Noise Generated by Boundary-Layer Interaction with Perforated Acoustic Liners

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A problem that occurs in the application of perforated plate acoustic duct liners is the noise generated by the turbulent boundary-layer flow over the holes in the liner surface. This flow not only generates noise but also thickens the boundary layer. To observe the noise generation, a series of tests has been run at the McDonnell Douglas Aerophysics Laboratory. These tests demonstrated that the sound pressure level generated at a liner surface can be as large as 158 dB for a duct Mach number of 0.4. The liner self-noise as measured in one liner panel was found to be affected by changes in the impedance of other liner panels. The tests showed that liner self-noise can be an important consideration in liner design.

I. Introduction

SELF-NOISE caused by flow over solid and porous surfaces, and in particular noise generated by airflows over perforated plate acoustic liners has been known to exist for some time.[1,2,3] Such flows not only generate noise but also increase boundary-layer thicknesses and reduce jet thrust from aircraft engine ducts. It is possible that self-noise in an engine duct with a large amount of acoustic lining could be high enough so that an increase in lining area would actually increase the duct noise level. Recently, tests were conducted at the Douglas Aircraft Company to measure the impedance of acoustic liners using the two-microphone method. A specially designed siren was used to generate the high amplitude sound waves needed for the tests. It was a surprise to find that the self-noise amplitude could be of the same order as the high amplitude sound introduced into the duct from the siren. The self-noise waveform was periodic, with a frequency much different from the liner resonant frequency. Because self-noise appears to be a basic problem connected with the use of perforated plate liners, a separate study of liner self-noise was carried out.

The phenomenon of self-noise reminds the authors of two related problems in unsteady aeroacoustics, that of the edge tone,[4,5] and that of vortex shedding behind a two-dimensional body.[6] In both problems an unsteady and periodic motion is generated by airflow over a rigid surface. Furthermore, the acoustic wavelength is much larger than a characteristic dimension of the surface so that near the surface the flowfield is primarily a hydrodynamic or a pseudosound[7] field. That is, pressure fluctuations in the near field are of the order ρu^2 rather than ρcu, where ρ is the fluid density, c is the speed of sound, and u is the magnitude of the fluid velocity at a typical location in the flowfield. In both the edge tone and the self-noise problems a jet of air impinges on a rigid surface; in the vortex shedding problem the "jet" is really the entire freestream, which comes to rest on the forward part of the bluff body. In each case hydrodynamic instability is responsible for the unsteady motion, and a portion of the stream energy is radiated as acoustic energy. This portion is quite small if the freestream Mach number U_∞/c is small compared to one, but it grows rapidly with Mach number.

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The present experiments on self-noise have been carried out in a duct having portions of the upper and lower walls covered with perforated-plate liners having cavities beneath the plate openings. Thus, the experiments are related to the open cavity experiments of Karamcheti[8] and of Sarohia[9] as well as the perforated tunnel wall experiments of Dougherty et al.[10] However, both Karamcheti and Sarohia used only one cavity at a time in their ducts, whereas the present perforated liners are made up of many parallel rows of cavities on both the upper and the lower duct walls. Sarohia comments that the cavity oscillations are not an acoustic resonance phenomenon. Dougherty et al. tested walls having many holes inclined at an angle of 60° so that the sharp edge of the hole tended to act like the edge of an edge tone system. The flow oscillations were greatly reduced by placing a "splitter plate" in each of the many holes, so that the shear layers might be stabilized. In the present experimental program the cavity flow oscillations were affected by taping over some or all of the cavity rows.

II. Experimental Arrangement

The experiments were carried out using a 6-ft (1830-mm) long duct with a 1-ft (305-mm) square cross section. The duct was mounted in a quiet wind tunnel circuit. With a solid wall test section in the tunnel circuit, measurements at a Mach number of 0.43 showed an overall sound pressure level (SPL) of 132.1 dB.[11] (All SPL's in this paper are given with respect to 20×10^{-6} N/m^2.) Willmarth,[12] by comparison, gives $(p'^2_{rms}/q) = 0.005$ for a turbulent boundary layer on a flat plate so that the overall SPL at $M = 0.43$ had the possibility of being as low as 130.3 dB. Since these SPL values are much less than those recorded during the self-noise experiments, the wind tunnel noise level is believed to be well below that generated by the liner self-noise.

Table 1 gives the magnitude of the geometric parameters of the perforated duct liners that were used for the upper and lower walls of the test duct. In the table σ is the perforated plate open area ratio, b is the depth of the cavity beneath the plate, d is the diameter to the circular perforations in the plate, and t is the plate thickness. The space below the plate was divided into cavities running perpendicular to the flow direction and located so that each cavity was centered about one row of the circular perforations. This construction is illustrated in Fig. 1.

Sound pressures were measured by two 1/8-in. diam B & K microphones placed in one of the liner cavities and on the liner surface. The black dot in the center of the liner top view in Fig. 1 is a typical location for the surface microphone; the cavity microphone was always placed at the bottom of a cavity and at a location about 1 inch from the surface microphone.

Table 1 Geometric parameters of the duct liners

LINER TYPE	σ	b IN. mm	d IN. mm	t IN. mm
501	0.065	0.383 9.72	0.100 2.54	0.040 1.01
513	0.065	0.351 8.91	0.156 3.97	0.040 1.01
515	0.065	0.650 16.51	0.156 3.97	0.040 1.01
517	0.065	0.274 6.96	0.156 3.97	0.040 1.01
519	0.040	0.351 8.91	0.156 3.97	0.040 1.01
521	0.100	0.351 8.91	0.156 3.97	0.040 1.01

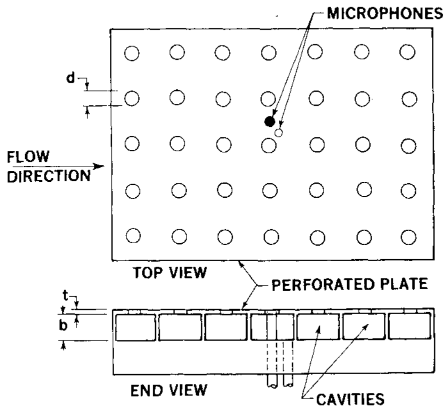

Fig. 1 Geometrical arrangement of a typical liner test panel.

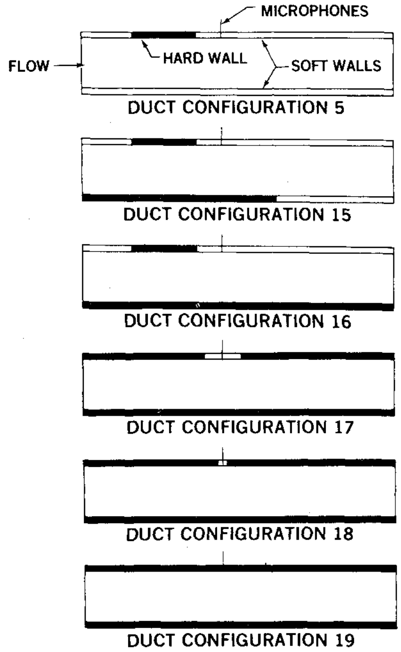

Fig. 2 Duct configurations used for measurements of liner self-noise.

Figure 2 illustrates some of the duct and liner configurations used in the testing. For example, in Configuration 5 the entire lower surface, the first 12 in. of the upper surface, and the last 36 in. of the upper surface were all made of type 501 liners. A solid wall, an aluminum plate and a horn used for siren sound inputs during impedance observations, extended from Station 12 to Station 27. The remaining 9 in. from Station 27 to Station 36 on the upper surface was a type 513 liner, which contained the two microphones.

Configuration 15 was derived from Configuration 5 simply by using 0.003-in. thick vinyl tape to cover over the holes on the lower surface liner between Stations 0 and 42. This tape treatment produced a rather "hard" surface, as was verified by acoustic impedance measurements using the siren and the two-microphone method. The measurements gave impedance values of the order of 10 ρc in magnitude, much larger than with the vinyl tape removed.

Configurations 16 through 19 were also generated from Configuration 5 by using vinyl tape to cover the areas indicated by the heavy black lines. For Configuration 18 only the microphone row of holes was not covered by tape; for Configuration 19 only the surface microphone was uncovered.

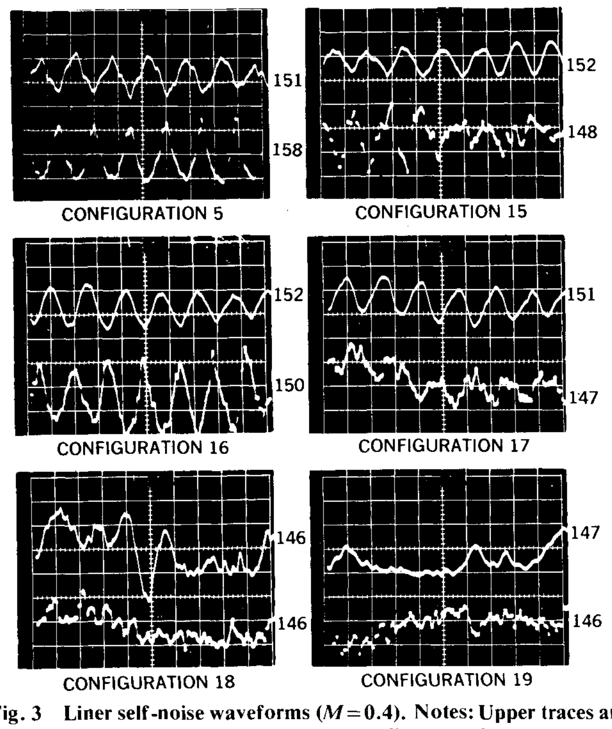

Fig. 3 Liner self-noise waveforms ($M=0.4$). Notes: Upper traces are cavity pressure vs time. Lower traces are linear surface pressure vs time. Overall SPL in dB is given to the right of the waveforms. Time scale is 100 μs per division.

III. Observations of Liner Self-Noise Generation

In Fig. 3 are samples of the waveforms recorded from oscilloscope photographs of the microphone output. The duct Mach number was $M=0.4$. For Configuration 5 we see almost periodic signals from both microphones at a frequency $f=6600$ Hz. The cavity SPL was 151 dB and the surface SPL was 158 dB. The two signals are 180° out of phase, indicating that when the particle flow through the liner orifice has penetrated as far as it is to go into the cavity, then the surface pressure is a minimum. The Strouhal number $S=fd/U_\infty$ based on the duct freestream speed U_∞ is 0.195. Values of these parameters at $M=0.2$ through $M=0.5$ are shown on Figs. 4 and 5.

The waveforms are changed by the addition of the tape to give Configurations 15 through 19. Notice on Fig. 3 that for Configuration 17 the cavity SPL is still the same as in Configuration 5 and the waveform is still periodic; however, the surface SPL is greatly reduced and the waveform is no longer periodic. This lack of periodicity is indicated on Fig. 5 by the absence of a symbol for Configuration 17 in the lower portion of the figure. Further tape addition reduces even more the amplitude and periodicity of the cavity pressure.

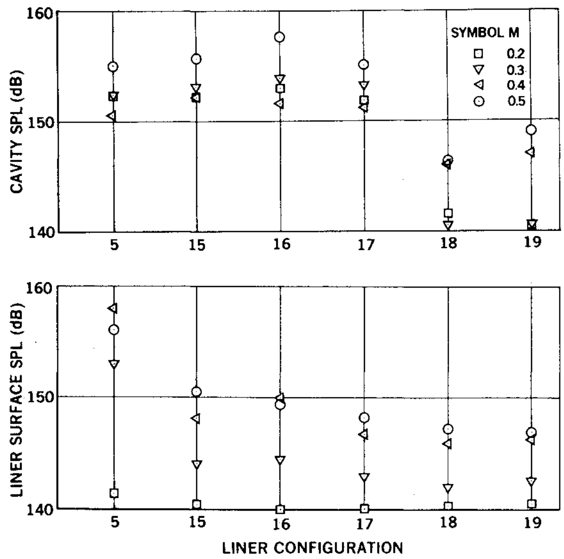

Fig. 4 Self-noise of liners – SPL.

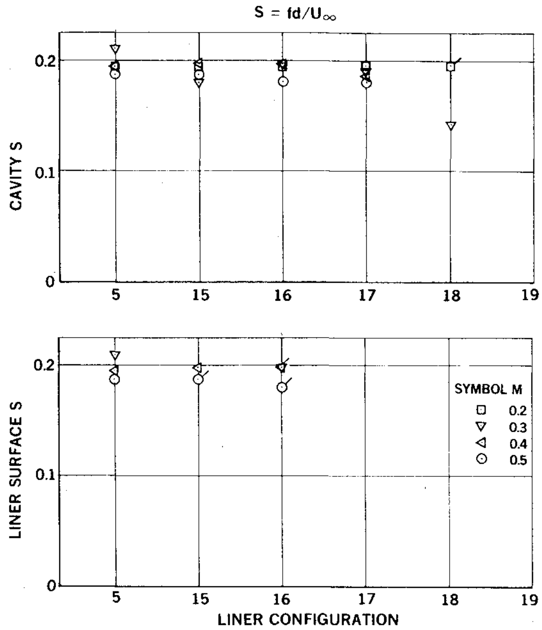

Fig. 5 Self-noise of liners – Strouhal numbers.

Similar changes as a function of configuration changes are shown in Fig. 4. It is interesting that the cavity SPL stays high until the tape is used to cover all but one row of holes, whereas the surface SPL drops greatly with the first addition of tape to the lower surface. This indicates that the first addition of tape must interfere with wave propagation across the duct but not with the local interaction of the boundary layer with the liner orifices, which must produce the large SPL in the cavity.

Each of liners 515, 517, 519, and 521 were tested in place of liner 513 in Configuration 5 with the result that the SPL's and the waveforms were much the same as those for liner 513. Hence, the self-noise generation appears to be primarily a function of the liner hole size rather than the other geometric parameters.

IV. Observations on the Strouhal Numbers

Figure 5 is remarkable because it shows that $S \approx 0.2$ for all values of Mach number. Almost the same value of S was found by Feder,[13] who tested liners with hole sizes 0.062 in. to 0.250 in. in a 5- by 5-in. duct with flow speeds of 100 to 700 fps. He noted that liner backing depth b did not appear to be an important parameter in determining f. This is supported by test results using liners 515, 517, 519, and 521, which also showed that the open area ration σ is not an important parameter in determining S.

Like values of S were obtained by Mutte[14] and by Panton.[15] Mutte ran his tests in a duct, but Panton mounted individual Helmholtz resonators on the side of the fuselage of a sailplane. His resonators were excited strongly only when they were of a size that had a resonant frequency such that S was approximately 0.2.

Demetz and Farabee[16] have recently reported that S depends on the ratio δ/d, where δ is the boundary-layer thickness. For δ/d near 10, as in the present experiments, S is only a very weak function of δ/d; larger values of δ/d result in decreased values of S. For δ/d of the order of 1 or less, S varies rapidly with δ/d.

Since for all these experiments the liner hole diameters d are much less than the acoustic wavelengths, $\lambda = c/f$, the flowfields near the holes are essentially hydrodynamic rather than acoustic so that only a small portion of the field energy is radiated away as sound; this means that we would not expect changes in c or Mach number U_∞/c to affect the value of S significantly, as is borne out by the experiments.

It is interesting that S for a circular cylinder in a freestream is also about 0.2 (Ref. 6), whereas for an edge tone system S based on the velocity at the center of the nozzle is about 0.3 (Refs. 4 and 5). For his cavities and with a turbulent boundary layer, Karamcheti[8] found that $S = 0.35$, although a strong second harmonic frequency was also present; when he used a laminar boundary layer S was on the order of 0.8. Sarohia[9] did cavity testing with only laminar boundary layers and found that S varied from 0.5 to 0.6 in the fundamental mode of oscillation; two higher modes also were observed. Dougherty et al.[10] observed that wind-tunnel walls with holes had a wide range of modes. The fundamental mode occurred for S approximately equal to 0.1; however S was also a weak function of Mach number. These examples show that several quite different flowfields have nearly the same value of Strouhal number.

V. Effects of Stream Velocity on SPL

In Fig. 4 it is indicated that SPL generally increases with Mach number. However, on the surface for Configuration 5 the SPL reaches a maximum at $M = 0.4$ and then falls off. This same maximum was observed in a series of about 20 runs again using liner 513 but in a configuration somewhat different from Configuration 5. These 20 data points show that the decrease in SPL with M extends past $M = 0.6$.

For the hydrodynamic near field one might expect the pressure fluctuations to be proportional to $U_\infty{}^2$ or M^2, so that the mean square of the pressure fluctuations should vary like $U_\infty{}^4$. The data on Fig. 4 for the near field, in particular for the cavity SPL, indicate that the power level varies at a rate that is proportional to a lower power of U_∞. This may be the result of the fact that such hydrodynamic oscillations are limited in amplitude by nonlinear aspects of the hydrodynamic instability that are poorly understood.

Ffowcs-Williams[17] in his study of acoustic liner self-noise concludes that the sound radiant energy should go like $U_\infty{}^4$ for liners with a small number of holes or small σ, and like $U_\infty{}^6$ for large values of σ. Ver[18] has correlated some data at Mach numbers between 0.01 and 0.03 for values of σ between 0.30 and 0.78. He found that the sound power level in a duct varies like $U_\infty{}^{5.5}$.

Dougherty et al.[10] show experimentally that the sound power level in their ducts generally varied like $U_\infty{}^4$ for $\sigma = 0.06$, but that the power level increased by 10 dB or more near Mach numbers where the waves were reinforced by interactions with other portions of the duct. The resonant Mach number was predicted by a simple formula given by Varner,[19] but this formula does not predict the $M = 0.4$ apparent resonance observed in the present experiments.

VI. Conclusions

Noise generated by boundary-layer interactions with perforated plate acoustic liners is primarily that from interactions with the holes. The essentially hydrodynamic near field has a Strouhal number of about 0.2 based on freestream and hole diameter, independent of variation in Mach number or liner geometry.

The sound pressure level at a point on the liner surface is affected by interactions with other portions of the same and the opposite walls of the duct. Moreover, the measured sound pressure levels on the surface do not vary monitonically with Mach number but exhibit a maximum at about $M=0.4$ for the present experiments. Self-noise sound pressure levels on a liner surface can be as large as 158 dB for sea level conditions and duct Mach numbers near 0.4.

Designers of perforated-plate acoustically absorptive duct linings must keep in mind the potential deleterious self-noise effects on the acoustical performance of the linings. Hole diameters in the perforated plate should be small enough so that the characteristic frequency of the self-noise is above the highest frequency in the range of interest for each specific application.

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