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Cavity Resonance Suppression Using Miniature Fluidic Oscillators

Ganesh Raman
Dynacs Engineering, Co., Inc., Brook Park, Ohio

Surya Raghu
Bowles Fluidics Corporation, Columbia, Maryland

Timothy J. Bencic
Glenn Research Center, Cleveland, Ohio

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Ganesh Raman[1]
Dynacs Engineering Co., Inc.
Propulsion Analysis Section
NASA Glenn Research Center Group
2001 Aerospace Parkway
Brook Park, Ohio 44142

Surya Raghu[2]
Bowles Fluidics Corporation
6625 Dobbin Road
Columbia, Maryland 21042

Timothy J. Bencic[3]
NASA Glenn Research Center
21000 Brook Park Road
Cleveland, Ohio 44135

Abstract

We present a novel approach to suppressing jet-cavity interaction tones using miniature fluidic devices. We first characterize miniature fluidic oscillators and then assess their effectiveness for cavity tone suppression. Further, we evaluate mass flow requirements for effective unsteady fluid mass addition. The fluidic devices used had no moving parts and could provide oscillatory flow of prescribed waveforms (sine, square, and saw-toothed) at frequencies up to 3 KHz. Our testbed 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 an (length/depth) ratio of 6. In addition to schlieren photography and acoustic measurements we used photoluminescent Pressure Sensitive Paint (PSP) to map pressures on the cavity's floor for the unperturbed and fluidically excited cases. 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 rates 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 fluidic excitation affected cavity tones only marginally (1dB reduction). Furthermore, acoustic excitation at the same frequency as that produced by the fluidic device or its harmonic at comparable amplitudes did not affect the cavity resonance. Our results provide not only an example of the effectiveness of fluidic excitation but offer grounds for believing that vast possibilities exist for its use in aeroacoustic control.

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[1]Senior Research Engineer, Associate Fellow AIAA.
[2]Principal Research Scientist, Senior Member AIAA.
[3]Electronics Engineer.

1. Introduction

1.1. Motivation

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 above mentioned applications. While our long term goal is to understand cavity flows well enough to devise effective suppression techniques, this paper describes an innovative method that uses fluidic devices to suppress cavity tones.

1.2. Background

1.2.1 Previous Work on Fluidic Devices

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 (see Morris (1973)). In the 1970s fluid control techniques were applied to a jet nozzle by Viets (1975) who referred to his device as the flip-flop nozzle. Experiments at NASA Glenn extended the operation of flip-flop nozzles to supersonic speeds (Raman et al. (1993)). Raman et al. (1994) first evaluated the potential for their use as excitation devices and then applied such devices for jet mixing control (Raman & Cornelius (1995, 1996), Raman (1997)). Devices of the Viets type were quite bulky, oscillated at frequencies less than 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 technique 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 Corporation (Bray (1984), Stouffer (1985)). The characteristics of such devices and examples of their use appear in Raghu & Raman (1999) and Raghu et al. (1997). In the present work we use these devices to suppress flow-induced cavity tones.

1.2.2 Previous Work on Cavity Tones and Their Suppression

Below we recount some relevant work in cavity acoustics and its suppression that places the present technique in perspective. Cavity tones are generally attributed to embryonic disturbances in the shear layer that grow while convecting downstream and whose interaction with the downstream edge produces pressure emissions that propagate upstream to close a resonant loop. Models for resonant frequencies produced by flows over cavities were proposed by Rossiter (1962, 1966). The interested reader is referred to the book by Lucas et al. (1997) for a summary of the extensive literature on cavity flows.

Relevant to this study is a recent paper by Raman et al. (1999) which showed that jet-cavity interaction tone frequencies could be of two types: dependent on or independent of flow velocity. They proposed simple, yet and physically insightful correlations for these tones. They also used PSP on the floor of a L/D (length/depth) = 8 cavity to show that the three classifications (open, transitional, or closed) proposed by Stallings & Wilcox (1987) were very dependent on flow Mach number but the classifications provided no guidance whatsoever for tone frequency or amplitude. The jet-cavity configuration chosen for the present work was the same as that used by Raman et al. (1999) for their cavity tone studies.

Over the years a variety of cavity resonance suppression techniques have been tested. Heller & Bliss (1975) suggested using a slanted trailing edge and introducing vorticity into the shear layer to eliminate cavity resonance. Smith et al. (1992) used multi-steps and pins extending into the supersonic approach flow to attenuate cavity tones. More recently the focus has shifted to active control of flows over cavities (Cattafesta et al. (1997), Shaw & McGrath (1996)) because of the potential for these techniques to suppress resonance over a range of operating conditions and various cavity geometries. McGrath & Shaw (1996) attempted active control using a low-frequency leading-edge oscillator and a high-frequency tone generator to suppress cavity resonance. Shaw (1998) also discusses using pulsed jets to eliminate cavity tones. Recent papers have provided insightful details of cavity resonance suppression mechanisms.

Lamp & Chokani (1999) compared the effects of steady and oscillatory blowing and illustrated the advantage of pulsed excitation. Fabris & Williams (1999) evaluated the response of cavity and shear layer response to unsteady bleed forcing. The present experiment that is distinctly different from those mentioned above provides a unique implementation of the pulsed blowing technique using miniature fluidic jets.

1.3. Objectives

Listed below are our specific objectives:

(I) To characterize miniature fluidic oscillators.
(II) To assess their effectiveness for cavity tone suppression.
(III) To evaluate mass flow requirements for unsteady fluid mass addition.
(IV) To segregate the various effects present when fluidic excitation is used.

1.4. Organization of Paper

In Section 2, we characterize the miniature fluidic devices used in the present work. In section 3 we describe the jet-cavity arrangement, experimental apparatus, and measurement techniques. Section 4 discusses results of fluidic excitation technique. In section 4.1 we briefly revisit jet-cavity interaction tones. Section 4.2 discusses fluidic excitation results, 4.3 attempts to segregate the various effects, and 4.4 presents PSP results.

2. Characterization of Miniature Fluidic Devices

Figure 1 shows a schematic of the miniature fluidic devices used in the present work. The general operational features of bi-stable 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 figure 1 by stating that the flow from the power nozzle attaches to one of the walls of the interaction region due to 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 Corporation (see Raghu & Raman (1999) and US Patents 4463904, 4645126, and 4508267). The exit dimensions of the fluidic nozzles used in this study were 1.693 mm by 0.954 mm for the square-wave nozzle, 1.634 by 0.979 mm for the saw-tooth wave nozzle, and 2.014 by 0.485 mm for the sine wave nozzle. The flow characteristics of the fluidic nozzles were visualized using spark photography. Figure 2 shows the oscillatory patterns of water flow from such nozzles. Water is used in these photographs for illustrative purposes only. For all other experiments reported in this paper the working medium is air. We will distinguish the nozzles based on the waveform shape they produce. The waveforms are sinusoidal, saw-tooth, and square. For a more detailed study we chose the square-wave device. Figure 3 shows the frequency (primary frequency and two harmonics) versus nozzle pressure for the miniature fluidic square-wave device. The nozzle that generated a square-wave produced oscillations between a nozzle pressure of 0.4 and 40 psig (the corresponding frequencies were 592 and 2760 Hz.).

Figure 4 shows spectra measured at various nozzle pressure ratios. The microphone was located at $x/D = 1.4$, $y/D = -4$, $z/D = -0.3$ relative to the fluidic nozzle's exit for the nozzle that produces the square waveform. We recorded these spectra when the main jet flow was turned off, with only the fluidic device operating.

3. 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 5 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.

3.1. Measurement Techniques

A spark schlieren system was used for flow visualization. The system included a Palflash light source, a microscope objective, two spherical mirrors (15.24 cm dia., 91.44 cm focal length), and a vertical knife-edge. The light source consisted of an electric arc in an inert atmosphere of argon gas that could produce a 1-microsecond pulse of high intensity light (4 Joules). Photographs were taken by allowing light from the knife-edge to fall directly on Polaroid film.

The acoustic measurements were made using 0.635 cm (1/4 inch) dia. B & K microphones. The microphones were calibrated using a B & K pistonphone calibrator, with corrections for day-to-day changes in atmospheric pressure. The sound pressure levels reported in this paper are in dB (relative to 20 μPa).

3.2 Photoluminescent Pressure Sensitive Paint

Pressure sensitive paint (PSP) was used to map the steady pressures within the cavity for various operating conditions. The principle of operation for these paints is well documented in the literature (Kavandi et al. (1990), McLachlan et al. (1992), Morris & Donovan (1994)) and will only be mentioned briefly here. Certain chemical compounds when illuminated by light in a specific band of wavelengths exhibit luminescence. The luminescent light intensity is inversely proportional to the partial pressure of oxygen. The PSP used in our research was obtained from McDonnell Douglas Aerospace/Boeing (MDA PF2B). We primed the cavity with a glossy white base coat (MDA WAL-2) before applying the PSP. The NASA Glenn PSP system was described by Bencic (1995). Figure 6 depicts the imaging setup used in the current set of experiments. Two filtered, 75-Watt halogen tungsten lamps with integral reflectors placed in an air-cooled housing excited the paint molecules. The light wavelength required for excitation (430 to 470 nm bandwidths) was obtained by selective band-pass filtering of the illumination lamps. Interference filters passed light in the excitation band and reflected unwanted light outside this band. The low-power light sources rendered the photolytic decomposition of PSP insignificant. The camera was a cooled scientific grade imager capable of 14-bit resolution or approximately 16,000 intensity graduations. It had a spatial resolution of 512 x 512 pixels. The camera was optically filtered to allow only the luminescent light to be incident on the imager (detection band pass was from 530 to 650 nm). The acquired images were processed using an intensity-based data reduction technique. This technique requires the two images─a "wind off" (I_{ref}) reference image, and a "wind on" (I_{data}) data image─to determine the magnitude of the pressure measurements. By taking the ratio of I_{ref} and I_{data}, we corrected nonuniformities in paint application and lighting. An *a priori* or batch PSP calibration that depended on the composition of the paint was applied to the ratio image, and an *in-situ* calibration using data from static pressure taps on the cavity floor corrected the initial calibration.

4. Jet-Cavity Tones and Their Suppression

4.1 Jet-Cavity Tones

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. (1999). 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 (1962) equation, whereas the latter type was correlated by Raman et al. (1999) using a reduced frequency parameter ($fL/a_o = n/4$ (n = 1, 2,3)). Figure 7 shows the cavity tones present for the L/D = 6 cavity used in the present work. Between M = 0.4 and 0.65, the frequencies are predicted by the Rossiter (1962) equation. At higher Mach numbers, the reduced frequency correlation models data very well. Later sections will show that fluidic excitation can suppress both types of cavity tones.

4.2. Fluidic Excitation of Jet-Cavity Flow

Figure 8 shows schlieren photographs that illustrate the operation of fluidic devices in the cavity (both upstream and downstream) with the main jet flow off and at low main-jet flow rates. Flow from the square-wave fluidic oscillator was made visible using helium at 32 psig. The schlieren photographs of figure 9 (a,b,c) show the effectiveness of upstream and downstream 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. From figure 9 it can be seen that organized vortices in the upper shear layer (figure 9(a)) are no longer visible when upstream fluidic excitation is used (figure 9(b)). However, they persist when the fluidic device is located downstream (figure 9(c)). Figure 10 shows data similar to that of figure 9 but at a higher Mach number of 0.69.

The qualitative observations from the schlieren photographs are confirmed by narrowband spectra (figures 11(a-e)) that indicate the amplitude of the tone drops by 10 dB under upstream fluidic control. In contrast, downstream fluidic control has no effect. Figure 12 shows the effect of upstream and downstream fluidic excitation at various mass flow rates from the fluidic device. Once again it is very clear that downstream fluidic excitation has no effect even at the highest mass flow rates. As seen from the schlieren images (figures 9(a) and 10(a)) 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 12 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/sec or approximately 0.12% of the main jet's flow) can suppress jet-cavity tones by as much as 10 dB. Figure 13 shows the effectiveness of upstream fluidic excitation in suppressing cavity tones at various Mach numbers. Figure 13(a) shows that this technique is effective over the range of M from 0.4 to 0.7 and can suppress the two types of cavity tones shown in figure 7. Several observations can be made from figure 13(b). First, at all Mach numbers a certain “threshold” nozzle pressure (or mass flow) of the fluidic nozzle has to be exceeded before any suppression occurs. Second, this threshold nozzle pressure increases systematically with the flight Mach number. Finally, beyond a certain rate of mass injection no further suppression is obtained.

4.3 Comparison with Steady Mass Injection and Acoustic Excitation

Since the fluidic exciters used in the present work produced audible tones (see figure 4) that acoustically excited the cavity and also provided periodic fluid mass addition at the two spanwise extremes of the cavity, we attempted to study the relative dominance of these two effects using two separate experiments. In the first experiment steady fluid mass addition was accomplished at the two spanwise extremes of the cavity such that the total mass flow from the other two ports was equal to that from the fluidic exciter. Figure 14 shows that a steady mass addition of 1.2×10^{-3} kg/sec only marginally suppresses the cavity tone (1 dB). Recall that the same mass if fluidically oscillated can suppress cavity tones by as much as 10 dB.

In a second experiment an acoustic driver located upstream (within the plenum) provided excitation at the same frequency and comparable amplitudes as the fluidic exciters (see schematic in figure 15). The spectra shown in figure 15 were measured using microphone 2 located at x = 0, y = 0, z/D = 6 (see figure 5). Figures 15(a,b) show the spectra of the acoustic excitation signals at frequencies of 2752 and 5500 Hz (corresponding to the fundamental and harmonic frequencies of the fluidic oscillator). Results for the cavity tone under various conditions (unsuppressed, excited acoustically at the fundamental frequency, and excited acoustically at the harmonic) are shown in figures 15(c-e). It is clear that acoustic excitation had no effect on the cavity tones. Results from this section suggest that it is not the amount of mass injected or the amplitude and frequency of the tone produced by the fluidic exciter that suppresses the cavity resonance but the periodic sweeping motion of the fluid in the "y" direction that destroys the spanwise coherence leading to tone suppression.

4.4 Pressure Distributions on the Cavity Floor

PSP measurements were made for cases with and without fluidic excitation. The bottom of the cavity was coated with photoluminescent pressure sensitive paint. The PSP results indicate the steady pressures within the cavity expressed as a pressure coefficient ($C_p = (p-p_a)/p_a$) with and without fluidic excitation. Time-averaged pressure maps on the floor of the cavity are shown in figures 16, 17 for M = 0.485, 0.56. Three cases are presented in these figures: (a) no suppression, (b) upstream square-wave fluidic excitation, and (c) downstream square-wave fluidic excitation. The axial pressure distribution along the y/D = 0 line of the cavity for the two Mach numbers is given in figure 18. From the PSP results the following inferences can be made. Fluidic excitation at the upstream end of the cavity significantly alters the pressure distribution on the floor of the cavity, whereas downstream excitation has very little effect. If one refers to the Stallings and Wilcox (1987) classification of cavity flows, then our unsuppressed cavity is of the open type and fluidic excitation causes cavity pressures to resemble those of the transitional type (see figures 18(a,b)).

Concluding Remarks

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 testbed for this technique was the flow-induced resonance produced by a jet flowing over a cavity with an L/D (length/depth) ratio 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 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.

Since the fluidic oscillator produced unsteady mass flow addition accompanied by an audible acoustic tone, we performed additional experiments to segregate the various effects. Our results showed that steady mass flow addition at the same levels as those for fluidic excitation affected cavity tones very marginally (1dB reduction). Additionally, acoustic excitation at the same frequency as that produced by the fluidic device and at comparable amplitudes had no effect on the cavity resonance. Finally, our results suggest that fluidic excitation could be a potential candidate for use in flow and noise control applications.

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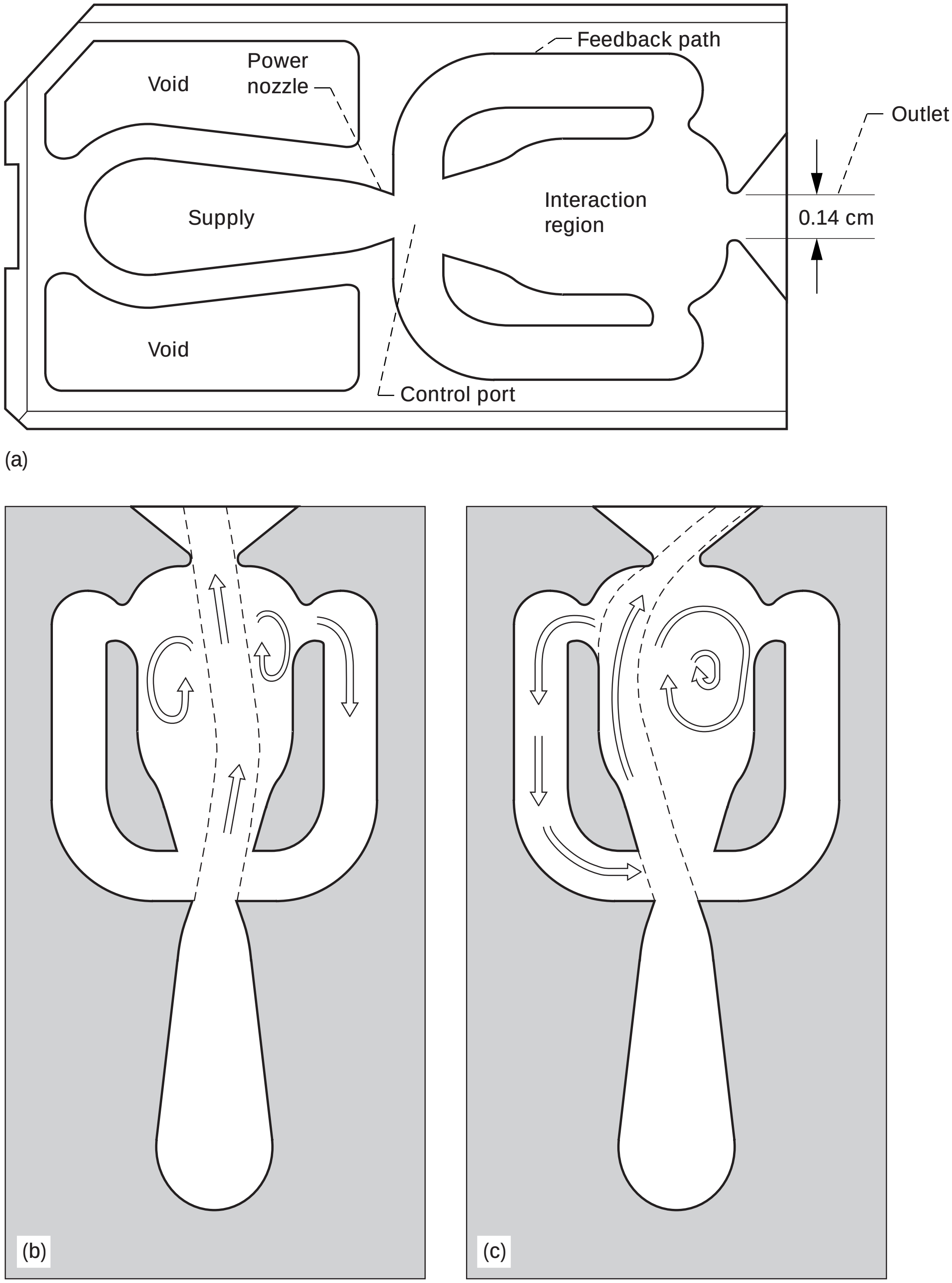


Figure 1.—Schematic showing design and operation of miniature fluidic devices: (a) Design details (based on Bray (1984) and Stouffer (1985)) and (b, c) Internal flow during the two phases of oscillation (Courtesy of Bowles Fluidics Corporation, U.S. patents 4463904, 4645126, 4508267 and others pending).

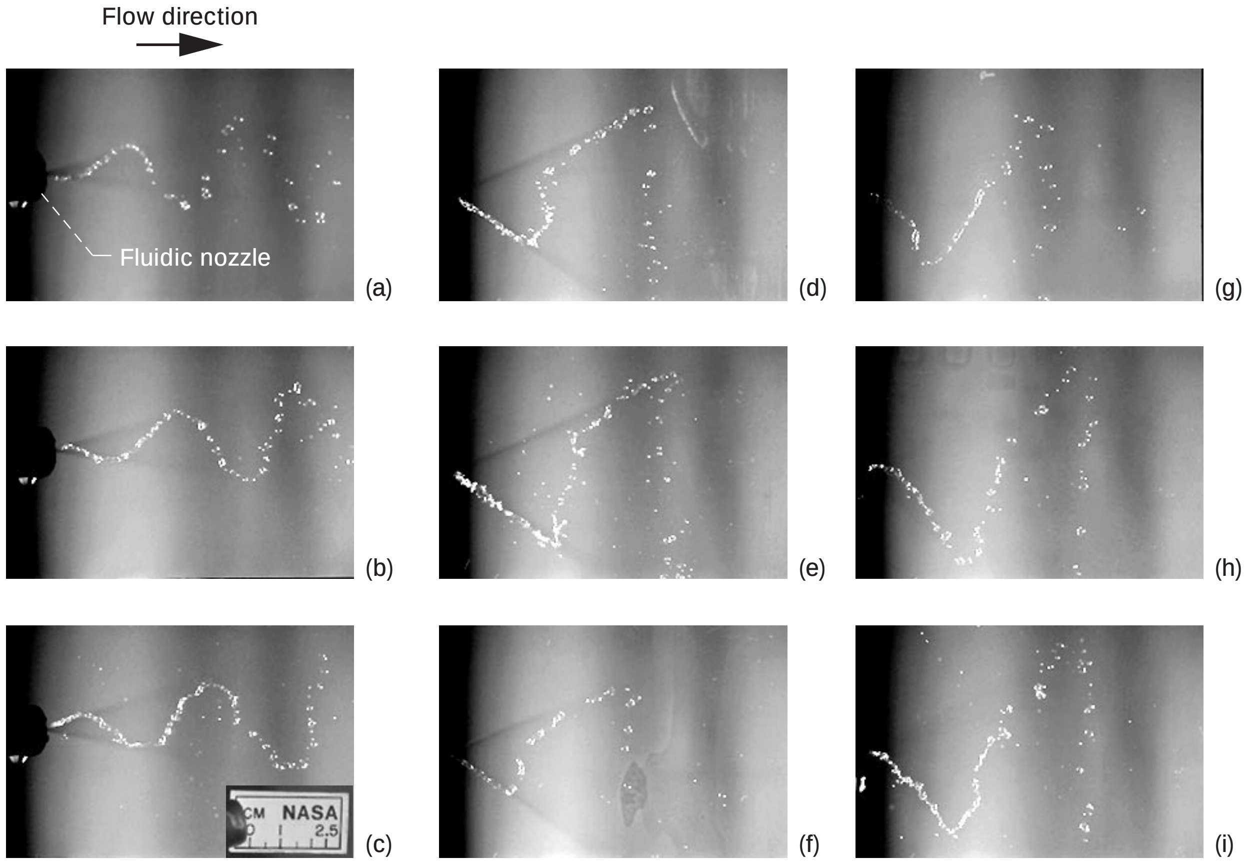


Figure 2.—Excitation signals of various waveforms produced by miniature fluidic devices. Waveform visualized for illustrative purposes using water flow and a microsecond light pulse: (a-c) Sinusoidal wave. (d-f) Square wave. (g-i) Saw-toothed wave. Nozzle pressure (a, d, g) 2 psig, (b, e, h) 4 psig, and (c, f, i) 6 psig.

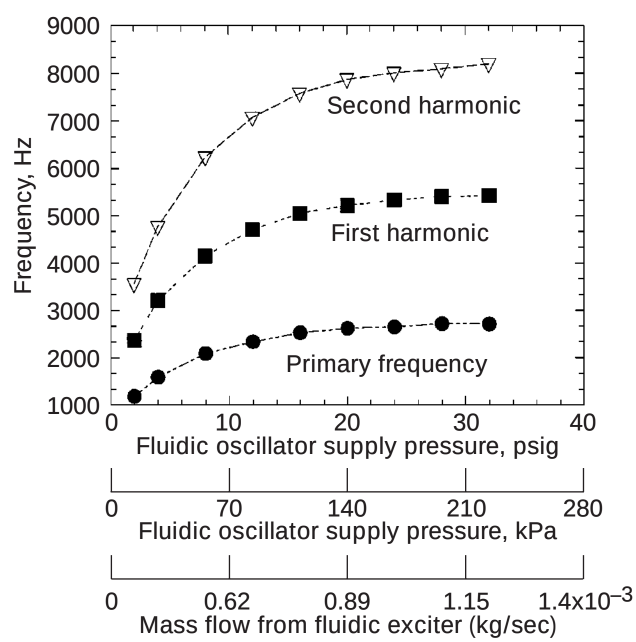


Figure 3.—Frequency versus nozzle supply pressure/ mass flow rate for the square-wave fluidic exciter.

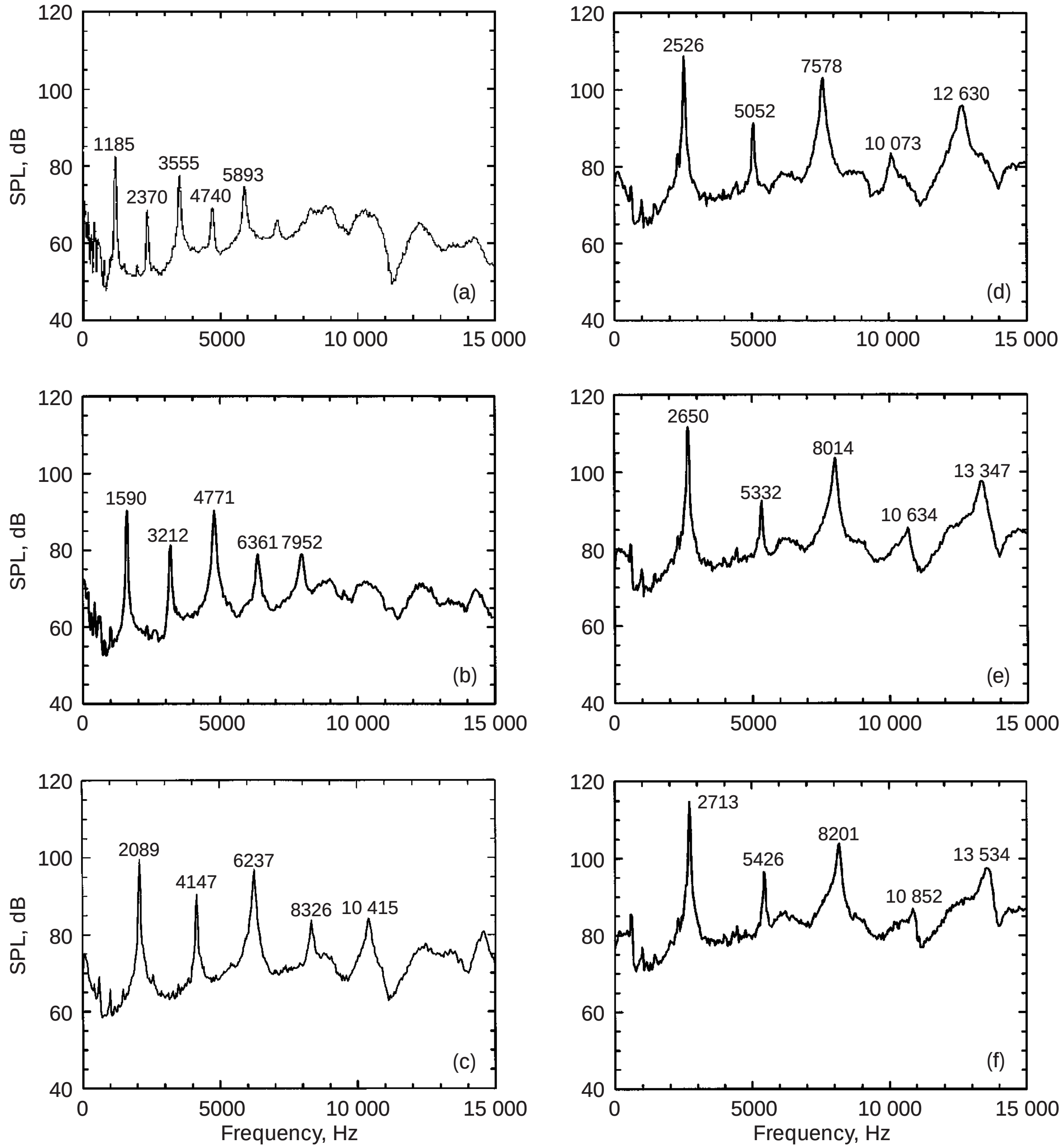


Figure 4.—Spectra measured using a near-field microphone for the square-wave fluidic oscillator. Nozzle pressure in psig: (a) 2, (b) 4, (c) 8, (d) 16, (e) 24, and (f) 32. Microphone located at x/D = 1.4, y/D = –4, z/D = –0.6 (origin for the coordinate system is the exit of the jet-cavity nozzle).

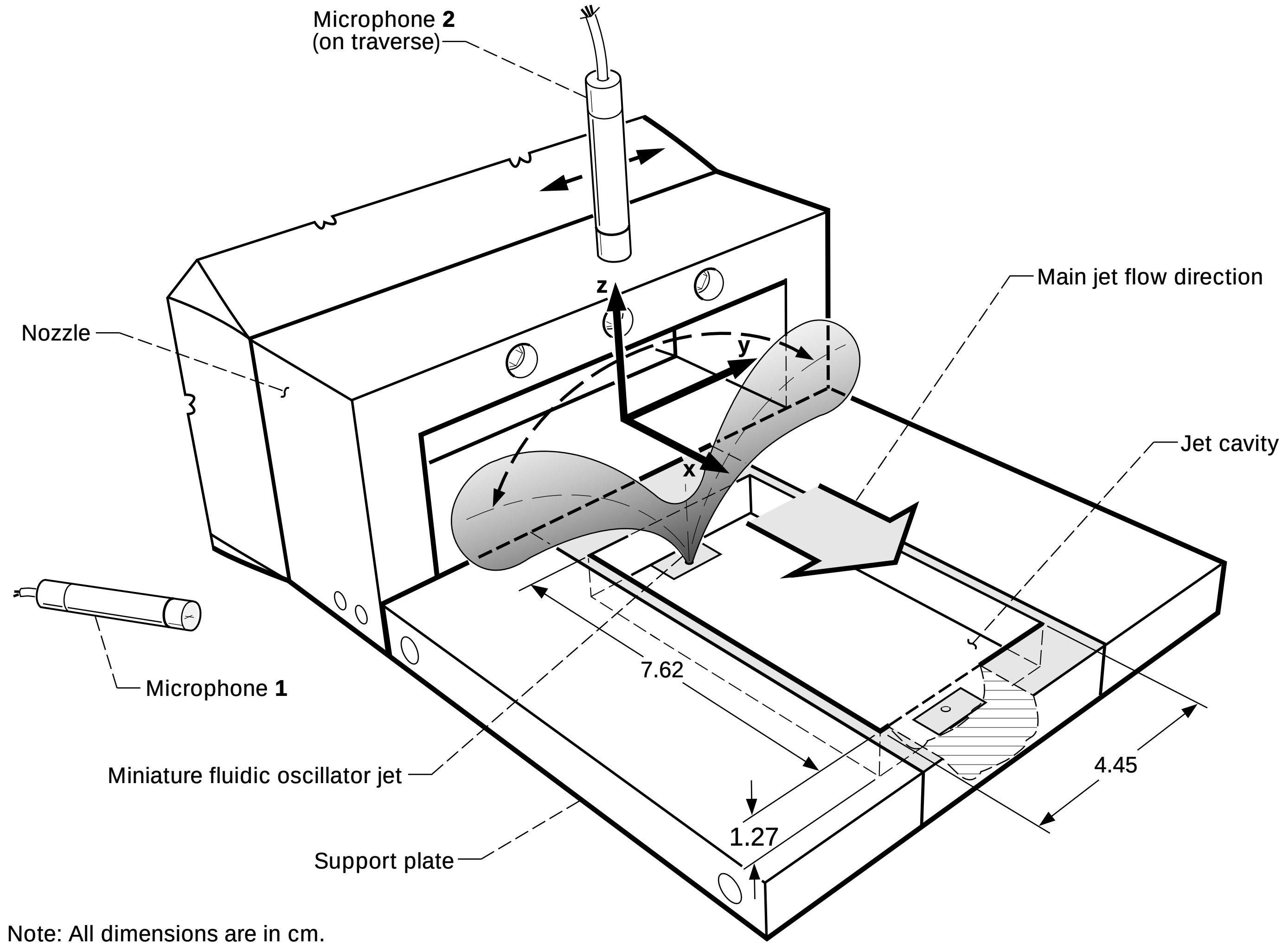


Figure 5.—Schematic showing jet-cavity configuration, microphones, and measurement planes.

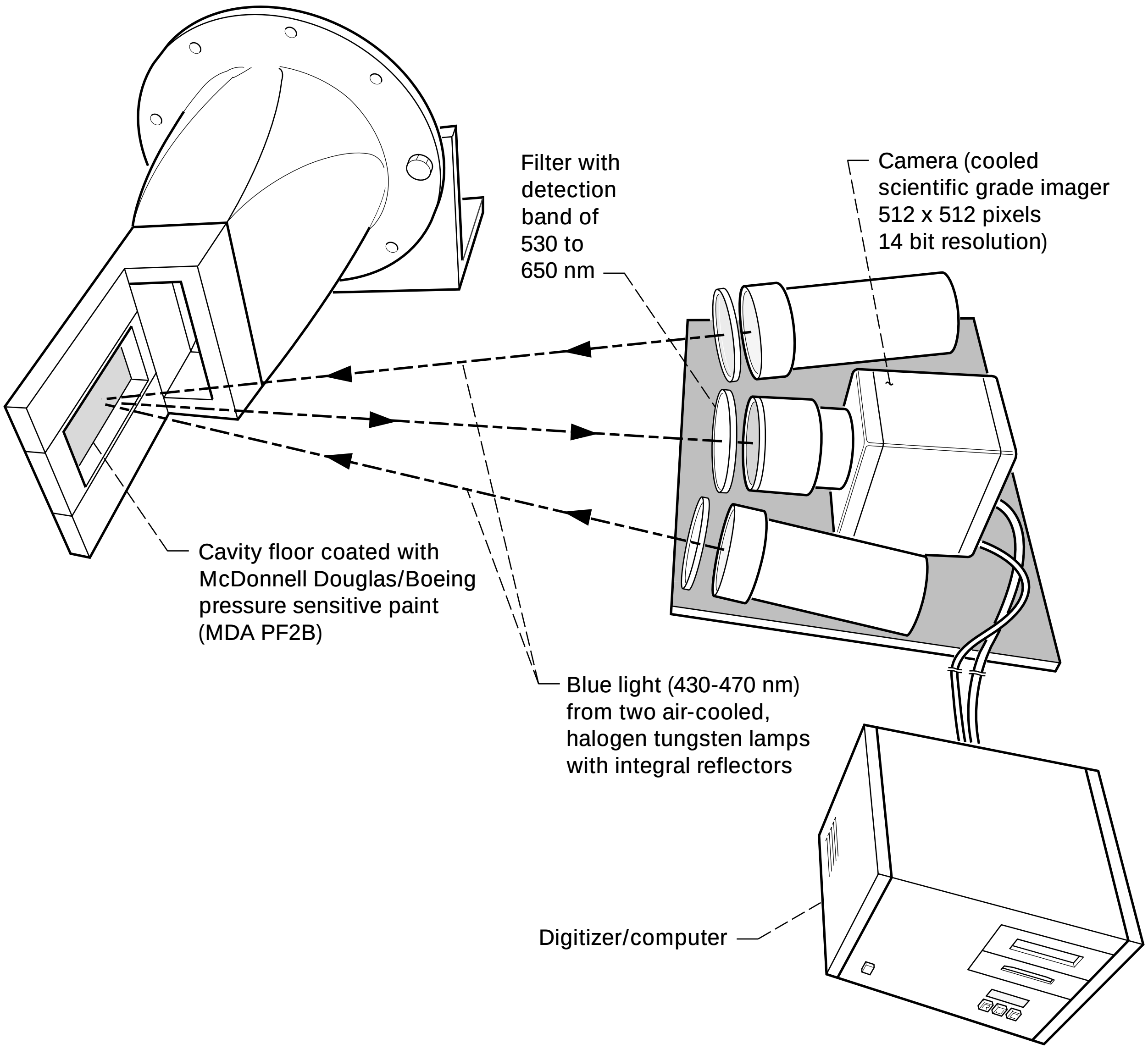


Figure 6.—Schematic showing jet-cavity configuration and photoluminescent pressure sensitive paint apparatus.

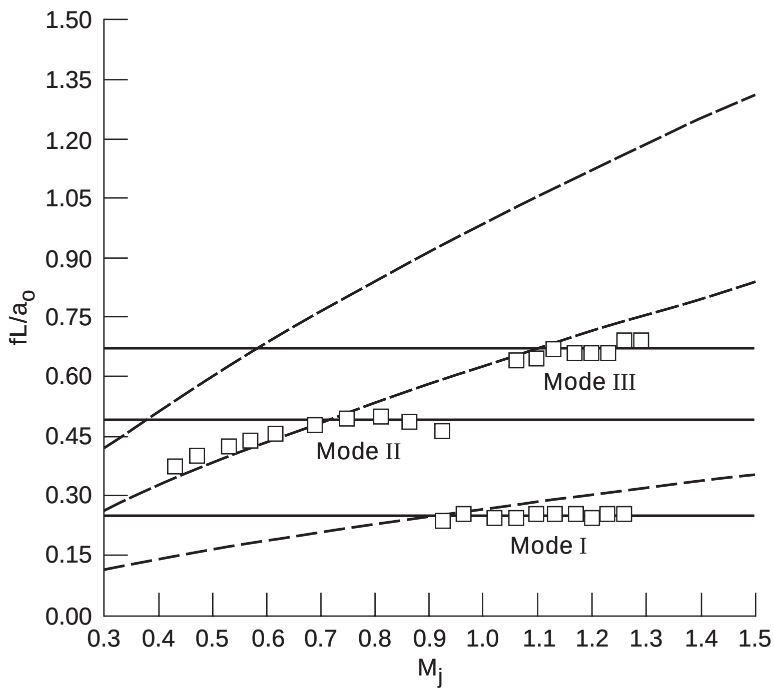


Figure 7.—Tones produced by jet-cavity interaction at various Mach numbers. Dashed lines represent Rossiter's (1962) prediction, and solid lines represent a correlation provided by Raman et al. (1999).

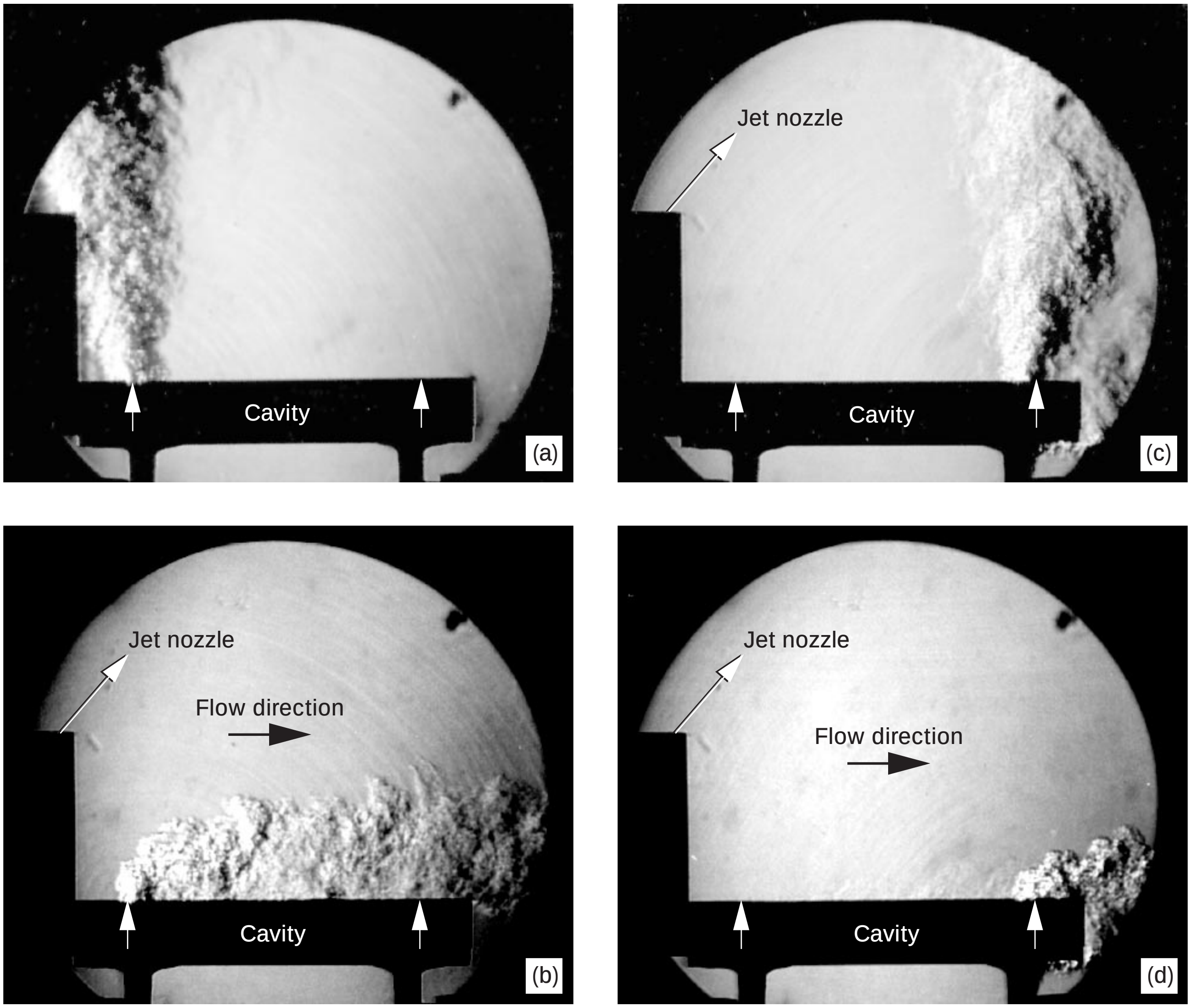
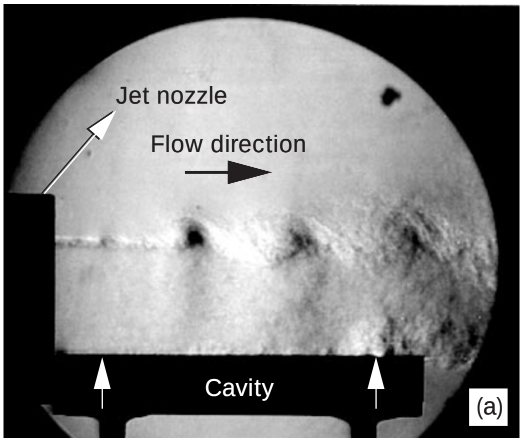
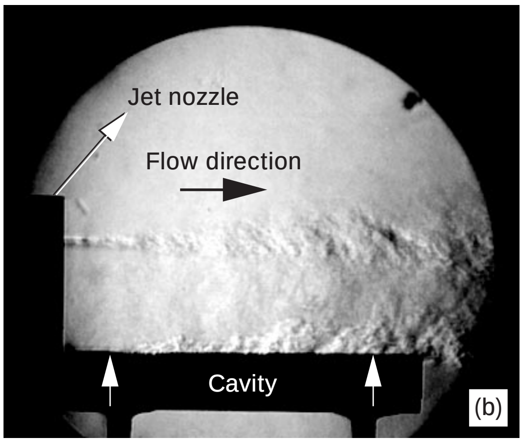


Figure 8.—Schlieren photographs that illustrate operation of fluidic devices in the cavity. (a) Upstream excitation with main jet flow off, (b) Upstream excitation with main jet flow at M = 0.2, (c) Downstream excitation with main jet flow off, and (d) Downstream excitation with main jet flow at M = 0.2. Note that the flow from the square-wave oscillator (Nozzle pressure = 32 psig) is made visible by the use of helium and that the plane of oscillation of the fluidic jet is perpendicular to the plane of the page. White arrows mark upstream and downstream edges of cavity.





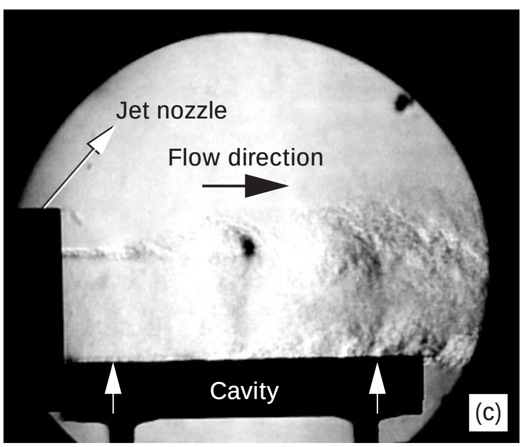
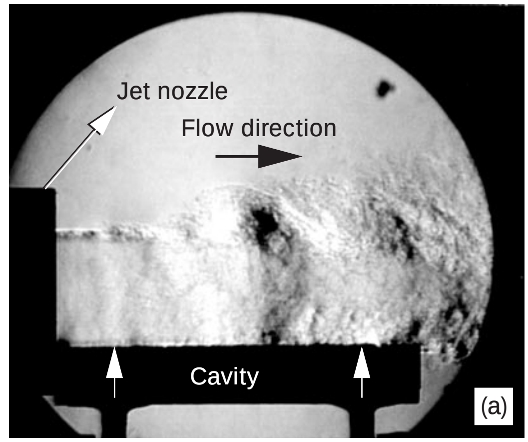


Figure 9.—Schlieren photographs illustrating effect of square-wave fluidic excitation on jet-cavity interaction. Main jet flow is at M = 0.485: (a) Unperturbed, (b) Upstream excitation, and (c) Downstream excitation. For (b,c) the fluidic nozzle pressure is 32 psig. Flow from fluidic nozzle is made visible by the addition of helium. White arrows mark upstream and downstream edges of cavity.



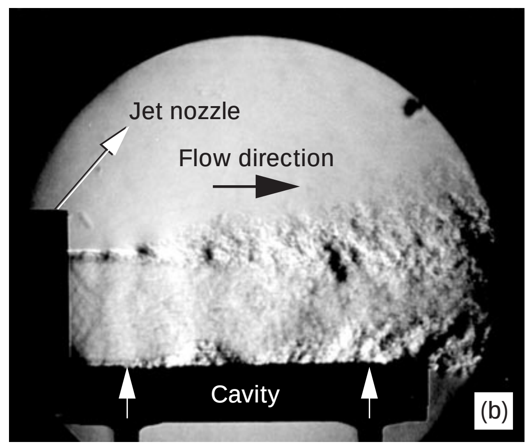


Figure 10.—Schlieren photographs illustrating effect of square-wave fluidic excitation on jet-cavity interaction. Main jet flow is at M = 0.69: (a) Unperturbed, and (b) Upstream excitation, fluidic nozzle pressure = 32 psig. Flow from fluidic nozzle is made visible by the addition of helium. White arrows mark upstream and downstream edges of cavity.

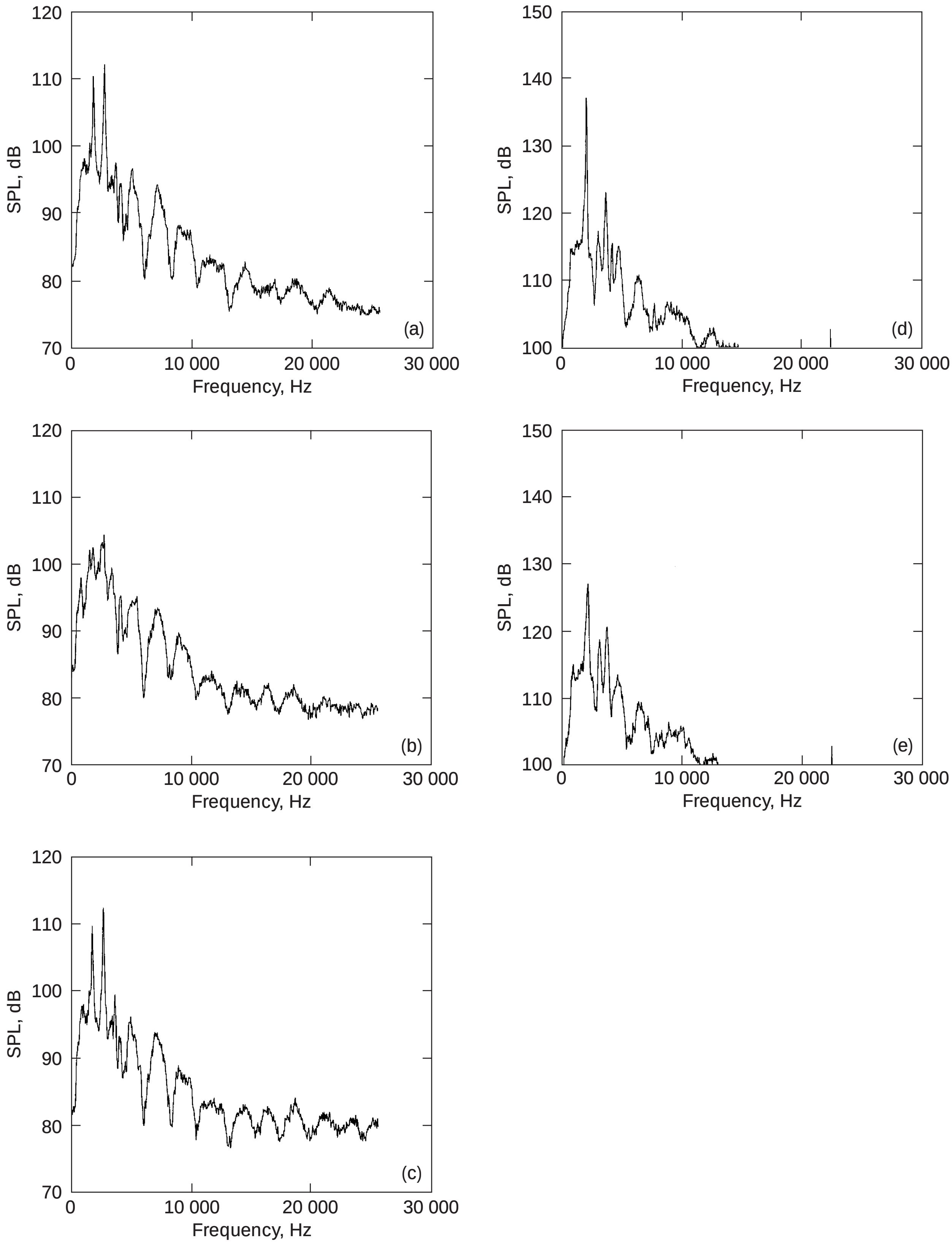


Figure 11.—Microphone spectra corresponding to the schlieren images of Figures 10 and 11: (a-c) M = 0.485 and (d, e) M = 0.69. (a) Unperturbed, (b) Upstream excitation, (c) Downstream excitation, (d) Unperturbed, and (e) Upstream excitation. For the excited cases the fluidic nozzle's pressure was 32 psig.

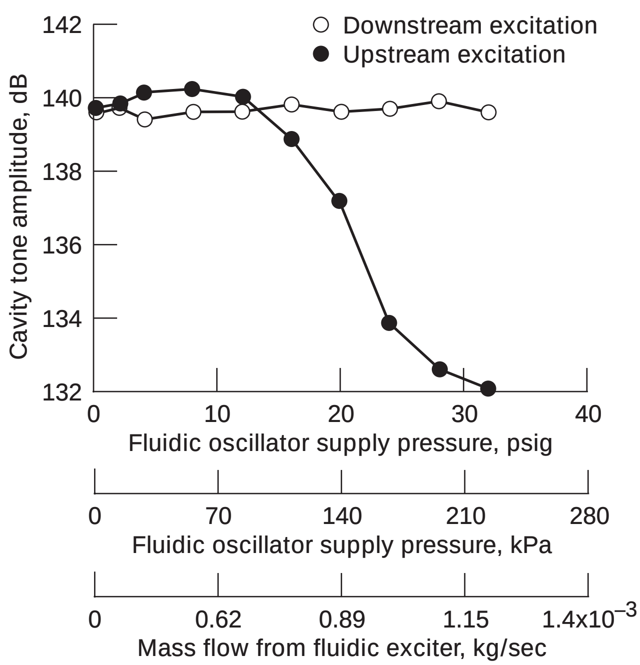


Figure 12.—Fluidic oscillator supply pressure and mass flow requirements for jet-cavity tone suppression. Main jet M = 0.69.

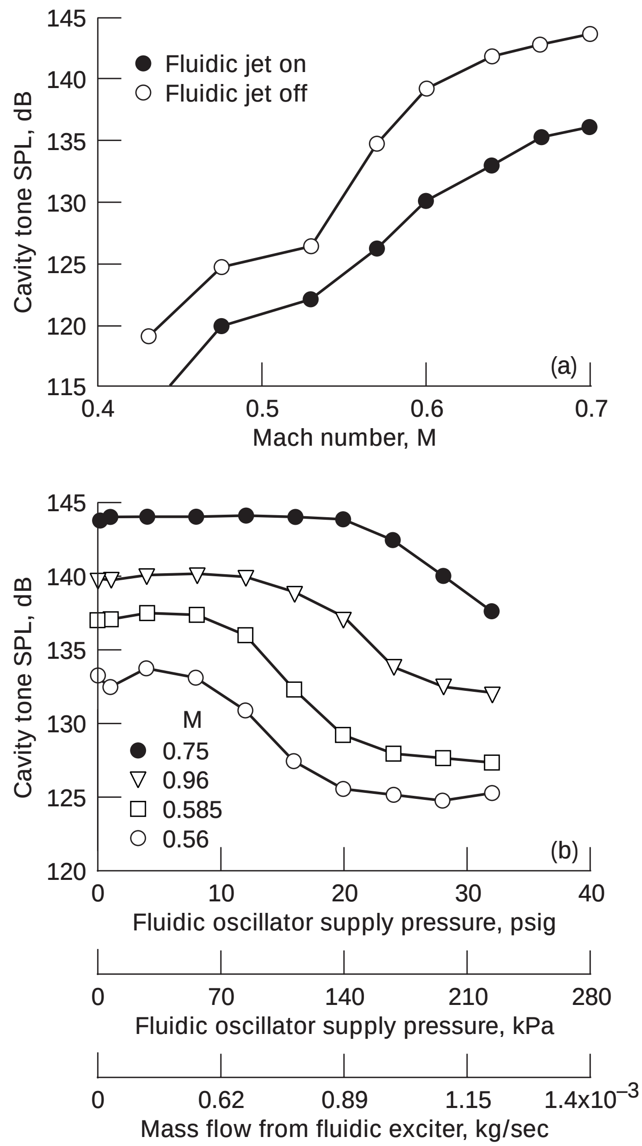


Figure 13.—Jet-cavity tone suppression at various Mach numbers and at various levels of mass injection: (a) Mach number dependence for upstream excitation, fluidic nozzle pressure = 32 psig and (b) Suppression at various M and mass injection levels.

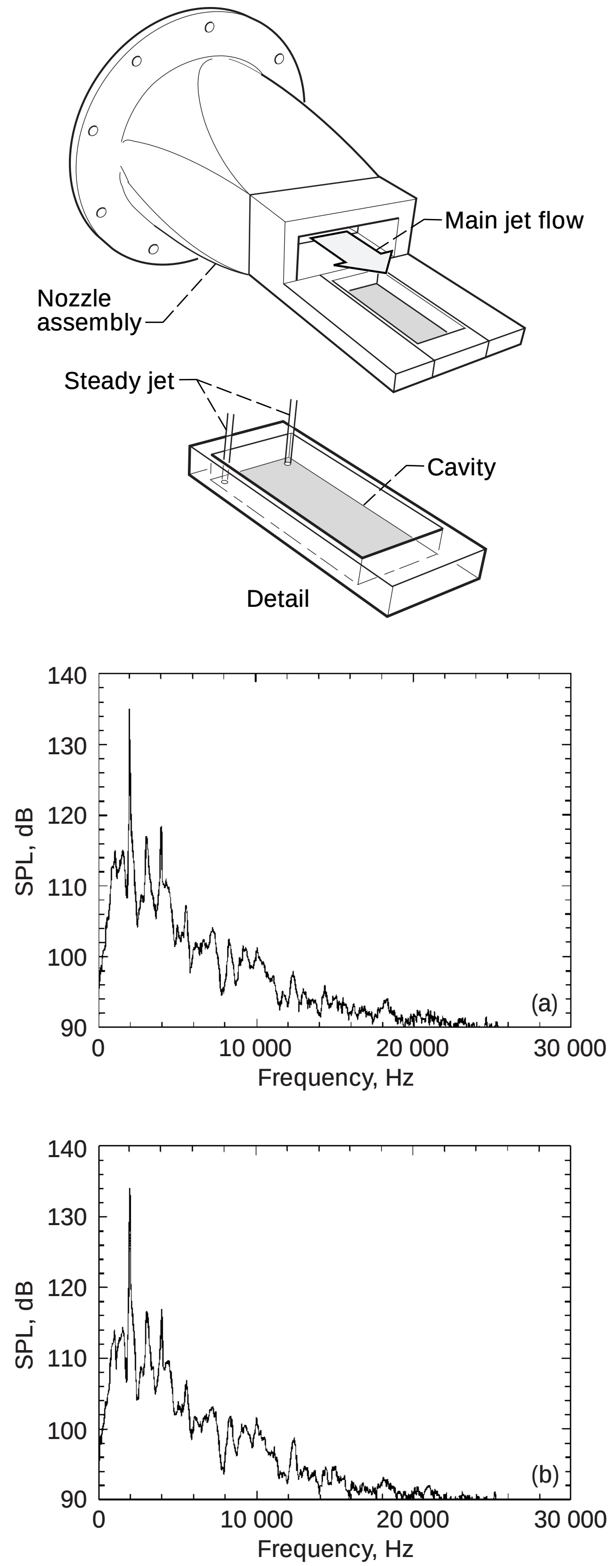


Figure 14.—Effect of steady blowing at the two upstream spanwise extremes of the cavity. Total mass flow is the same as that from the fluidic device operating at 32 psig: (a) Unperturbed and (b) Steady blowing.

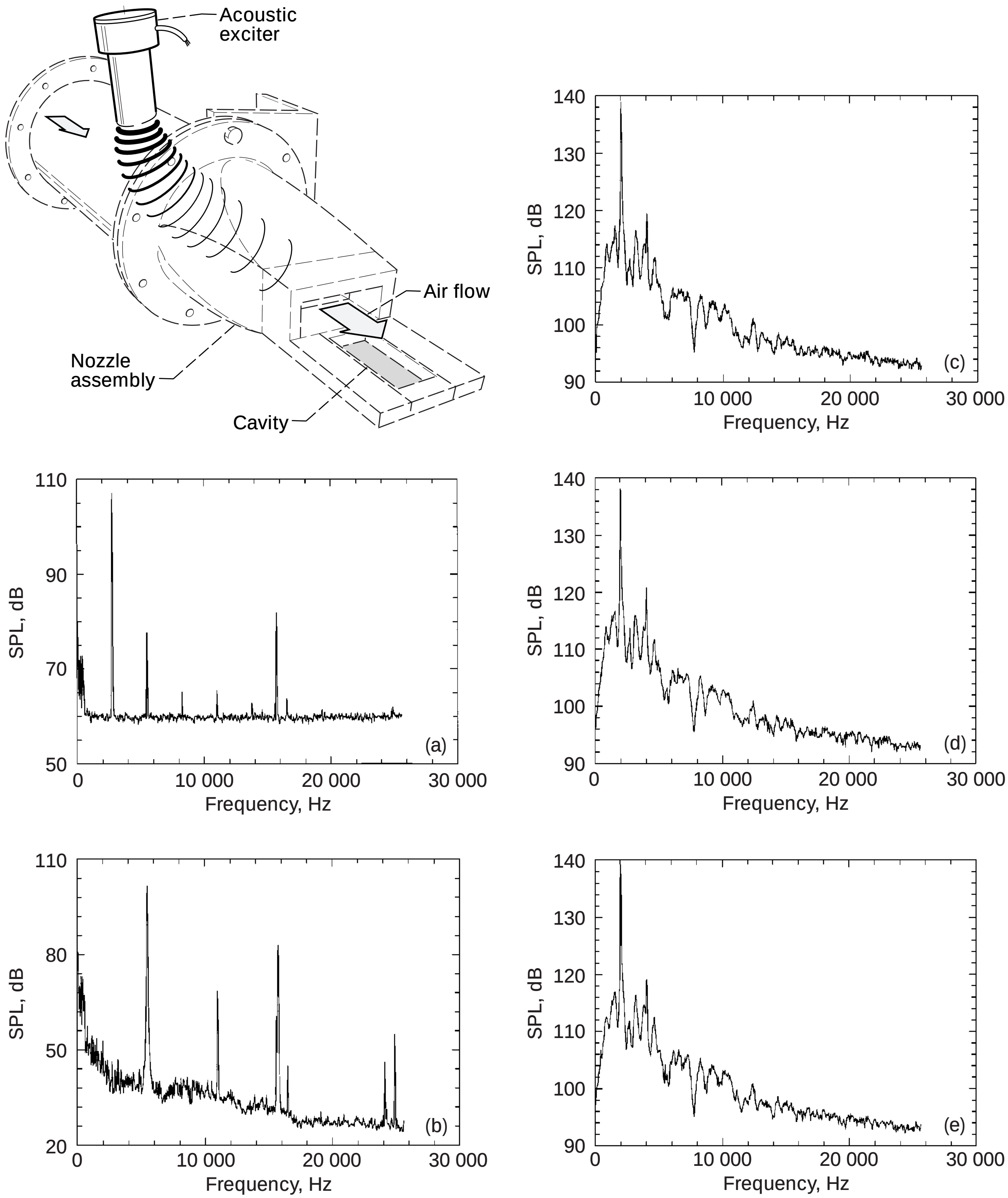


Figure 15.—Effect of acoustic excitation at the same frequency as fluidic excitation: (a) Excitation spectrum for primary frequency, (b) Excitation spectrum for harmonic frequency, (c) Unexcited jet-cavity tone, (d) Excited at primary frequency, and (e) Excited at harmonic frequency.

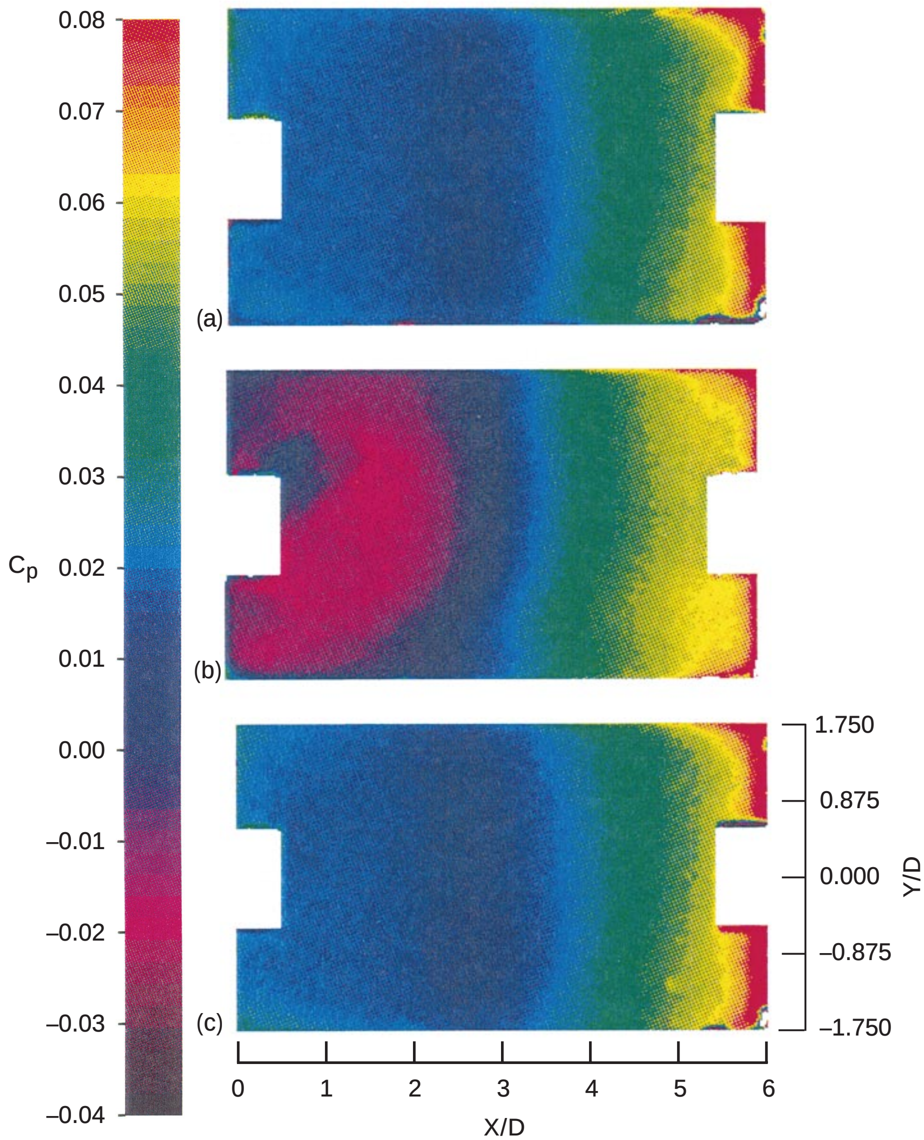


Figure 16.—Pressure maps of the cavity floor using photoluminescent pressure sensitive paint. Main jet Mach number = 0.485: (a) Unperturbed, (b) Upstream fluidic square-wave excitation, and (c) Downstream fluidic square-wave excitation. For the excited cases the fluidic nozzle's pressure was 32 psig.

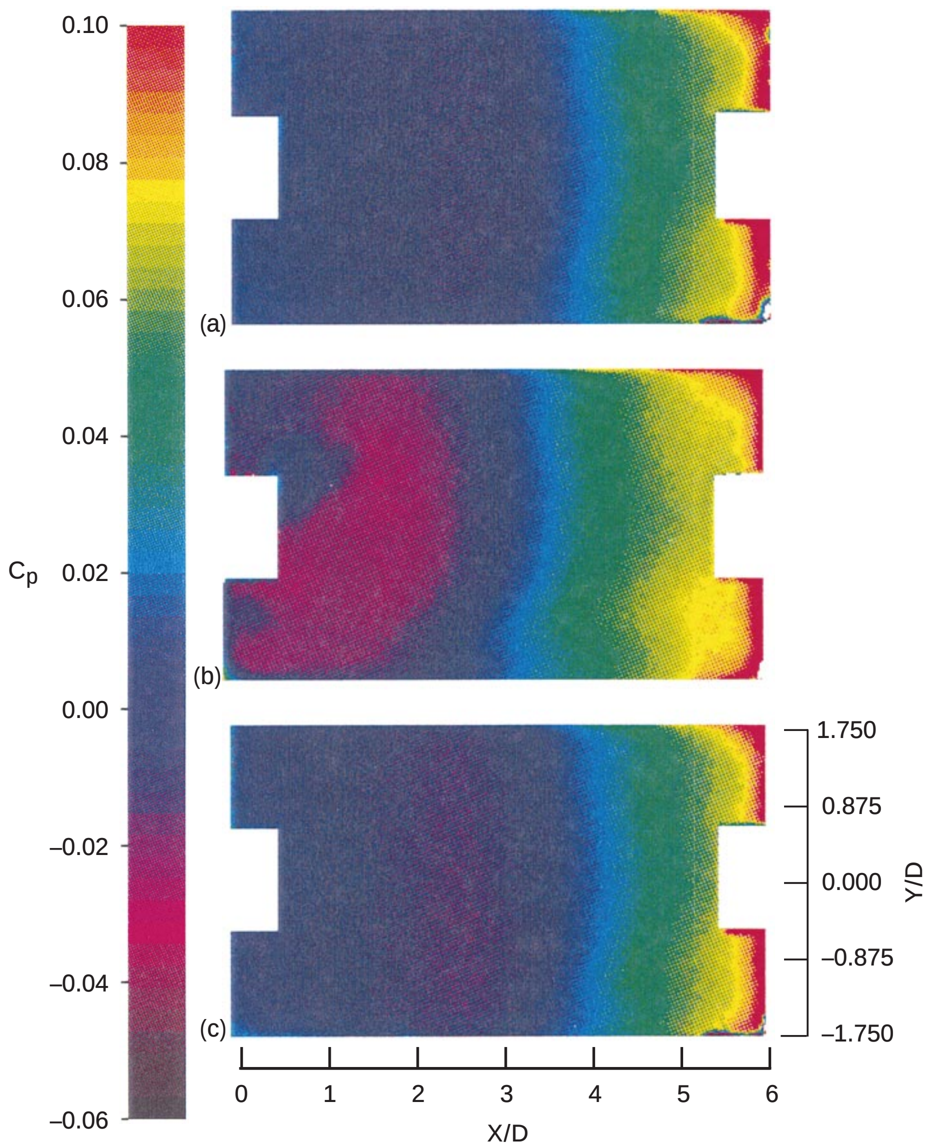


Figure 17.—Pressure maps of the cavity floor using photoluminescent pressure sensitive paint. Main jet Mach number = 0.560: (a) Unperturbed, (b) Upstream fluidic square-wave excitation, and (c) Downstream fluidic square-wave excitation. For the excited cases the fluidic nozzle's pressure was 32 psig.

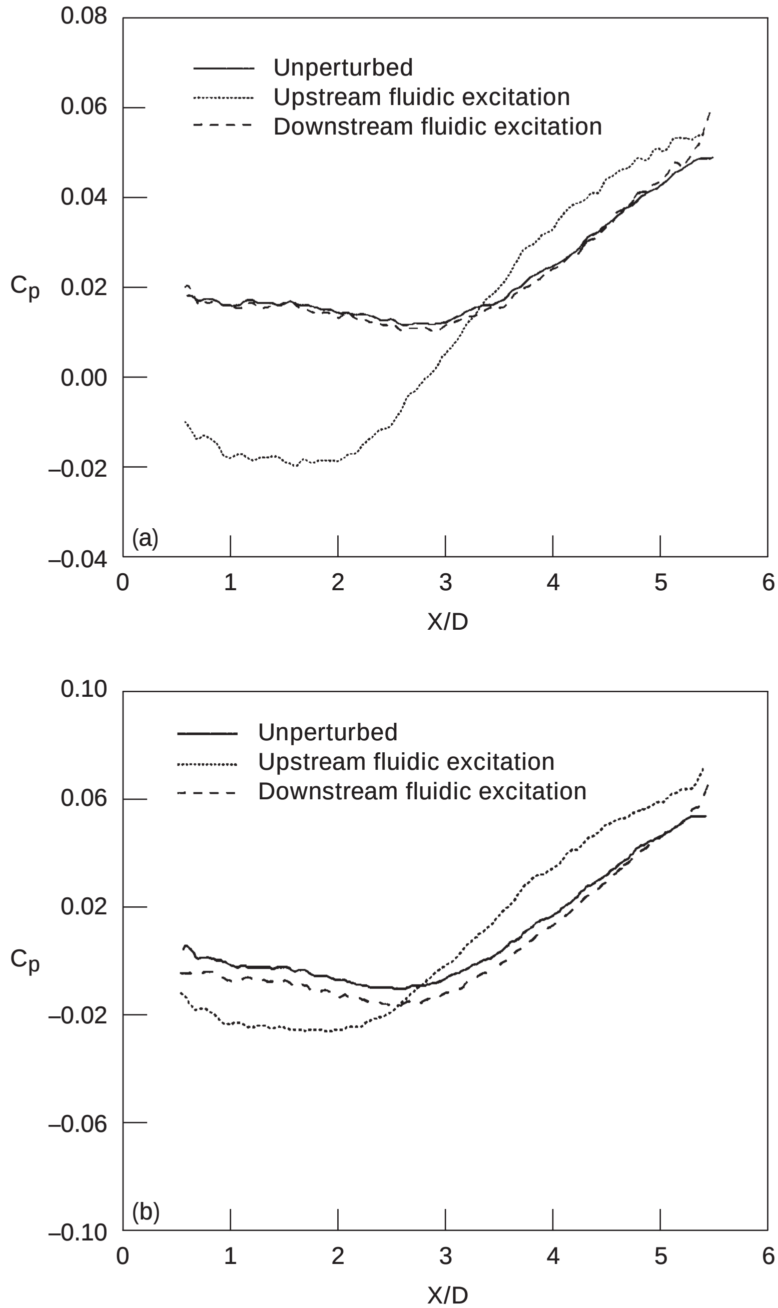


Figure 18.—Comparison of the centerline pressure coefficient with and without fluidic excitation: (a) Corresponds to cases described in Fig. 16 and (b) Corresponds to cases described in Fig. 17.

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13. ABSTRACT ***(Maximum 200 words)***
We present a novel approach to suppressing jet-cavity interaction tones using miniature fluidic devices. We first characterize miniature fluidic oscillators and then assess their effectiveness for cavity tone suppression. Further, we evaluate mass flow requirements for effective unsteady fluid mass addition. The fluidic devices used had no moving parts and could provide oscillatory flow of prescribed waveforms (sine, square, and saw-toothed) at frequencies up to 3 KHz. Our testbed 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 an (length/depth) ratio of 6. In addition to schlieren photography and acoustic measurements we used photoluminescent Pressure Sensitive Paint (PSP) to map pressures on the cavity's floor for the unperturbed and fluidically excited cases. 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 rates 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 fluidic excitation affected cavity tones only marginally (1 dB reduction). Furthermore, acoustic excitation at the same frequency as that produced by the fluidic device or its harmonic at comparable amplitudes did not affect the cavity resonance. Our results provide not only an example of the effectiveness of fluidic excitation but offer grounds for believing that vast possibilities exist for its use in aeroacoustic control.

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