Control of Cavity Noise

V. Sarohia* and P. F. Massier†
Jet Propulsion Laboratory, Pasadena, Calif.

Experiments have been conducted on axisymmetric shallow cavity flows with the aim of investigating methods to modify cavity shear flows such that cavity noise may be reduced. The experiments indicate the presence of large gross lateral motion of the shear layer close to the downstream cavity corner which, on interaction with it, results in production of cavity flow noise. Results also show that the continuous injection of a fluid mass at the base of the cavity has a stabilizing effect on cavity shear flows. This stability is believed to have been achieved by supplying the mass required for cavity shear-layer entrainment externally. This also was accompanied by a delay in large periodic lateral motion of the cavity shear layer close to the downstream cavity corner as observed without the mass injection. Thus, the addition of a continuous fluid mass appears to be an effective means of suppressing cavity flow noise.

Nomenclature

a_∞	= freestream acoustic velocity
b	= cavity width (cavity length)
d	= cavity depth
dB	$\equiv 10\log_{10}(\overline{u'^2}/\overline{u'^2_{ref}})$; $10\log_{10}(\overline{p'^2}/\overline{p'^2_{ref}})$ dB
D	= diameter of the nozzle axisymmetric model
f	= frequency, Hz
fb/U_∞	= nondimensional frequency
l	= nose length of the model
$\dot{m}$	= rate of mass injected
M_∞	$\equiv U_\infty/a_\infty$ freestream Mach number
p'	= pressure fluctuations of radiated cavity flow noise
$(\overline{p'^2})^{1/2}$	= rms pressure fluctuations of radiated cavity flow noise
u'	= velocity fluctuations in direction x
$(\overline{u'^2})^{1/2}$	= rms velocity fluctuations in direction x
U_∞	= freestream velocity in front of the model
x	= streamwise coordinate
θ	= angle, deg
ρ	= density
σ	$\equiv \dot{m}/\pi D b_{min}(\rho U_\infty)$; nondimensional mass injection parameter
$(\ )_{min}$	= corresponds to the conditions for onset of cavity oscillations
$(\ )_{ref}$	= reference quantity

I. Introduction

PERIODIC oscillations in cavities have been observed over a large range of Mach numbers and Reynold numbers, with both laminar and turbulent boundary layers and over a wide range of length-to-depth ratios. Flows over cavities are of interest because cavity flows emit strong acoustic tones at high subsonic and supersonic flows. This property of the cavity flow can be employed to seed the flow with high-intensity sound waves. Also, the presence of cavities on aircraft structures influences the drag and heat transfer and may cause intense periodic oscillations, which in turn may lead to severe buffeting of the aerodynamic structure accompanied by the production of sound. In general, noise generated by such flows is undesirable, as for example, flows over landing gear cavities. Thus, as other presently dominant aircraft noise sources are reduced, airframe noise becomes increasingly important, and consequently the reduction of cavity noise is a problem that needs investigation.[1]

The phenomenon of oscillations in flows over cavities has been studied by many investigators in the past.[2-14] Few experiments have been conducted,[15-17] however, with the aim of investigating methods to modify cavity shear flow such that cavity noise may be reduced. Its role is more complex in flows over shallow cavities (i.e., having a depth $d \lesssim$ length b of the cavity) than in deep cavities (i.e., $d \gg b$). In deep cavities, the shear layer has been observed to act as a forcing mechanism and oscillation phenomena in them are due to an acoustic resonance in the depth mode.[8] In contrast to deep cavities, the mechanism of oscillations in flows over shallow cavities is one of the propagating disturbances which get amplified through the shear flow[13] rather than one of standing longitudinal acoustic waves. Since cavity oscillations and associated radiated noise arise due to instability of the cavity shear flow, one can, in principle, reduce cavity noise by modifying the stability characteristics of the cavity shear flow.

The foregoing conclusions are confirmed further by the investigation of Franke and Carr[15] in which the effect of cavity geometry on flow-induced cavity pressure fluctuations was studied. By modifying the cavity geometry at leading and trailing cavity corners, it was shown that the effectiveness of suppressing cavity flow oscillations depended largely on the development of cavity shear layer (see Fig. 9 in Ref. 15). Dougherty et al.[16] also showed that the noise induced by cavity flows can be reduced by modifying the cavity geometry.

In a previous investigation on oscillations in flows over shallow cavities,[13] it was shown that intense cavity oscillations were accompanied by large gross lateral motion of the cavity shear layer at a cavity oscillation frequency close to the downstream corner. Results indicated that cavity oscillations could be delayed with the introduction of a small quantity of air at the base of the cavity. Smoke pictures of the cavity shear flow[13] showed that, with mass injection, the shear layer effectively was blown out of the cavity. This reduced the interaction with the downstream cavity corner, and, consequently, cavity oscillations were postponed. No detailed and systematic measurements of the shear-layer oscillations and the radiated noise with mass injection were undertaken.

Heller and Bliss[17] also postulate that large periodic mass exchange close to the downstream cavity corner accompanies the cavity flow oscillations. As pointed out by them, this periodic mass exchange close to the downstream cavity corner may supply the mass entrained by the oscillating cavity shear

Presented as Paper 76-528 at the 3rd AIAA Aero-Acoustics Conference, Palo Alto, Calif., July 20-23, 1976; submitted Sept. 3, 1976; revision received Feb. 14, 1977.
Index categories: Jets, Wakes, and Viscid-Inviscid Flow Interactions; Aeroacoustics.
*Senior Scientist. Member AIAA.
†Group Supervisor. Associate Fellow AIAA.

layer. In fact, a large increase in cavity shear-layer entrainment occurs when the cavity begins to oscillate (see Fig. 11 in Ref. 13). It is apparently possible to stabilize the shear layer by a continuous mass addition at the base of the cavity and thus avoid intense periodic lateral motion of the shear layer. This, consequently, will reduce the radiated cavity flow noise.

It therefore was deemed mandatory that detailed simultaneous measurements of the cavity shear-layer velocity fluctuations and the radiated cavity noise should be made. Such a study will give insight into the source for cavity flow generated noise. This will, in turn, help in devising methods for cavity flow noise reduction. Investigation of shear-layer velocity fluctuations, with and without mass addition, would help to elucidate further the mechanism of noise reduction of cavity flow noise by mass injection. This investigation was undertaken. The results are discussed in the following sections.

II. Experimental Arrangements

Model and Wind Tunnel

The investigation consisted of a series of experiments using two axisymmetric cavity models as sketched in Fig. 1. The axisymmetric nozzle cavity model (Fig. 1a) had an internal diameter D of approximately 10 cm, with a fixed depth d of the cavity; $d \doteq 1.17$ cm. This model had an arrangement by which the cavity width b could be varied continuously from zero to $b \simeq 6.25$ cm. To study the effect of mass injection on cavity flow oscillations, air was injected circumferentially along the base of the cavity. The injected mass was measured accurately by flowing this mass through a choked nozzle flow system. Great care was taken to inject the cavity mass uniformly along the circumference. This cavity model was attached to the exit of the 10-cm-diam nozzle flow. The exit Mach number M_∞ could be varied from zero to $M_\infty \simeq 0.5$. This nozzle cavity model had a provision for inserting a Kistler piezoelectric pressure transducer at the base of the cavity to measure the cavity pressure fluctuations. The model was located in an anechoic chamber in which the radiated cavity noise was measured. Over the range of Mach numbers at which this cavity flow was studied, the boundary-layer separation at the upstream cavity corner was turbulent.

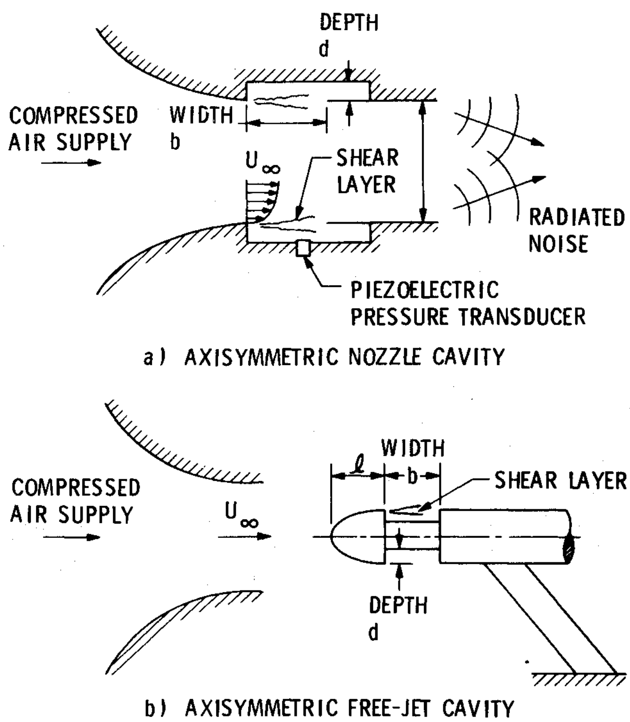

Fig. 1 Schematic diagram of the axisymmetric model.

The other model tested was 5.08 cm in diameter. It was placed in a 12.7-cm open jet tunnel (see Fig. 1b) and carefully centered along the axis of the freejet. The intensity of longitudinal velocity fluctuation in the freestream $(\overline{u'^2})^{1/2}$ was approximately 1% at $U_\infty \simeq 100$ m/sec. The depth d of the 5.08-cm-diam model could be varied in steps of 1.91, 1.27, 0.64, and 0.32 cm. The width could be varied continuously from approximately zero to 5 cm. The accuracy of measuring width b was ± 0.002 cm. The model had a family of ogive noise shapes with different nose lengths l. With the help of these ogive noise lengths, both laminar and turbulent boundary-layer flows at the upstream cavity corner were obtained. To analyze the cavity flow, a hot-wire probe was inserted from outside into the shear layer. The hot-wire probe was brought from outside and could be moved very precisely along and across the cavity shear flow. This model also had a provision for injecting a mass from the base of the cavity.

Instrumentation

Constant temperature hot-wire anemometry was used extensively in measuring both mean and fluctuating quantities. A Thermo-Systems Inc. constant temperature anemometer model 1050 was used. Throughout this study the probe wire of 0.0005-cm (0.0002-in.) diameter and 0.2-cm (0.08-in.) length was held in the fine tips of the hot-wire probe. The output of the hot-wire was fed to an EMR all-digital real-time spectrum analyzer to analyze the frequency contents of the cavity flow. The spectrum analyzer had variable bandwidths to locate closely separated signals. The output of the spectrum analyzer was fed to an $x-y$ plotter to measure the relative amplitude of the frequency content in the hot-wire signal. Hot-wire output also was displayed simultaneously on the oscilloscope.

To measure the pressure fluctuations inside the cavity, a 3.2-mm-diam Kistler piezoelectric pressure transducer was employed. The far-field cavity flow generated noise was measured with 1.27-cm-diam microphones. The microphone data were recorded on tape and played back through the spectrum analyzer to obtain the spectrum of the cavity flow noise signal.

III. Experimental Results

Nondimensional Frequency of Cavity Oscillations

The phenomenon of oscillations in flows over shallow cavities is one of a propagating disturbance which gets amplified through the cavity shear layer.[13] The important length scale, in shallow cavity flows to nondimensionalize the frequency f, is the width b of the cavity. The influence of freestream Mach number M_∞ and width b/d on non-

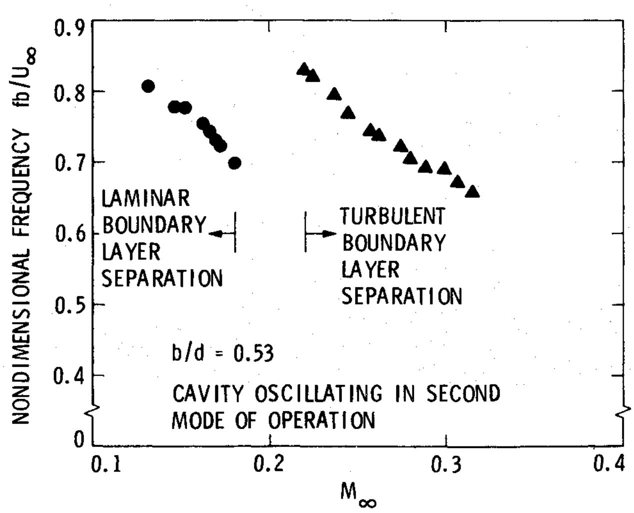

Fig. 2 Effect of upstream Mach numbers on nondimensional frequency for both laminar and turbulent boundary-layer separation.

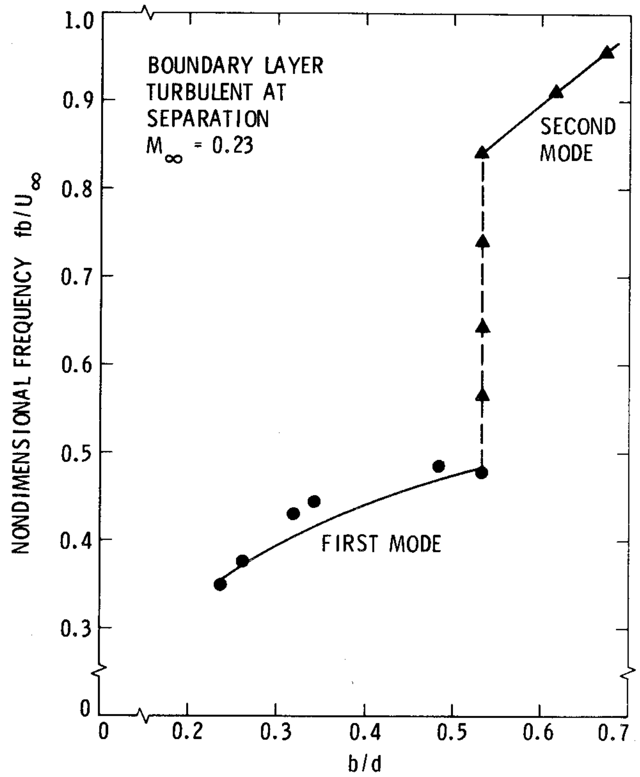

Fig. 3 Effect of width on nondimensional frequency.

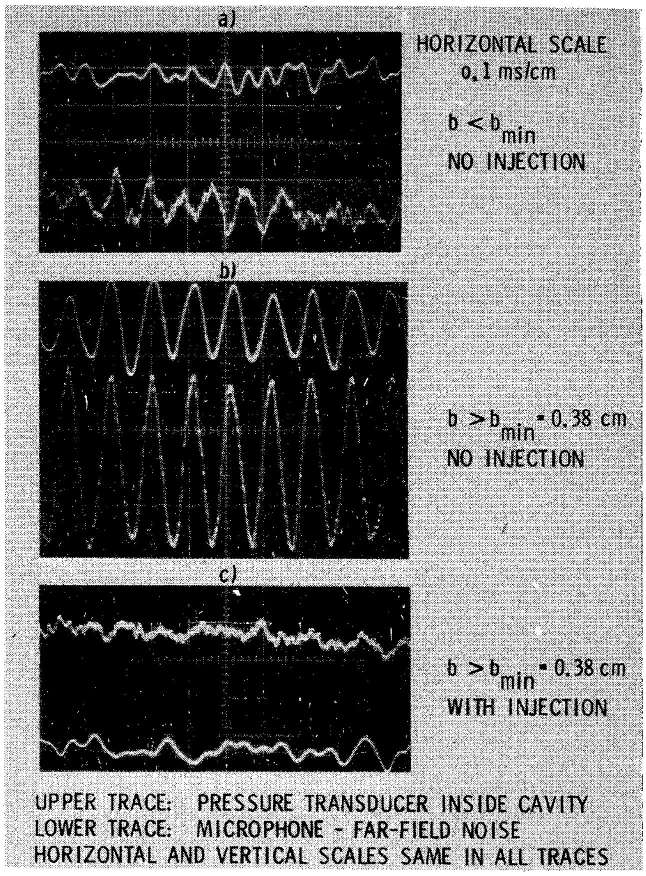

Fig. 4 Oscilloscope traces of pressure fluctuations inside the cavity and of the radiated cavity flow noise with $M_\infty = 0.47$ and $d = 1.17$ cm.

dimensional frequency for both laminar and turbulent cavity flows at the upstream cavity corner was studied. The frequency of cavity oscillations referred to in this section is that of cavity shear-layer velocity fluctuations close to the downstream corner. The same oscillation frequency was picked up by the pressure transducer inside the cavity (near-field) and in the far-field radiated cavity noise.

The influence of freestream Mach number on nondimensional frequency for a fixed $b/d = 0.53$ is shown in Fig. 2. The cavity flow began to oscillate with a nondimensional frequency of about 0.8 at M_∞ of about 0.13. At $M_\infty \simeq 0.13$, the cavity flow was laminar and stayed so until $M_\infty \simeq 0.18$. The nondimensional frequency decreased as the freestream Mach number was increased. At $M_\infty \simeq 0.18$, the boundary layer at separation was no longer laminar. The cavity flow ceased to oscillate for Mach number $0.18 \lesssim M_\infty \lesssim 0.22$, for which the boundary layer at separation was transitional. At $M_\infty \simeq 0.22$, the cavity flow began to oscillate, with a sudden jump to a nondimensional frequency $fb/U_\infty \simeq 0.25$. With increasing Mach number, this nondimensional frequency decreased similarly to the one for laminar boundary-layer cavity flow at separation. It should be noted that this band of nondimensional frequency, both for laminar and turbulent boundary-layer separation, corresponds to the second mode of cavity flow oscillation.

Figure 3 shows the effect of width on cavity oscillations at Mach number $M_\infty = 0.23$. The boundary-layer flow at the upstream cavity corner was a turbulent one. No cavity flow oscillations occurred below $b/d = 0.23$, which represents the minimum width $(b/d)_{\min}$. First mode fluctuations occurred at a nondimensional frequency of about 0.35. There was an increase in nondimensional frequency as b/d was increased. As the critical value of $b/d = 0.53$ was reached, oscillations jumped to a higher mode. At this width, both of these modes occurred alternately. The two modes, for both laminar and turbulent boundary-layer separation, never occurred simultaneously. The second mode of cavity oscillations occurred at an approximate nondimensional frequency of 0.84. This increased as the width was increased further. Beyond $b/d > 0.67$, the flow over the cavity became irregular and the periodic fluctuations ceased to exist or were weaker than turbulent fluctuations in the shear layer.

Influence of Mass Injection on Onset of Cavity Flow Oscillations

It has been observed experimentally for flow over cavities that, for given flow conditions, there exists a minimum width $b_{\min}$ below which no oscillations occur. Also, no cavity oscillations occur below a minimum velocity $U_{\infty\ \min}$ for a given cavity geometry.

The oscilloscope traces of pressure transducer output inside the cavity and a microphone located in the far field are indicated in Fig. 4. The freestream Mach number $M_\infty = 0.47$, and $b_{\min}$ was approximately 0.38 cm. For $b < b_{\min}$, there were periodic pressure fluctuations of very small amplitude inside the cavity. As the minimum width $b_{\min} = 0.38$ cm was reached, a sudden jump in the cavity pressure oscillation resulted. There was a large increase in amplitude of cavity pressure oscillations as well as the radiated noise. Figure 4b indicates such a condition. It should be noted that horizontal and vertical scales in the traces in Figs. 4a-c were identical. The corresponding hot-wire inserted inside the cavity shear layer showed that these large-amplitude pressure oscillations for $b > b_{\min}$ both in the near and far fields were accompanied by a sudden jump in the energy in the periodic velocity fluctuations. This also resulted in violent periodic lateral motion of the cavity shear layer close to the downstream cavity corner.

The influence of continuous mass injection at the base of the cavity for $b > b_{\min} = 0.38$ cm on cavity pressure oscillation is indicated in Fig. 4c. On comparing Fig. 4c with Fig. 4b, it is clear that mass injection virtually eliminated the periodic pressure cavity oscillations and, consequently, the radiated noise. Corresponding hot-wire surveys of the shear layer indicated that the mass injection resulted in diminishing the periodic velocity fluctuations in the cavity shear layer. It was observed that, for a given mass injection, cavity oscillations reappeared when either width b or the freestream Mach number was increased. The oscillations could be delayed with a further addition of mass.

The effect of rate of mass addition on the onset of cavity oscillations was studied in detail. The rate of mass injection was defined by the nondimensional quantity as

$$\sigma \equiv \dot{m}/\pi D b_{\min} (\rho U_\infty)$$

where $\dot{m}$ is the rate of mass injection and ρU_∞ is the flow around the cavity per unit area. Figure 5 indicates the typical results showing the influence of the nondimensional mass injection parameter σ on the onset of cavity oscillations. On comparing minimum width for $\sigma = 0$, it is evident that one can, in principle, delay oscillations by increasing the mass injection σ. The relationship between $b_{\min}$ and σ was approximately linear until $\sigma \simeq 0.162$ was reached, at which time there occurred a sudden jump in $b_{\min}$. As shown in Fig. 5, the oscillations could be delayed for much larger $b_{\min}$ with a lower nondimensional mass injection parameter σ. This sudden change in $b_{\min}$ vs σ was attributed to a change in mode of cavity flow operation (see Fig. 3).

During the course of this investigation, under certain conditions of flow and cavity geometry. the addition of mass at cavity base resulted in insignificant reduction or sometimes even an enhancement of radiated cavity flow noise. Careful study of the cavity shear flow revealed that under these flow conditions, small perturbation introduced by mass injection resulted in switching of the cavity flow from one mode of operation to another. Thus, with mass injection, cavity flow generated noise of a different frequency corresponding to a different mode of cavity flow oscillations.

Effect of Mass Injection on Cavity Shear Layer

As pointed out earlier, the radiated cavity noise is generated by violent periodic lateral motion of the cavity shear layer close to the downstream cavity corner. The cavity shear layer was studied with a hot-wire inserted in the cavity shear layer under a wide range of flow and cavity geometries. This was done with and without the mass injection and for both laminar and turbulent boundary-layer separation.

The results in Fig. 6 show the influence of mass injection on the spectrum of cavity shear-layer velocity fluctuations close to the downstream cavity corner. The boundary layer at the upstream cavity corner was laminar. A large drop occurred in the amplitude of shear-layer velocity fluctuations as shown in Fig. 6. Similar results for the turbulent boundary-layer separation with $M_\infty = 0.24$ are indicated in Fig. 7. There was an increase in the low-frequency random velocity fluctuations. But, as is clear from Fig. 7, there was a reduction of 12 dB in the velocity fluctuations; i.e., the energy in periodic velocity fluctuations was reduced by a factor of a little over 10 with mass injection.

Effect of Mass Injection on Radiated Cavity Flow Noise

Since the cavity noise is closely related to cavity shear-layer fluctuations, if velocity fluctuations are delayed for a given

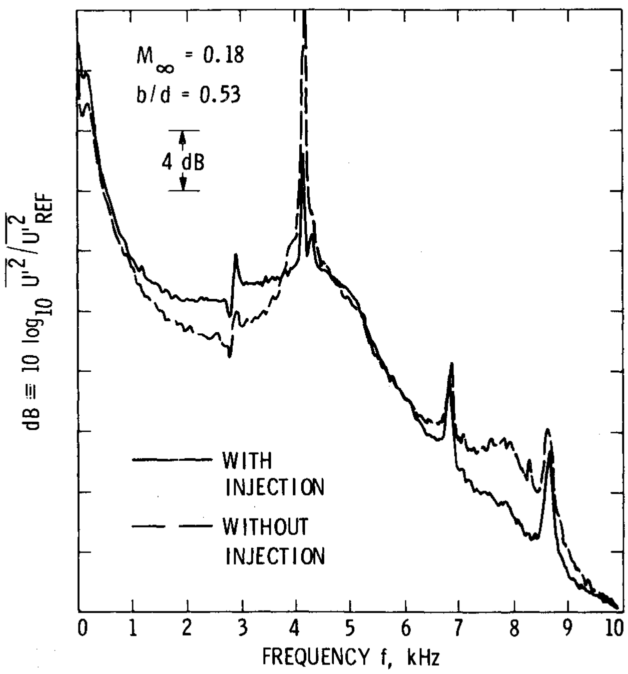

Fig. 6 Effect of mass injection on spectrum of shear-layer velocity fluctuations – laminar boundary layer.

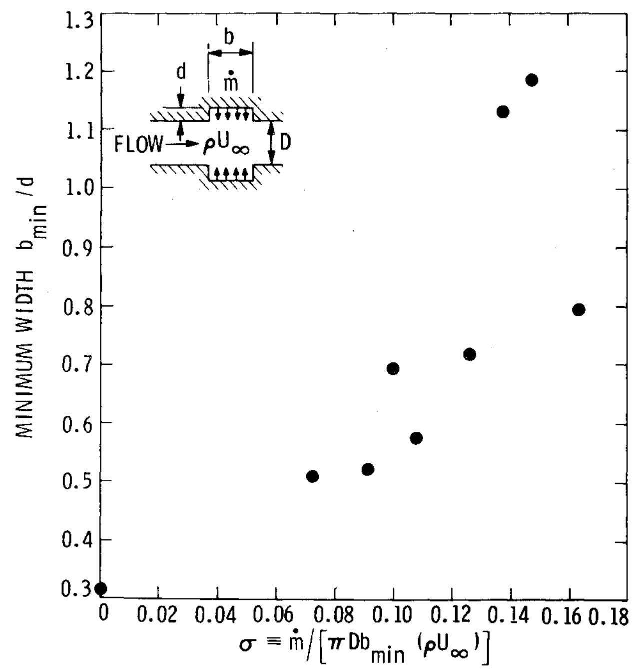

Fig. 5 Influence of mass injection on onset of cavity oscillation.

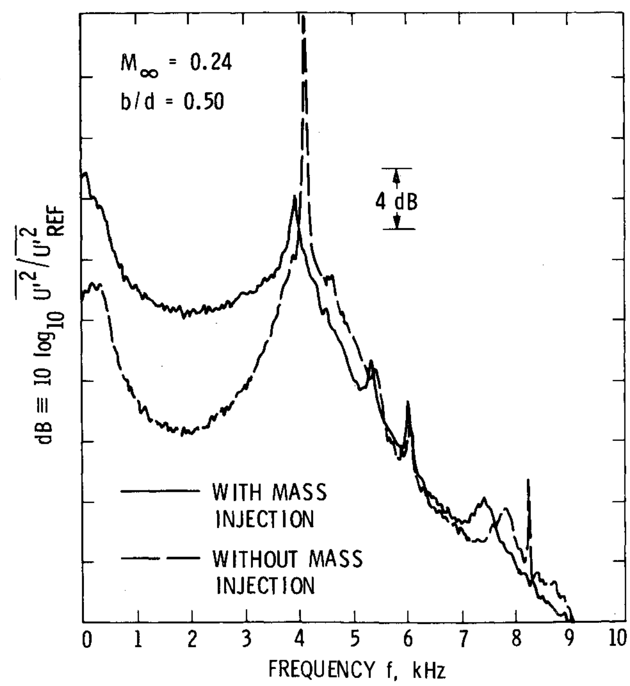

Fig. 7 Effect of mass injection on spectrum of shear-layer velcity fluctuations – turbulent boundary layer.

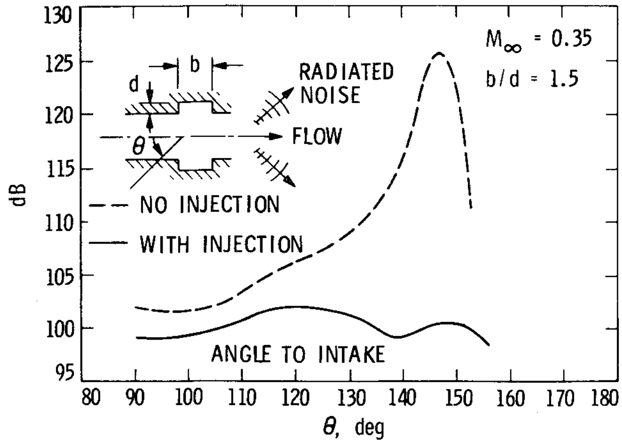

Fig. 8 Effect of mass injection on radiated cavity flow noise.

cavity geometry with mass injection, the radiated noise also will be reduced. The overall angular distribution of the radiated noise from the cavity (Fig. 1a) for a fixed freestream Mach number $M_\infty = 0.35$ with width $b/d = 1.5$ is shown in Fig. 8. Also shown is the noise when the mass injection was sufficient to suppress the cavity shear-layer velocity fluctuations. As would be expected, there was a remarkable reduction of radiated cavity noise.

IV. Conclusions

1) The phenomenon of oscillations in flows over cavities with both laminar and turbulent boundary-layer separation results from propagating disturbances which are amplified along the cavity shear layer. The phenomenon of oscillations in shallow cavities is not an acoustic resonance phenomenon in the longitudinal mode.

2) The present investigation indicates that, for both laminar and turbulent boundary-layer separation, the cavity shear flow oscillates at one dominant frequency. Higher harmonics of fundamental frequency of cavity oscillations close to the downstream cavity corner are due to superimposed nonlinear velocity fluctuations. These higher harmonics should not be confused with the higher modes of cavity flow oscillations.

3) The radiated cavity flow noise from shallow cavities is due to interaction of the violently oscillating shear layer with the downstream cavity corner.

4) Present results show that flow-induced cavity noise can be controlled by mass injection at the base of the cavity. Cavity flow radiated noise is accompanied by large gross lateral motion of the cavity shear layer close to the downstream cavity corner. This gross periodic motion is believed to result in mass exchange between the cavity fluid and the freestream fluid which is required for cavity shear-layer entrainment, as postulated by Heller and Bliss.[17] By mass injection at the base of the cavity, the continuity of the cavity mass is provided. This may have resulted in eliminating these gross periodic shear-layer osicllations at the downstream cavity corner. This, in turn, results in suppressing the cavity-flow-generated far-field noise. Depending on the cavity configuration and flow, the mass required to suppress the cavity flow noise was approximately 5 to 15% of the freestream mass ρU_∞.

Acknowledgment

This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under Contract NAS7-100, sponsored by the National Aeronautics and Space Administration. The authors gratefully acknowledge the help of Joseph M. Smyth in conducting these experiments. The assistance of D. Feller, F. H. Slover, and S. J. Kikkert in fabricating and assembling these experiments is appreciated greatly.

References

[1] Morgan, H. G. and Hardin, J. C., "Airframe Noise – The Next Aircraft Noise Barrier," *Journal of Aircraft*, Vol. 12, July 1975, pp. 622-624.

[2] Brazier, J. G., "The Hydrostatic Channel and A3D-1 Bomb Bay Buffeting Tests," Douglas Aircraft Co. Rept. No. ES 17825, Dec. 27, 1954.

[3] "Investigation of B-47 Bomb Bay Buffeting," Boeing Airplane Co., Rept. D-12675, Feb. 15, 1952.

[4] Bilanin, A. J. and Covert, E. E., "Estimation of Possible Excitation Frequencies for Shallow Rectangular Cavities," *AIAA Journal*, Vol. 11, March 1973, pp. 347-351.

[5] Charwat, A. F., Roos, J. N., Dewey, F. C., and Hitz, J. A., "An Investigation of Separated Flows. Part 1. The Pressure Field," *Journal of Aerospace Science*, Vol. 28, 1961, pp. 457-470.

[6] Covert, E. E., "An Approximate Calculation of the Onset Velcity of Cavity Oscillations," *AIAA Journal*, Vol. 8, Dec. 1970, pp. 2189-2194.

[7] Dunham, W. H., "Flow-Induced Cavity Resonance in Viscous Compressible and Incompressible Fluids," *Fourth Symposium on Naval Hydrodynamics, Ship Propulsion and Hydrodynamics*, Rept. ARC-73, Vol. 3, Office of Naval Research, Washington, D. C., 1962.

[8] East, L. F., "Aerodynamic Induced Resonance in Rectangular Cavities," *Journal of Sound Vibrations*, Vol. 3, 1966, pp. 277-287.

[9] Heller, H. H., Holmes, D. G., and Covert, E. E., "Flow Induced Pressure Oscillations in Shallow Cavities," *Journal of Sound Vibrations*, Vol. 18, 1971, pp. 454-552.

[10] Karamcheti, K., "Sound Radiated from Surface Cutouts in High-Speed Flows," Ph.D. Thesis, California Institute of Technology, June 1956.

[11] McGregor, W. and White, R. A., "Drag of Rectangular Cavities in Supersonic and Transonic Flows Including the Effects of Cavity Resonance," *AIAA Journal*, Vol. 8, Nov. 1970, pp. 1959-1964.

[12] Rossiter, J. E., "Wind Tunnel Experiments on the Flow Over Rectangular Cavities at Subsonic and Transonic Speeds," Communicated by the Deputy Controller Aircraft (Research and Development) Ministry of Aviation, R&M No. 3438, Oct. 1964 (replaces R.A.E. TR 64037 – A.R.C. 26621).

[13] Sarohia, V., "Experimental Investigation of Oscillations in Flows Over Shallow Cavities," AIAA Paper 76-182, Washington, D. C., Jan. 1976.

[14] Stull, F. D., Curran, E. T., and Velkoff, H. R., "Investigation of Two-Dimensional Cavity Diffusers," AIAA Paper 73-685, Palm Springs, Calif., July 1973.

[15] Franke, M. E. and Carr, D. L., "Effect of Geometry on Open Cavity Flow-Induced Pressure Fluctuations," AIAA Paper 75-492, Hampton, Va., 1975.

[16] Dougherty, N. S. Jr. and Anderson, C. F., "An Experimental Study on Suppression of Edgetones from Perforated Wind Tunnel Walls," AIAA Paper 76-50, Washington, D. C., Jan. 1976.

[17] Heller, H. H. and Bliss, D. B., "The Physical Mechanism of Flow-Induced Pressure Fluctuations in Cavities and Concepts for Their Suppression," AIAA Paper 75-491, Hampton, Va., March 1975.