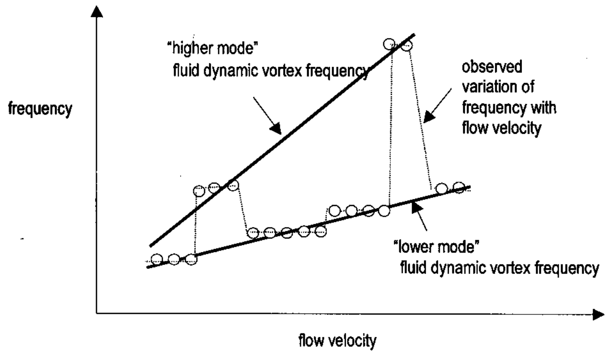

Fig. 7 Schematic representation of the frequency shifts obtained in this study. Circles are representative of the experimental data points

tude decreases with increasing restrictor inner diameter. The mean velocity at which high amplitude occurs does not show any trend. Pure audible tones are excited only at higher velocities for restrictors with larger inner diameters. The acoustic pressure amplitudes does not show any distinct trend ; however, the maximum amplitude excited seems to reduce with increase in restrictor inner diameter.

The overall trends are explained based on the idea advanced by Stubos et al. [7] regarding the length scales for reattachment of the flow downstream of the first restrictor. They point out that the distance between the restrictors should be less than the zone of disturbance of the flow in the downstream region of the first restrictor for significant acoustic amplitudes to be registered. When the restrictor size is large, the recirculation zone in its downstream region is correspondingly small. So, it takes large velocity for the region of disturbance to fill a given gap between the restrictors when compared to the case with a small restrictor size for significant acoustic amplitudes to be excited.

In some cases, it appears that the frequencies may jump down as well as jump up with increase in mean flow velocity. On closer inspection, this reveals a pattern of two distinctly different linear variations of fluid dynamic vortex shedding frequency with increase in velocity, around which the frequency jumps are centered. This is depicted in Fig.7. Some literature suggests that this could mean an abrupt excitation of higher modes and presence of multiples of an integral number of vortices in between the inhibitors at some times as compared to all other times - somewhat like a mode shift in the fluid dynamic vortex shedding process. This has been suspected in the case of feedback from the duct exit in experiments with long ducts [10].

Conclusion

Cold flow simulations of vortex shedding in segmented solid rocket motors were performed with multiple restrictors. It was observed that when the restrictor spacing was small, high amplitude acoustic oscillations at discrete frequencies could be established. It was observed that the dominant frequencies lock on to the modes of the duct over ranges of flow velocities, and jump between the different modes. When the spacing between the restrictors was increased, the lock-on starts at higher flow rates. Restrictors with larger inner diameters lead to the excitation of lower frequencies.

The frequency jumps indicate a pattern resembling lock-on of the vortex shedding frequency to the duct acoustic modes. But, in the present experiments, vortex shedding appears to occur at two possible frequencies under similar conditions. This may possibly be due to vortex pairing or merging while they interact with the acoustic oscillations in the duct.

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