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Technical Notes

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Cavity Resonance Suppression Using Miniature Fluidic Oscillators

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Introduction

WE present a novel approach to suppressing jet-cavity interaction tones using a miniature fluidic device. We first characterize the miniature fluidic oscillator and then assess its effectiveness for cavity tone suppression. Further, we evaluate mass flow requirements for effective unsteady fluid mass addition. The fluidic device used had no moving parts and could provide oscillatory flow of prescribed waveforms (square waveform) at frequencies up to 3 kHz. Our test bed for a detailed evaluation of the fluidic excitation (square wave) technique was the flow-induced resonance produced by a jet flowing over a cavity with a length/depth ratio of 6. The jet Mach numbers considered were 0.485 and 0.69. When located at the upstream end of the cavity floor, the miniature fluidic device was successful in suppressing cavity tones by as much as 10 dB with mass injection levels of the order of only 0.12% of the main jet flow. Similar mass flow rates of oscillatory flow near the downstream end of the cavity floor had no effect on the resonant cavity tones. Additionally, steady upstream mass flow addition at the same levels as those for oscillatory mass addition (fluidic) affected cavity tones only marginally (1 dB). Our results provide not only an example of the effectiveness of fluidic excitation but offer grounds for believing that promising possibilities exist for its use in aeroacoustic control.

Motivation and Background

Flows over cavities occur in aircraft weapons bays, wheel wells, in-flight refueling ports, pressure vents in the space shuttle's cargo bay, and a host of other applications. Cavity flow resonance can cause numerous problems in all of the applications just mentioned. Although our long-term goal is to understand cavity flows well enough to devise effective suppression techniques, this Note describes an innovative method that uses fluidic devices to suppress cavity tones.

Fluidics is the technology of using fluid phenomena such as wall attachment and stream interaction to perform the functions of sensing, logic, and control. Consequently fluidic devices have no moving parts, for example, turbulence amplifiers, wall attachment devices, active- and passive-momentum interaction devices, and vortex devices.[1] In the 1970s fluid control techniques were applied to a jet nozzle by Viets,[2] who referred to his device as a flip-flop nozzle. Raman and coworkers first evaluated and applied such devices for jet mixing control.[3,4] Devices of the Viets[2] type were quite bulky, oscillated at very low frequencies (<500 Hz) and posed difficulties when they had to be integrated into a functioning practical device. In the present work we move the application of this device to a more refined level by using miniature fluidic devices with all feedback paths built into the body of the device. These fluidic devices were invented, designed, and fabricated at Bowles Fluidics Corp.[5,6]

Previous Work on Cavity Tones and Their Suppression

Next we recount some relevant work in cavity acoustics and its suppression that places the present technique in perspective. Cavity tones are generally atttibuted to embryonic disturbances in the shear layer that grow while convecting downstream and whose interaction with the downstream edge produces pressure emissions that propagate unstream to close a resonant loop. Models for resonant frequencies produced by flows over cavities were proposed by Rossiter.[7] Relevant to this study is a recent paper by Raman et al.,[8] which showed that jet-cavity interaction tone frequencies could be of two types: dependent on or independent of flow velocity. They proposed simple yet physically insightful correlations for these tones. They also used pressure-sensitive paint on the floor of a L/D (length/depth) $= 8$ cavity to show that the three classifications (open, transitional, and closed) proposed by Stallings and Wilcox[9] were very dependent on flow Mach number, but the classifications provided no guidance whatsoever for tone frequency and amplitude. The jet-cavity configuration chosen for the present work was the same as that used by Raman et al.[8] for their cavity tone studies. For the $L/D = 6$ cavity under consideration, the measured frequencies correlate with $fL/a_0 = (n+1)/4$ ($f =$ frequency, $L =$ cavity length, $a_0 =$ ambient speed of sound, $n = 1, 2, 3$, etc.).

Over the years a variety of cavity resonance suppression techniques has been tested. More recently the focus has shifted to active control of flows over cavities[10–14] because of the potential for these techniques to suppress resonance over a range of operating conditions and various cavity geometries. The present experiment that is distinctly different from those just mentioned provides a unique implementation of the pulsed blowing technique using miniature fluidic jets. Our specific objectives include 1) characterization of miniature fluidic oscillators, 2) assessment of their effectiveness for cavity tone suppression, and 3) evaluation of mass flow requirements for unsteady fluid mass addition.

Characterization of Miniature Fluidic Devices

Figure 1a shows a schematic of the miniature fluidic devices used in the present work. The general operational features of bistable fluidic devices have been known for many years and will not be described here in great detail. For our purposes it is sufficient to describe Fig. 1a by stating that the flow from the power nozzle attaches to one of the walls of the interaction region as a result of the Coanda effect. Backflow through the internal feedback passage can cause the jet to detach from one wall and attach to the opposite wall. The process then repeats itself, thus producing a self-sustaining oscillation. The devices were designed and fabricated at Bowles Fluidics Corp.

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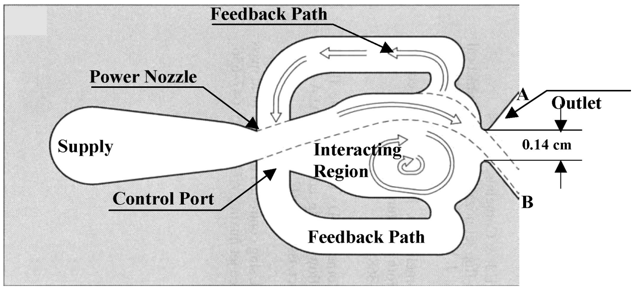

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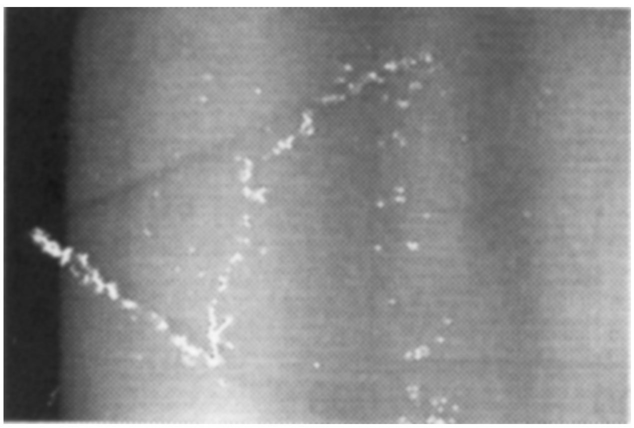
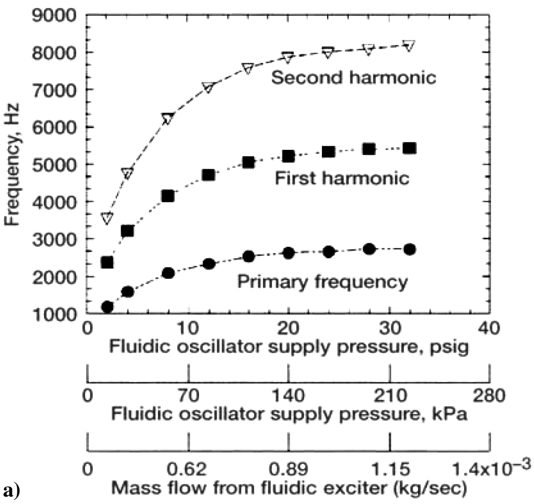


b)

Fig. 1 Schematic showing design and operation of miniature fluidic device: a) design detail based on Bray[5] and Stouffer[6] and b) flow visualization using water injection depicting square-wave behavior of oscillatory jet exiting the nozzle, where supply pressure = 4 psig.



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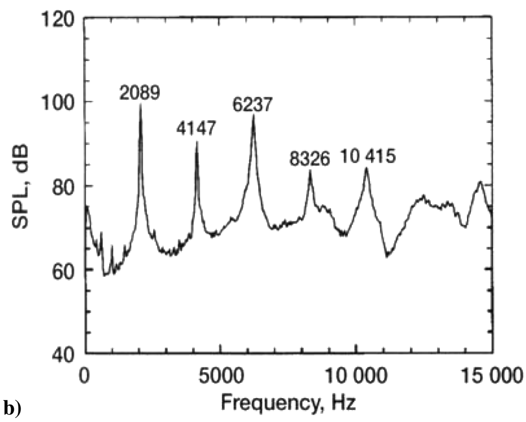

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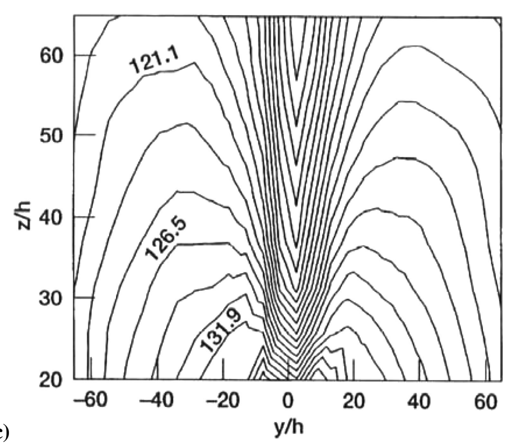

c)

Fig. 2 Fluidic actuator characteristics: a) frequency vs nozzle supply pressure/mass flow rate for the square-wave fluidic exciter; b) spectra measured using near-field microphone for the square-wave fluidic oscillator, where supply pressure = 4 psig, and c) sound pressure levels measured in the near field of the actuator.

The exit dimensions of the fluidic nozzles used in this study were 1.693×0.954 mm for the square-wave nozzle, 1.634×0.979 mm for the sawtooth wave nozzle, and 2.014×0.485 mm for the sine-wave nozzle. (The present results focus only on the square-wave nozzle.)

The flow characteristics of the fluidic nozzles were visualized using water injection and spark photography using a microsecond spark for a light source. Figure 1b shows the square-wave oscillatory patterns of water flow from such a nozzle operated at 4 psig. Water is used in these photographs for illustrative purposes only. For all other experiments reported in this Note, the working medium is air. Figure 2a shows the frequency (primary frequency and two harmonics) vs nozzle pressure for the miniature fluidic square-wave device (microphone located at $x/D = 0$, $y/D = 0$, $z/D = 6$). The nozzle that generated a square wave produced oscillations between a nozzle pressure of 0.4 and 40 psig in the frequency range from 592 to 2760 Hz. For bistable fluidic devices of fixed internal feedback path dimensions, the frequency increases with flow rate until saturation. The nature of the saturation is device dependent.[6,7] The mass flow was estimated using supply pressure and isentropic relations.

Figure 2b shows a spectrum measured using a near-field microphone at various nozzle pressure ratios. The microphone was located at $x/D = 1.4$, $y/D = -4$, and $z/D = 0.3$ relative to the fluidic nozzle's exit for the nozzle that produces the square waveform. Note that the microphone locations were different for the data in Figs. 2a and 2b. We recorded these spectra when the main jet flow was turned off, with only the fluidic device operating at 4 psig. A B&K 0.635-cm ($\frac{1}{4}$-in.) microphone was used for the measurements, with the exception of Fig. 2c for which a 0.3175-cm ($\frac{1}{8}$-in.) microphone was used, and all sound pressure levels (SPL) reported are relative to 20 μPa. A map of the near-field pressures is shown in Fig. 2c. The two lobes of SPL clearly indicate the bistable nature of the jet (i.e., the jet is at one extreme or the other and transitions vary rapidly between the two states). The main significance of this result is that a single miniature fluidic actuator cannot only add oscillatory mass but can distribute mass over a lateral extent.

Jet-Cavity Arrangement

Experiments were conducted in a supersonic jet facility at the NASA Glenn Research Center. An existing jet nozzle was modified by adding an adaptor to which we could attach rectangular cavities of various dimensions. The jet flow thus formed the flight stream over the cavity. The cavity dimensions were D (depth) = 1.27 cm and W (width) = 4.445 cm. We used a cavity with $L/D = 6$ for the present experiments. Figure 3 shows a sketch of the nozzle-cavity arrangement that includes the location of the fluidic devices (seen as rectangles in the sketch) at upstream and downstream ends of the cavity.

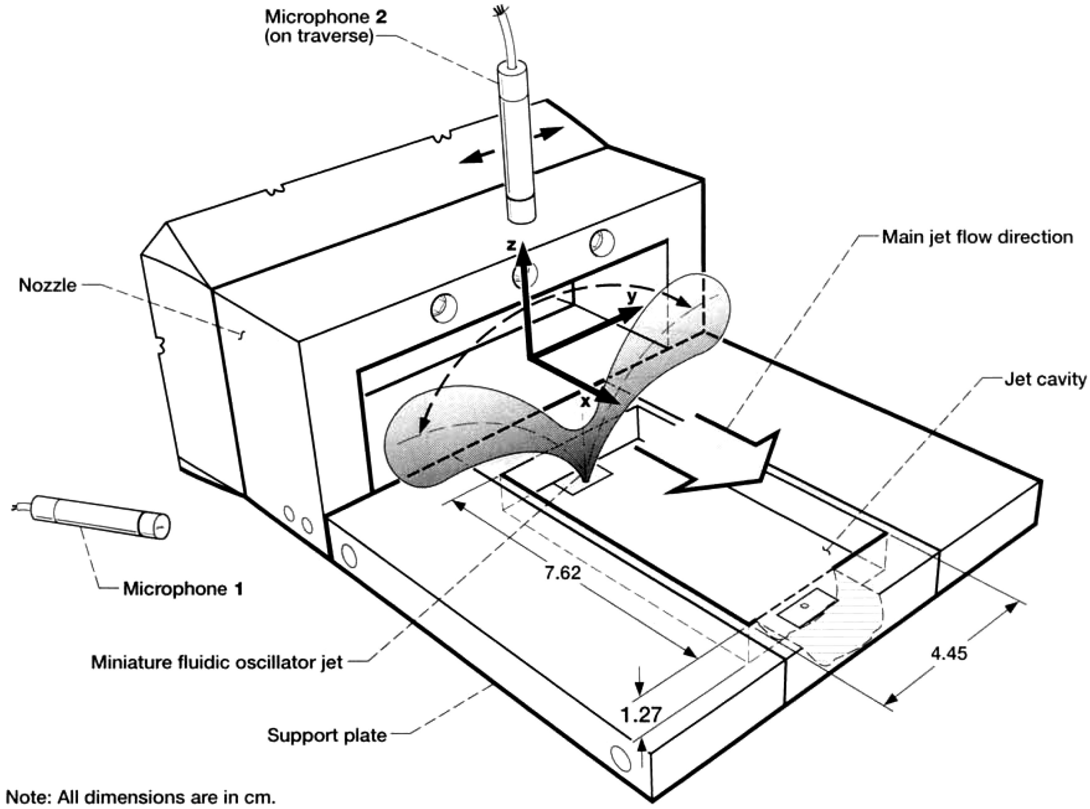

Fig. 3 Schematic showing jet-cavity configuration, microphones, and measurement planes.

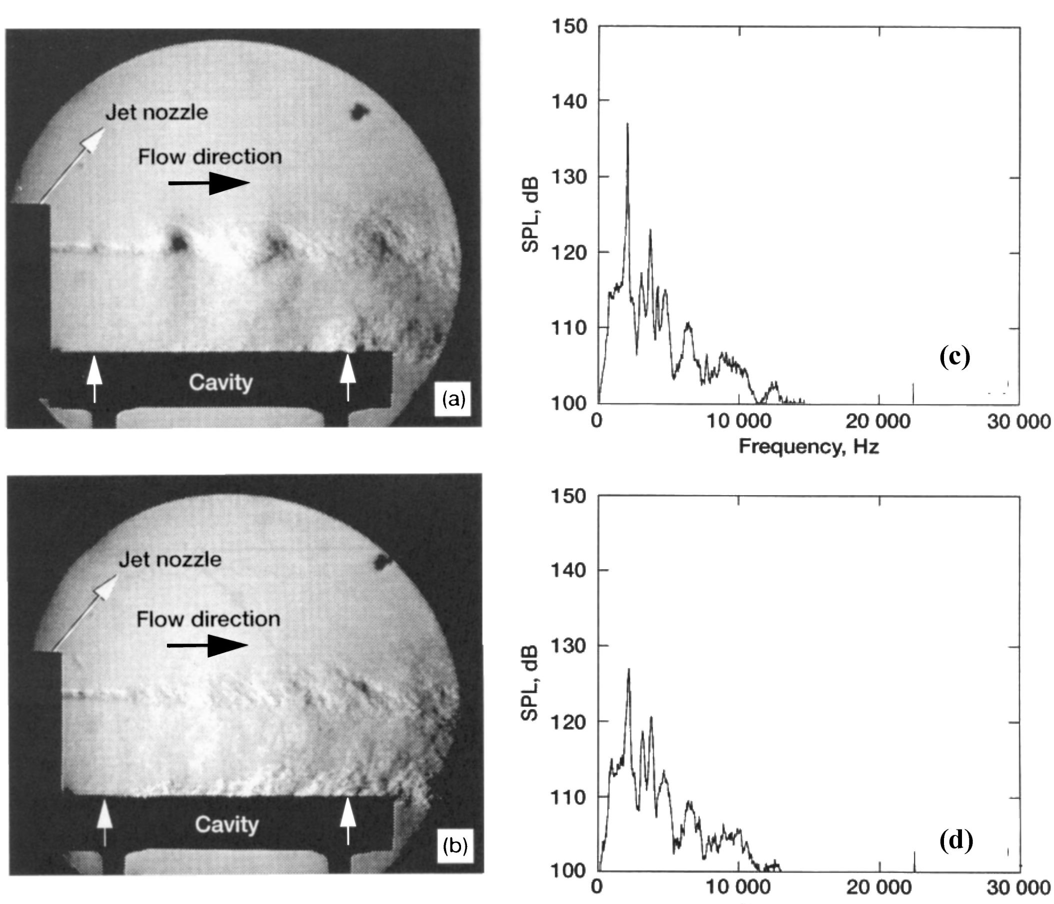

Fig. 4 Schlieren photograph and microphone spectra illustrating effect of square-wave fluidic excitation on jet-cavity interaction. Main jet flow is at $M = 0.485$: a) unperturbed; b) fluidic excitation, where supply pressure = 32 psig; c) spectra, unperturbed; and d) spectra (with fluidic excitation at 32 psig).

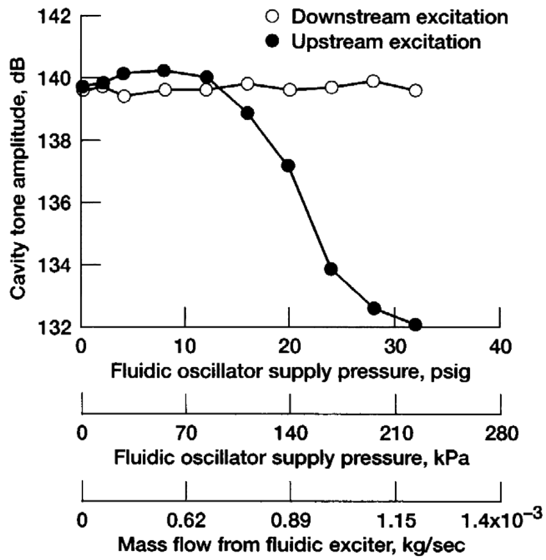

Fig. 5 Fluidic oscillator supply pressure and mass flow requirements for jet-cavity tone suppression. The main jet's flow is at $M = 0.69$.

Cavity Acoustics Suppression Using Fluidic Oscillators

Before we describe attempts to suppress resonant cavity tones, some comments on the types of tones present for the configuration under consideration are in order. The present set of experiments employed the same jet-cavity configuration used by Raman et al.[8] They showed that jet-cavity interaction tone frequencies could be of two types: dependent or independent of flow velocity. The former type correlates well with the Rossiter[7] equation, whereas the latter type was correlated by Raman et al.[8] using a reduced frequency parameter.

The schlieren photographs of Figs. 4a and 4b show the effectiveness of upstream fluidic excitation on cavity resonance at $M = 0.485$. We note that the outer shear layer lets us visualize vortical events (shear-layer instabilities) when the jet is excited by the jet-cavity interaction tone. When the cavity tone is suppressed, dominant vortices in the upper shear layer are no longer visible.

The qualitative observations from the schlieren photographs are confirmed by narrowband spectra (Figs. 4c and 4d) that indicate that the amplitude of the tone drops by 10 dB under upstream fluidic control. Figure 5 shows the effect of upstream and downstream fluidic excitation at various mass flow rates from the fluidic device. (Microphone location for Figs. 4 and 5 was $x/D = 0$, $y/D = 0$, and $z/D = 6$.) It is very clear that downstream fluidic excitation has no effect even at the highest mass flow rates. As seen from the schlieren images and as expected from shear-layer dynamics, flow disturbances grow and attain very high amplitudes closer to the downstream edge. Therefore, one would have to provide large amounts of energy to affect the process by forcing at the downstream edge. In contrast, at the upstream edge the coherent disturbances are embryonic and can be easily disturbed by low levels of appropriately tailored active control. Figure 5 also shows the mass flow requirements for fluidic excitation. Note that very low levels of fluid mass injected into the cavity (1.15×10^{-3} kg/s or approximately 0.12% of the main jet's flow) can suppress jet-cavity tones by as much as 10 dB. Although at first it might appear difficult to separate frequency and mass flow effect, it is helpful to recall from Fig. 2a that the frequency remains approximately constant beyond 15 psig. However, strong suppression commences only beyond 15 psig suggesting that mass addition does play a role. However the mass flow requirements can be minimized using oscillatory mass addition.

Conclusions

We described a novel approach to suppressing jet-cavity interaction tones using miniature fluidic devices. The fluidic devices studied had exit dimensions ranging from 0.5 to 1 mm, had no moving parts, and could provide oscillatory flow of prescribed waveforms at frequencies up to 3 KHz. Our test bed for this technique was the flow-induced resonance produced by a jet flowing over a cavity with an L/D (length/depth) radio of 6. When located at the upstream end of the cavity floor, these miniature fluidic devices suppressed cavity tones by as much as 10 dB with mass injection rates of the order on only 0.12% of the main jet flow. Our results showed that steady mass flow addition at the same levels as those for fluidic excitation affected cavity tones very marginally (1-dB reduction). Finally, our results suggest that fluidic excitation could be a potential candidate for use in flow and noise control applications.

References

[1]Morris, N. M., *An Introduction to Fluid Logic*, McGraw–Hill, London, 1973.

[2]Viets, H., "Flip-Flop Jet Nozzle," *AIAA Journal*, Vol. 13, No. 10, 1975, pp. 1375–1379.

[3]Raman, G., and Cornelius, D., "Multiple Fluidic Devices Provide Flow-Mixing Control," *NASA Tech Briefs*, Vol. 20, Oct. 1996, pp. 91, 92.

[4]Raman, G., "Using Controlled Unsteady Fluid Mass Addition to Enhance Jet Mixing," *AIAA Journal*, Vol. 35, No. 4, 1997, pp. 647–656.

[5]Bray, H. C., "Cold Weather Fluidic Fan Spray Devices and Method," U.S. Patent 4463904, 1984.

[6]Stouffer, R. D., "Liquid Oscillator Device," U.S. Patent 4508267, 1985.

[7]Rossiter, J. E., "The Effect of Cavities on the Buffeting of Aircraft," Royal Aircraft Establishment, TM 754, London, 1962.

[8]Raman, G., Envia, E., and Bencic, T. J., "Tone Noise and Nearfield Pressure Produced by Jet-Cavity Interaction," *AIAA Journal*, Vol. 40, No. 8, 2002, pp. 1503–1511.

[9]Stallings, R. I., Jr. and Wilcox, F. J., "Experimental Cavity Pressure Distributions at Supersonic Speeds," NASA TP-2683, 1987.

[10]Cattafesta, L. N., III, Garg, S., Choudhari, M., and Li, F., "Active Control of Flow Induced Cavity Resonance," AIAA Paper 97-1804, 1997.

[11]Shaw, L., and McGrath, S., "Weapons Bay Acoustics: Passive or Active Control," AIAA Paper 96-1617, 1996.

[12]Ziada, S., "Feedback Control of Globally Unstable Flows: Impinging Flows," *Journal of Fluids and Structures*, Vol. 9, No. 8, 1995, pp. 907–923.

[13]Ziada, S., "Interaction of a Jet-Slot Oscillator with a Deep Cavity Resonator and Its Control," *Journal of Fluids and Structures*, Vol. 15, No. 6, 2001, pp. 831–843.

[14]Ziada, S., Ng, H., and Blake, C., "Flow-Excited Resonance of a Confined Shallow Cavity in Low Mach Number Flow and Its Control," *Journal of Fluids and Structures*, Vol. 18, No. 1, 2003, pp. 79–92.

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