DUCT RESONANCE IN HIGH PRESSURE RATIO THRUST AUGMENTING EJECTORS

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Introduction

Unsteady effects in various forms, when imposed on the mixing process between the two streams in an ejector duct such as that shown in figure 1, can greatly enhance the levels of entrainment and thrust augmentation. As part of a broader investigation of the use of ejectors for improving the static thrust of rocket motors, the effect of natural duct resonance on the performance of ejectors with very high pressure ratio primary jets of unheated air were investigated experimentally. A family of five convergent-divergent nozzles of different sizes but with the same exit to throat area ratio of 4.03 was tested with three constant cross sectional area ducts of different diameters, such that the duct to nozzle throat area ratio varied between 36 and 450. The primary jet stagnation pressures were up to 50 atm, covering such a range that the jet at the nozzle exit varied from highly overexpanded to underexpanded.

The thrust variations obtained experimentally with changing blowing pressure for a given ejector configuration showed irregularities which are not predicted or explained by the idealised ejector theory. These irregularities were found to be associated with discrete tones of acoustic radiation called screech. Similar phenomena were noticed by Quin, 1975, 1977. All of his experiments were performed with one underexpanded convergent nozzle blowing relatively low stagnation pressure unheated air jets at up to 6 atm at the inlet of a family of constant area ducts of one diameter (duct to nozzle area ratio 25) but with different lengths. He found that the discrete tone of acoustic radiation corresponded to the resonant mode of the mixing duct. With much higher pressures and area ratios, similar to those used in the present experiments, Fisher (1980) also observed thrust irregularities in a range of ejector geometries which were somewhat more pronounced than those reported by Quin.

Results and Discussion

Experimental results for a typical family of ejectors are shown in figure 2, in the form of duct thrust F versus the jet stagnation pressure P_o. Results shown in this figure are for different values of duct to nozzle exit area ratio A_D/A_n but for one ejector duct of fixed diameter and length. These were obtained by an X-Y Plotter, continuously activated by the output of a pressure transducer connected to the jet blowing pressure supply and a force cell connected to the ejector duct.

Spectral analysis of the noise radiated by each ejector at various points on the thrust/pressure characteristic was used to identify the fundamental frequency and harmonics of the discrete tone oscillations whenever they could be detected. A plot of the discrete tone fundamental frequency versus blowing pressure ratio P_o/P_1 for all ejector configurations of duct length to diameter ratio $L/D = 4$ is shown in figure 3. P_1 is the static pressure in the duct at the nozzle exit. From this figure it is obvious that the frequency was not a continuous function of blowing pressure, but that clear discontinuities occurred at certain pressures. Depending on the ejector configuration and range of pressure, more than one discontinuity can be identified.

For each family of ejectors having different nozzle sizes but the same duct diameter D_1 and length L_1, the tonal frequencies which defined the limits of different discontinuity ranges were nearly the same for each member of the family. However the levels of nozzle pressure ratio at which certain tones were generated, and at which the discontinuous frequency changes occurred, varied with nozzle size. For a new family of ejectors of duct diameter D_2, but with $L_2/D_2 = L_1/D_1$, the tonal frequencies changed by a factor equal to the ratio of duct diameters D_2/D_1.

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The theoretical transverse natural resonant modes for a long circular duct of constant cross sectional area are given by (Rschevkin, 1963):

$$f_{p,n} = \frac{C}{\pi D}\nu_{pn}$$

where c - Speed of sound in the duct medium
ν_{pn} - Roots of derivatives of Bessel function
P - Number of modal diameters
n - Number of modal circles.

The calculated resonant modes for the ducts used in our experiments are given in table 1. When compared with the experimental results in figure 3, these theoretical frequencies (with the notable exception of f_{11}) do not always coincide with the measured frequencies of apparent resonances. Indeed, it could be argued that there is a more consistent correlation of the theoretical frequencies with the frequency bands spanned by discontinuities between different resonant modes. This may not be surprising, in view of the fact that the theoretical modal frequencies were calculated for the ideal case of a duct with no flow and uniform pressure, and did not take into account the nonuniform flow structures through the duct. These nonuniformities, which are primary jet pressure ratio dependent, include coflowing streams and shock cell formations associated with over-or-underexpansion of the supersonic jet.

The limits of each frequency discontinuity in figure 3 are replotted as duct to nozzle exit area ratio A_D/A_n versus blowing pressure ratio P_o/P_1 in figure 4. The discontinuities can be grouped into bands, each of which assumes a linear relationship between A_D/A_n and P_o/P_1; and each of which can be ascribed a given value of the non-dimensional frequency parameter $fD/_C$.

The jet stagnation pressures which correspond to the maxima and minima on the thrust/jet pressure ratio characteristics for different ejector configurations are compared with those corresponding to the frequency discontinuities in figure 4. The maxima or minima are also shown to assume linear relationships between A_D/A_n and P_o/P_1. The pressures for the minimum duct thrusts coincided with those for the lower limits of frequency discontinuities.

Conclusions

The resonant modes of the mixing ducts of thrust augmenting ejectors can be correlated with gross changes observed in ejector performance. This provides a clue as to why these changes occur, but it does not explain how the performance is affected. The mixing between the primary jet and the entrained secondary stream is evidently enhanced by the duct resonance, but the flow mechanism which results in increased mixing is still to be described. Investigation of this aspect of the phenomena continues, using pressure probing and flow visualisation with single, two plane, and stroboscopic schlieren photography.

References

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4. Rschevkin, S.N, "A course of lectures on The Theory of Sound", Pergamon Press, 1963.

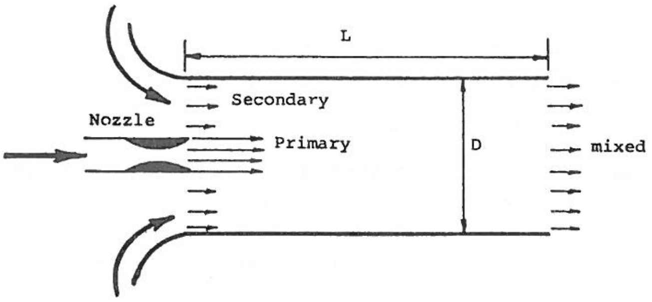

Figure 1: Schematic diagram for a thrust augmenting ejector.

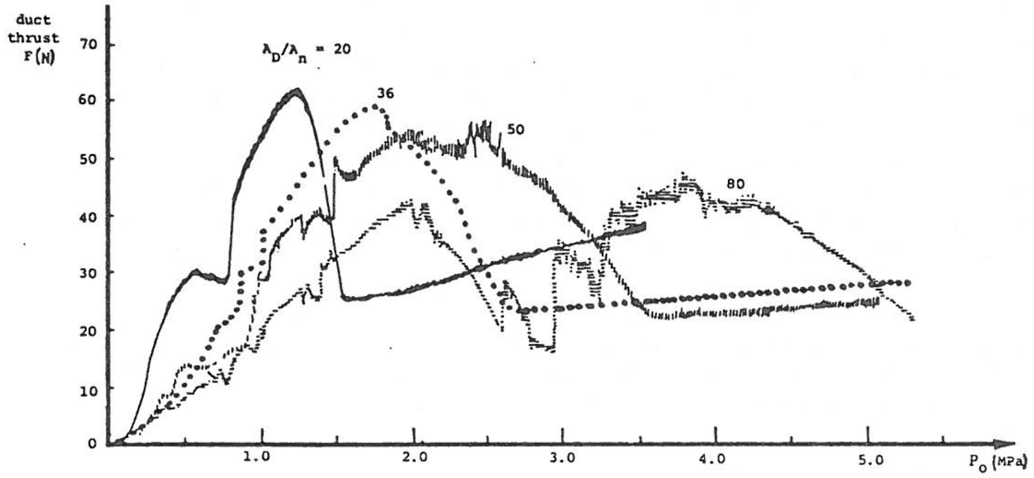

Figure 2: Ejector duct thrust for a family of ejectors of different nozzle sizes but with the same duct diameter and length.

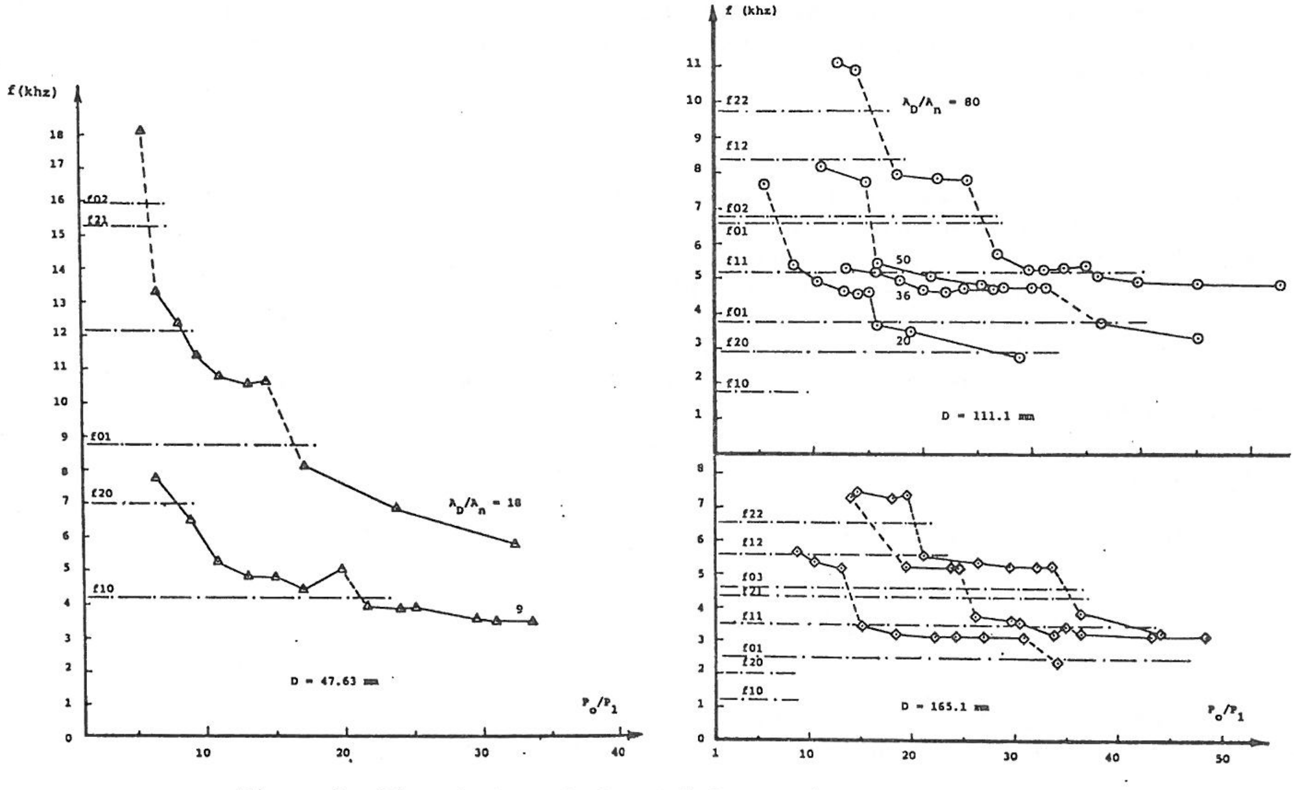

Figure 3: Discrete tone fundamental frequencies obtained for different ejector configurations.

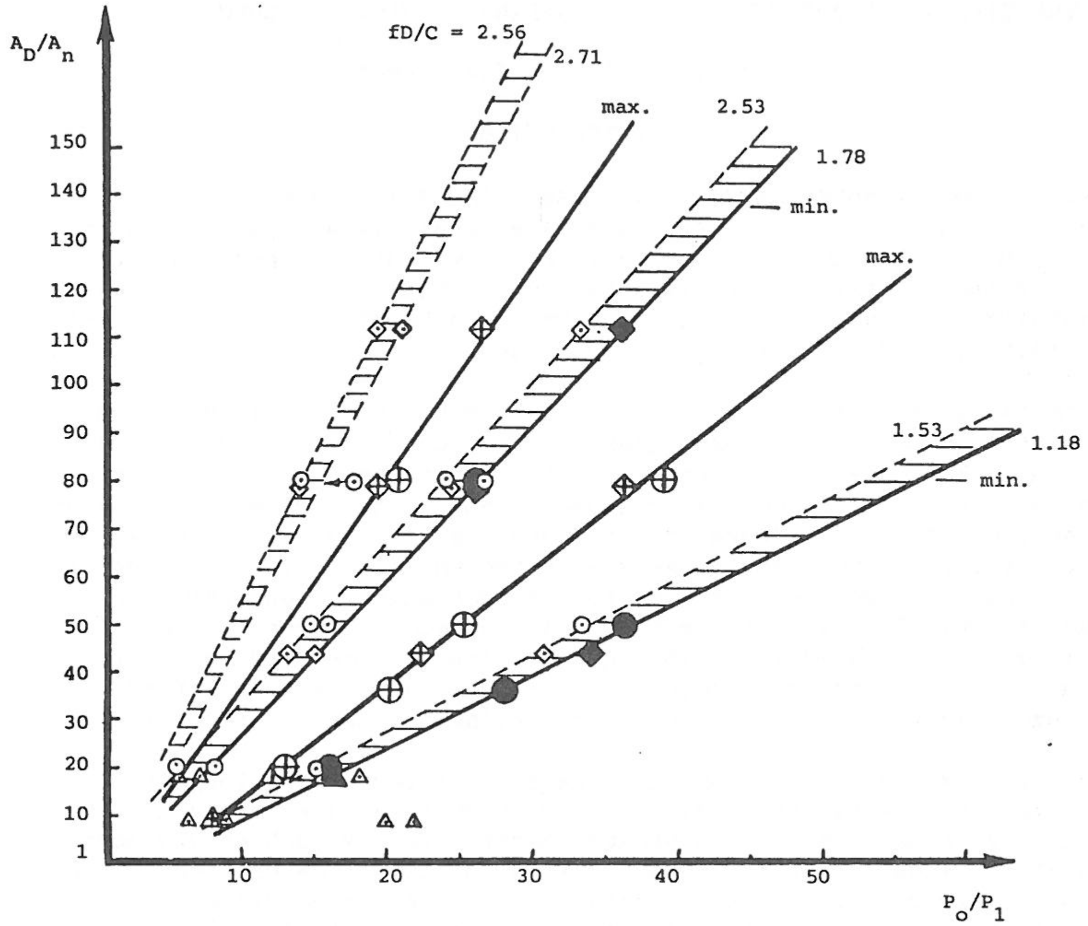

Figure 4: limits of frequency discontinuities obtained for different ejector configurations.

△, D = 47.6 mm; ⊙, D = 111.1 mm; ◇, D = 165.1 mm; △, ⊕, ◇, maximum duct thrust; ▲, ●, ◆, minimum duct thrust.

Duct diameter mm	No of nodal diameters(p) \ No of nodal circles (n)	0	1	2
47.6	0	0	8.70	15.93
111.1		0	3.73	6.83
165.1		0	2.51	4.60
47.6	1	4.18	12.11	19.4
111.1		1.79	5.19	8.32
165.1		1.20	3.49	5.60
47.6	2	6.93	15.22	22.63
111.1		2.97	6.52	9.70
165.1		2.00	4.39	6.53

TABLE 1 : Theoretical transverse resonant modes for the circular ducts used in the experiments.