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Vortex Shedding Studies in a Simulated Coaxial Dump Combustor

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PERIODIC shedding of vortices produce in highly sheared flows has been recognized as a source of substantial acoustic energy for many years. Flandro and Jacobs[1] were the first to suggest that this source of energy could be a significant contributor to acoustic instabilities in some solid propellant rocket motors. Subsequently, experimental studies by Brown et al.[2] demonstrated that vortex shedding from restrictors in large, segmented, solid propellant rocket motors couples with the chamber acoustics to generate substantial acoustic pressures. The maximum acoustic energies were produced when the shedding frequency matched one of the acoustic resonances of the combustor. Additional studies[3-5] demonstrated that the location of the restrictors on the acoustic mode is also important; in particular, that the maximum acoustic pressures are generated when the restrictors are located near a velocity antinode.

In addition to a segmented solid propellant rocket motor, highly sheared flow separations can be generated in a wide variety of rocket motor and ramjet engine designs. One such geometry is the sudden flow-area expansion found at the dump plane of coaxial-inlet ramjet engines and at the grain transition in boost/sustain-type tactical solid propellant rocket motors. Thus, it is conceivable that periodic vortex shedding could be a significant source of acoustic energy in these types of combustors as well.

To examine this possibility, in 1981, a test program was initiated using the cold-flow apparatus shown schematically in Fig. 1. This apparatus simulates the grain transition in a boost-sustain-type solid propellant rocket. In addition, it roughly approximates the inlet dump region of a coaxial-inlet solid-fuel ramjet engine. Approximately 33% of the nitrogen entered through a choked 5-cm-diam inlet, while the remaining flow entered laterally through a 10-cm-diam porous bronze tube downstream of the dump plane. The lateral flow was choked by a concentric flow-distribution tube upstream of the porous bronze tube; the same method was used in the segmented motor studies.[2] A Kistler pressure transducer was mounted just upstream of the choked exhaust nozzle and a single-element hot-wire anemometer was mounted through the dump plane to measure the mean and oscillatory flows in the recirculation zone. All tests were conducted at 275 kPa (40 psia) at the entrance plane to the exhaust nozzle.

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The first tests were conducted to determine if significant acoustic pressures could be generated in this type of geometry. The Mach number at the nozzle entrance (and, hence, the vortex-shedding frequency) was varied from 0.06 to 0.25 by changing the diameter of the exhaust nozzle. Figure 2 shows the rms acoustic pressure at the exhaust nozzle as a function of Mach number. The significant increase in acoustic pressure for $0.14<M<0.15$ was accompanied by clearly audible tones from the exhaust. These tones were not observed at the other Mach numbers.

Figure 3 shows the corresponding mean and oscillatory Mach numbers in the recirculation zone. Both recirculation Mach numbers maximize at the chamber Mach numbers where the acoustic pressures are also a maximum. The peak in mean speed is surprising at first; however, it is consistent with the intrusion of the edge of the vortex into the recirculation zone. Thus, these results indicate that periodic shedding of a vortex structure is responsible for the flow oscillations and acoustic pressures.

Figure 4 shows the frequency spectra of the acoustic pressure for three nozzle entrance Mach numbers; two of which produced significant oscillatory levels, as shown in Figs. 2 and 3, and one which produced the low background level. Comparing Fig. 4 with Figs. 2 and 3 shows that the increased rms levels are characterized by a single dominant fre-

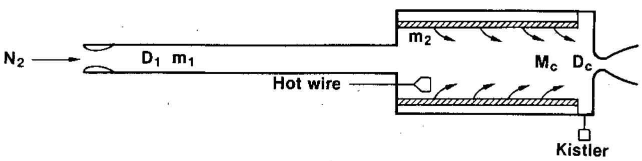

Fig. 1 Experimental apparatus.

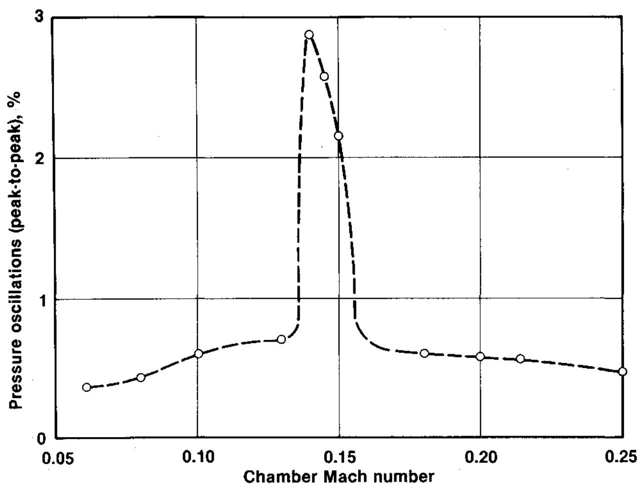

Fig. 2 Acoustic pressure levels.

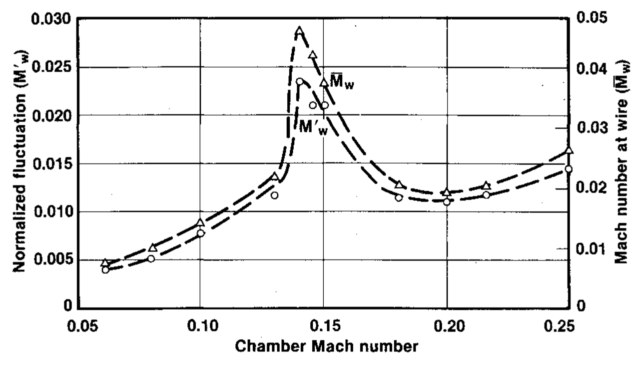

Fig. 3 Recirculation flow Mach numbers.

quency. Thus, these data support the hypothesis that periodic vortex shedding can generate substantial acoustic energy in this geometry. Furthermore, these results also suggest that this mechanism could account for the previously unexplained effect of sudden diameter change on solid propellant rocket motor instability as observed by Koreki et al.[6]

Additional tests were then conducted to explore the effect of inlet diameter on the acoustic oscillations. This diameter was reduced in two ways. First, a plastic tube was inserted into the 5-cm-diam inlet and mounted so that the exit plane was flush with the sudden expansion (as shown in Fig. 5b). The insert extended 20 diameters upstream into the inlet and had a tapered transition on the upstream edge. The second diameter change involved attaching a 4-cm-diam orifice plate

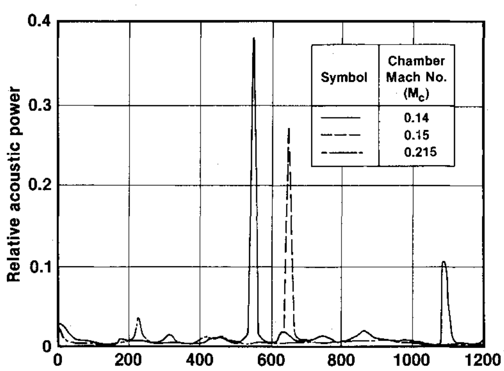

Fig. 4 Acoustic pressure spectra with baseline dump.

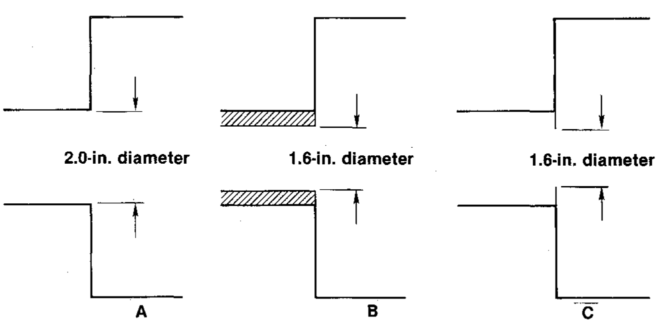

Fig. 5 Dump plane geometries.

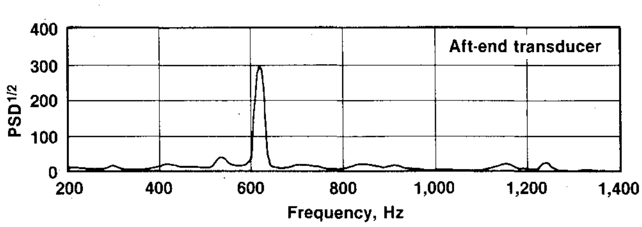

Fig. 6 Acoustic pressure spectra with dump insert.

Table 1
Critical Strouhal numbers characterizing significant oscillations

Dump diameter, cm	Frequency, Hz	Critical Strouhal No.	
		Diameter based	Step based
5.0	650	0.55	0.27
4.0	620	0.27	0.18

to the sudden expansion (as shown in Fig. 5c). Tests were then run over a range of Mach numbers using both geometries.

Figure 6 shows the spectra of acoustic pressure obtained with the tubular insert in the inlet at a chamber Mach number of 0.15. Here, the dominant frequency is 620 Hz, compared to 650 Hz in the baseline geometry. These data were obtained with identical exhaust nozzles and at the same mean chamber pressure. Thus, the mean speed at the dump was increased by 40%, yet significant oscillations had approximately the same frequency.

Table 1 compares the critical Strouhal numbers for these two sets of data. Two sets of numbers are shown, one using the dump diameter as the characteristic dimension and the other using the step height. The ratio of integers for these critical Strouhal numbers (2:1 based on diameter and 3:2 based on step height) is an interesting feature of these results. This suggests a change in the number of vortices within the separated flow. Recent work by Schadow et al.[7] has been directed at this aspect of the problem. Their results indicate that vortex pairing is important and may account for the apparent change in Strouhal number observed in this study. In addition, Flandro[5] predicted that the maximum acoustic driving occurs for a series of critical Strouhal numbers having the ratio of simple integers, which is consistent with the results in Table 1. The analysis also suggests each successive Strouhal number corresponds to an additional vortex within the separated shear layer.

The proper length scale to be used in the Strouhal number is somewhat uncertain. In this study, the diameter reflects the length of the shear-layer growth toward the centerline. On the other hand, the step height reflects the distance to the shear-layer reattachment point. The length most appropriate for this configuration requires further study.

Tests were then run using the 4-cm-diam orifice. The characteristic Strouhal numbers (based on the two characteristic dimensions: chamber Mach number and 650 Hz) were varied from 0.14 to 0.78 in increments of 0.02 to 0.03. Tests were also conducted at the specific Strouhal numbers shown in Table 1. No conditions producing significant acoustic energy were found. Thus, there appears to be a fundamental difference between the sharp-edged orifice and straight sudden expansion. Certainly, the velocity profiles are different near the dump plane. The flow from the sudden expansion separates right at the geometry change and has no vena contracta downstream. On the other hand, the flow from the orifice separates upstream and has a vena contracta downstream of the orifice. In addition, the orifice may inhibit the feedback of acoustic pressure to the point of flow separation. This may enhance the effectiveness of the orifice in preventing organized oscillations.

Finally, the acoustic frequencies and mode shapes were calculated for the baseline geometry using the one-dimensional Standard Stability Code.[8] In these calculations, the length of the apparatus was increased slightly to account for two-dimensional effects at the dump, as suggested by Oberg et al.[9] These calculations show that acoustic modes 7 and 8 were excited in the baseline geometry. Also, these modes have acoustic velocity antinodes at the dump plane. Hence, these results are consistent with the previous observations that the coincidence of large acoustic velocities and the flow separation are also important in the generation of pressure oscillations by periodic vortex shedding.[3,10]

In conclusion, these studies have shown that periodic vortex shedding can generate substantial acoustic energy in sudden dump geometries. A simple thin-plate orifice was also demonstrated to eliminate the acoustic oscillations. This result differs from the previously reported experience in segmented solid propellant rockets,[2] which showed flow separations from an orifice actually increased the generation of acoustic energy when impinged on a downstream orifice. Thus, these results further demonstrate the importance of vortex shedding contributions to acoustic stability analyses of rocket motors and ramjet engines.

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Advanced Design Propeller Noise Testing in an Anechoic Chamber

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THE rising interest in advanced design propellers (ADP) together with the availability of a Boeing cold air turbine drive (CATD) resulted in a cooperative program between NASA and the Boeing Company to test the NASA-owned SR-6 propeller. The experimental work reported here was accomplished in a large anechoic chamber with relative velocity provided by a freejet.

Test goals included combining the CATD propeller system with the freejet operation, acquiring high-quality noise data delineating transition from near to far field, and describing acoustic directivity for ADP. Test results were subsequently confirmed by testing in a wind tunnel.[1]

The Boeing-developed CATD is a single-rotation, two-stage turbine providing 800 hp at 10,000 rpm.[2] The freejet is a large ejector system which produces low velocity flow at a 4-ft diam exit nozzle. Mach numbers up to 0.25 were achieved, with $M = 0.15$ the typical operating condition.

Figure 1 shows the CATD mounted on a pedestal (monopod) in the Boeing Large Anechoic Test Chamber (LTC), which has a volume of 150,000 ft^3. This test arrangement allowed the propeller to operate in a nearly anechoic, or free-field, environment. Test parameters included propeller pitch angle, rpm, and relative velocity.

Multiple fixed microphones were located at various distances from the source (in and out of flow), and traversing microphones continuously sampled the noise. Three different traverse systems employed a total of seven microphones: three sideline traverse microphones at 3, 4, and 5 ft; three polar traverse centerline-high microphones at 4, 8, and 16 ft, moving from 45 to 145 deg as measured from the propeller rotation axis; and one 90-deg radial traverse microphone from 2 to 26 ft at centerline height. (Distances given are relative to the propeller shaft centerline).

During testing, on-line data were available by tracking the SPL level of the blade passage frequency and the next four harmonics. The tracking procedure produced directivity plots for evaluation of smoothness, shape, and expected values. Also, narrowband spectra could be produced by use of an FFT analyzer. These data supplement the harmonic data and serve to widen the frequency range.

Results

A primary test goal was to determine the distance of near-to far-field transition. If this distance were shown to be small enough, measurements could be made in a restricted area such as a wind tunnel without resorting to flight tests or ultralarge test facilities. Further, this distance becomes very important when ADPs are installed on aircraft.

Propeller noise measurements produce a huge volume of complex data. The plots shown are representative of the many available. For example, one way of examining the data is represented by Fig. 2. For a radially traversing microphone with each data sample normalized to a reference distance

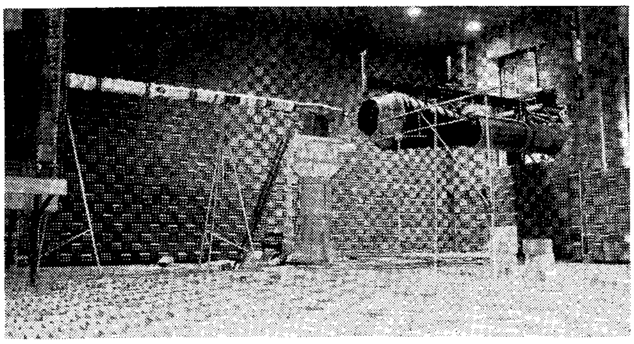

Fig. 1 ADP installation in Boeing large anechoic test chamber with freejet.

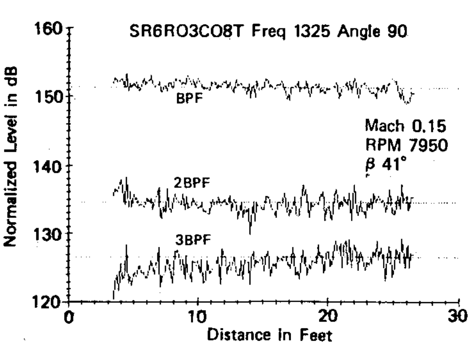

Fig. 2 Normalized SPL vs distance for ADP with freejet.

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