# An Experimental Investigation of Wake Edge Tones

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**The unsteady velocity and sound pressure fields in the vicinity of two flat plates aligned with the direction of flow were studied experimentally. The plates were colinear so that the wake of the upstream plate impinged on the downstream plate. These tests were performed at mean velocities ranging from the critical velocity required to achieve unsteady flow in the region between the plates up to velocities high enough to produce audible sound. The objective of these experiments was to resolve apparently conflicting reports in the literature concerning the role of the feedback of unsteady disturbances from a downstream edge in determining the properties of the unsteady flow in an upstream wake. The results of the observations reported here lead to the conclusion that feedback influences the character of the flow only when the unsteadiness arises from the instability of a laminar wake. It does not influence the shedding of a separated wake. Regular variations observed in the far-field sound pressure level with changes in spacing between blunt plates are attributed to the interaction of multiple sound sources rather than to feedback.**

## Nomenclature

$L$ = plate length
$P$ = sound pressure level
$Re$ = Reynolds number based on plate thickness, $Ut/\nu$
$S$ = plate spacing
$t$ = plate thickness
$U$ = mean velocity
$u'$ = rms level of the fluctuating component of streamwise velocity

## Introduction

ONE of the essential features of the edge tone is the feedback of unsteady disturbances from an upstream sound-producing edge into a sensitive shear layer. This feedback leads to self-sustained oscillations of the shear layer that may produce an audible tone. The frequency of these oscillations varies as the streamwise location of the edge is varied. One of the distinctive characteristics of the edge tone is that the frequency changes occur in stages. The frequency varies smoothly with changes in the edge location within a stage, but jumps at certain edge positions. The basic flow configurations for which edge tones have been reported include shear layers generated by jets and mixing layers.[1] However, the feedback process has not been unambiguously identified for wake-generated shear layers.

Smith and Karamcheti[2] studied the interaction between the wake of a circular cylinder and a downstream wedge at Reynolds numbers of 300-30,000. A minimum separation distance between the cylinder and wedge was required for the generation of a tone. The frequency of the tone varied monotonically with separation distances beyond the minimum, but no frequency staging or other evidence of upstream feedback of unsteady disturbances was reported. This result is consistent with the finding of Peterka and Richardson[3] that the frequency of a cylinder vortex street is only very weakly affected by sound.

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However, in a discussion of the sound emitted from two identical cylindrical rods aligned with a flowing stream and with their axes perpendicular to the flow direction, Morse and Ingard[4] state that a strong acoustic emission will occur under resonance conditions. The condition for resonance is $S \approx 4nd$, where $S$ is the separation distance between rods, $d$ the diameter of the rods, and $n$ an integer. They further state that this resonance is due to a feedback mechanism that amplifies the strength of the vortices shed by the upstream rod. Other reported evidence for the feedback in wake flows includes that of Roadman and Loehrke[5] for the flow between in-line flat plates at low velocities near the onset of unsteady flow, of Ziada and Rockwell[6] in the mixing layer between a plate with unequal fluid velocities on either side and a downstream wedge, and of Tam,[7] who proposed a feedback mechanism, in absence of a downstream edge, based on his review of data for discrete tones generated by isolated airfoils.

The present study was undertaken to look for evidence of feedback in the flow between in-line flat plates and specifically to rationalize the observations of Roadman and Loehrke.[5]

## The Experiments

The experiments were performed at the mouth of an open-jet wind tunnel. Two centrifugal fans drive the flow by blowing air into a large plenum chamber. Internal baffles and a perforated plate are used to produce a uniform mean velocity profile within the chamber. Aluminum honeycomb and two fine-mesh screens are also placed in the plenum chamber to reduce the turbulence level. The flow is accelerated through a 64:1 contraction ratio nozzle. The velocity of the $15.2 \times 15.2$ cm free jet formed at the nozzle exit may be varied from 0.5 to 21 m/s. At the lower speeds, velocity is controlled by altering the speed of the smaller of the two fans. The large fan runs at a constant speed and, when this fan is used, the tunnel velocity is controlled by throttling the inlet. The turbulence level at the jet mouth is low, but flow pulsations of 1-2% of the mean jet flow exist. However, the frequency of these pulsations is about an order of magnitude lower than the frequencies of the unsteady flows investigated and the amplitude is similarly low.

The test plates spanning the nozzle opening are supported on the ends, outside the flow, by a special traversing fixture.

The upstream plate is held in a fixed location on the nozzle centerline about 2 cm downstream from the opening. The second plate is held parallel to the first in a movable support that is confined by guideways to allow plate motion only in the streamwise direction. The testing arrangement is shown in Fig. 1. A hot-wire probe, used to measure the fluctuating component of the streamwise velocity near the leading edge of the second plate, is also fixed to the movable support so that its position relative to the second plate remains fixed as the spacing between plates is changed.

Several different plates were used in these tests, the properties of which are summarized in Table 1. The metal plates have a rectangular cross section and the upstream and downstream plates in a plate pair are identical except for the shape of the leading edge. The influence of the leading-edge shape is discussed in the next section. The plastic plate was formed into a streamlined shape by rounding the leading edge and tapering the plate from its midpoint to a sharp trailing edge. A rectangular aluminum plate with blunt edges was used as the downstream element with the streamlined plastic plate.

Sound pressure level measurements were made using a General Radio 1558 octave band noise analyzer. The microphone was located approximately 0.6 m above and slightly downstream from the test plates, well out of the flow. Output from the noise analyzer was routed through a high-pass filter to a Fluke 1952B countertimer to obtain the acoustic frequency. An average value was obtained by using a 10 s sampling period. The sound pressure level, in decibels re $2\times10^{-5}$ Pa, in the appropriate octave band was read directly from the meter on the instrument.

Velocity fluctuation data were obtained with a TSI 1050 constant-temperature anemometer and a laboratory constructed probe. The bridge output was routed to a TSI 1060 rms voltmeter to obtain the rms voltage. This value was converted to rms velocity using the measured mean output and the calibration curve. The hot-wire probe was calibrated daily. The mean velocity of the flow was determined by two methods: at low speeds a cylinder eddy shedding technique was used, while above 5 m/s the velocity was determined with a pitot probe and micromanometer.

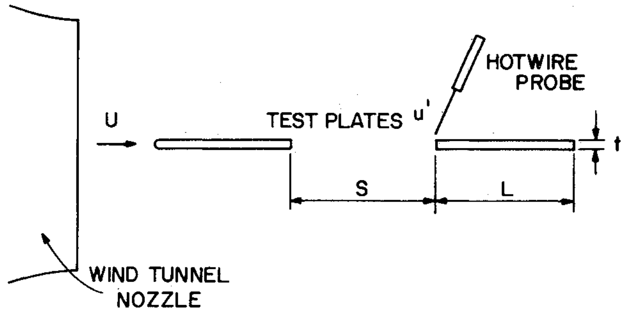


**Fig. 1 Test configuration.**

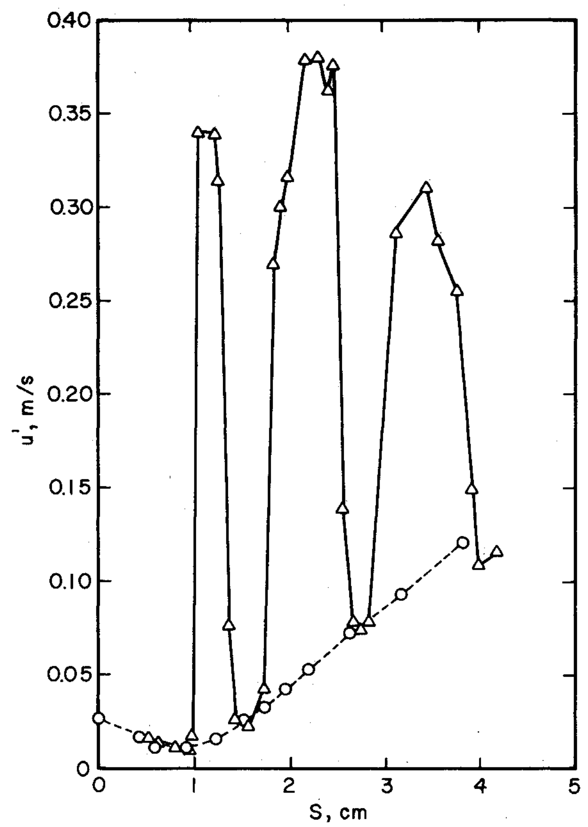


**Fig. 2 Amplitude of velocity fluctuations in the wake of an aluminum plate at $U=1.2$ m/s (single plate: ○, between a pair of plates: △).**

## Results and Discussion

A survey of the flow downstream from individual, isolated plates and between plate pairs was made prior to the study reported here. The results of this survey indicated that character of the tone produced by the flow over two plates and role of feedback were both sensitive to the shape of the leading and trailing edges of the upstream plate. The wake of a single thin (0.38 mm) plate was sinusoidal over a velocity range starting at critical Reynolds numbers ($Re=85$) and continuing up to $Re=130$. At higher flow rates the sinusoidal near wake was rapidly transformed into a wake with a broader frequency content a short distance downstream of the trailing edge. A similar, broad frequency content was noted in the wake of a thick (1.59 mm) plate with a blunt leading edge over nearly the entire range of velocities producing an unsteady wake. The wake spectrum became very pure, however, when the leading edge of this plate was rounded. A pure tone was obtained in the wake of a thick plate and in the flow between thick plates only when the leading edge of the upstream plate was rounded. The reason for this was not investigated. It was presumed to be due either to the introduction of three-dimensionality into the unsteady flow in the wake of a blunt plate due to nonuniform reattachment of the leading-edge separation bubble or to the turbulence generated in this separation bubble at higher Reynolds numbers. Lane and Loehrke[8] have found that for long blunt plates ($L/t>8$) a separation bubble forms for $Re>100$ and transition to unsteady flow in this bubble begins at $Re=325$. For all of the subsequent tests, the leading edges of the thick upstream plates were rounded. The leading edges of the thick downstream plates and of both thin plates were blunt.

**Table 1 Plate specifications**

| Material | Thickness, mm | Length, mm |
|---|---|---|
| Aluminum | 1.59 | 18.92 |
| Brass | 1.59 | 18.92 |
| Steel | 0.38 | 31.75 |
| Plastic | 1.59 max | 18.92 |

No significant difference was detected between the unsteady flow between pairs of aluminum plates and that between pairs of brass plates of identical dimensions, even though the natural flexural frequencies differed by 40%. The frequency of the oscillating wakes depended on velocity but not on the elastic properties of the plate, confirming that the phenomenon was purely hydrodynamic.

A minimum critical velocity is required to initiate unsteady flow between pairs of plates. This velocity is lower than that required to initiate unsteady flow in the near wake of a single, isolated plate. The amplitude of the velocity fluctuations measured at the leading edge of the downstream plate is shown in Fig. 2 as a function of plate spacing at critical conditions. Also shown for reference is the amplitude measured at the same location in the absence of the downstream plate. Sinusoidal oscillations alternately appear and disappear in the flow between the plates as the spacing is changed. The frequency of these oscillations does not change appreciably with the spacing. A value of 67 Hz was measured at each of the three peaks in amplitude shown in Fig. 2. These measurements are similar to those reported by Roadman and Loehrke[5] and clearly demonstrate an upstream influence of the second plate on the unsteady flow.

This evidence of feedback quickly disappears with increasing mean velocity. The character of the flow is quite different at velocities high enough to produce measurable sound. The amplitude of the velocity fluctuations and the sound pressure level at a higher mean velocity are shown in Fig. 3 as functions of plate spacing. The amplitude of the velocity fluctuations is very sensitive to the vertical location of the hot-wire probe at the leading edge of the downstream plate. While the relative probe position is fixed during each test, it could vary from test to test. For this reason, the amplitudes of the velocity fluctuations of one test should not be compared with those of another test. However, the variations of amplitude with plate spacing can be compared. In contrast to the regular, repeated changes in amplitude with spacing measured at the near critical mean velocity, the amplitude of the unsteady velocity fluctuations measured at the higher mean velocity (shown in Fig. 3) increases to a peak and then drops to a nearly constant level with increasing spacing. The frequency of the periodic velocity fluctuations observed at the leading edge of the downstream plate and the frequency of the periodic sound detected by the microphone are identical. The variation of this frequency with plate spacing is also indicated in Fig. 3. At zero plate spacing the measured low-level velocity and pressure fluctuations are associated with the vortex shedding from the downstream plate and the frequency of this shedding is commensurate with that of a single plate of length equal to the combined length of the two plates. The frequency drops with increasing spacing to a minimum value at a spacing of 0.5 cm and then increases again to approach the shedding frequency of a single isolated plate at large $S$. The region where the frequency change with spacing is most rapid corresponds to the region where the amplitude of the velocity fluctuations is maximum.

The variation of the far-field sound pressure level with spacing is not well correlated with the variation in amplitude of the velocity fluctuations. The sound pressure level increases as the spacing is increased from zero, but does not reach its maximum value at the same spacing as the maximum in $u'$. Additionally, repeated local minima and maxima are observed with increasing spacing. This variation in sound pressure level is consistent with the behavior described by Morse and Ingard[4] for flow over in-line cylinders. The spacing between the observed resonance peaks is approximately $4nt$. However, the location of the first significant peak corresponds to $n=2$, even though the peak in amplitude of $u'$ occurs near the $n=1$ location. This, plus the general lack of correlated peaks in $u'$, seems to imply that the mechanism responsible for the resonance peaks in $P$ is different from that suggested by Morse and Ingard. One possible explanation for the observations is that the far-field sound level results from two sources, one at the first plate and one at the second plate, and that as the spacing between plates changes the phasing between the two sources changes but the strength of the two sources does not. The measured sound level will be high at those spacings where the sources are in phase and low where they are out of phase.

The streamlined plastic plate was constructed to eliminate separation on the wake-forming plate. Although the maximum thickness of this plate is the same as that of the aluminum plate, the wake is thinner because of the absence of trailing-edge separation. The critical velocity for the onset of unsteady flow between the streamlined plate and the

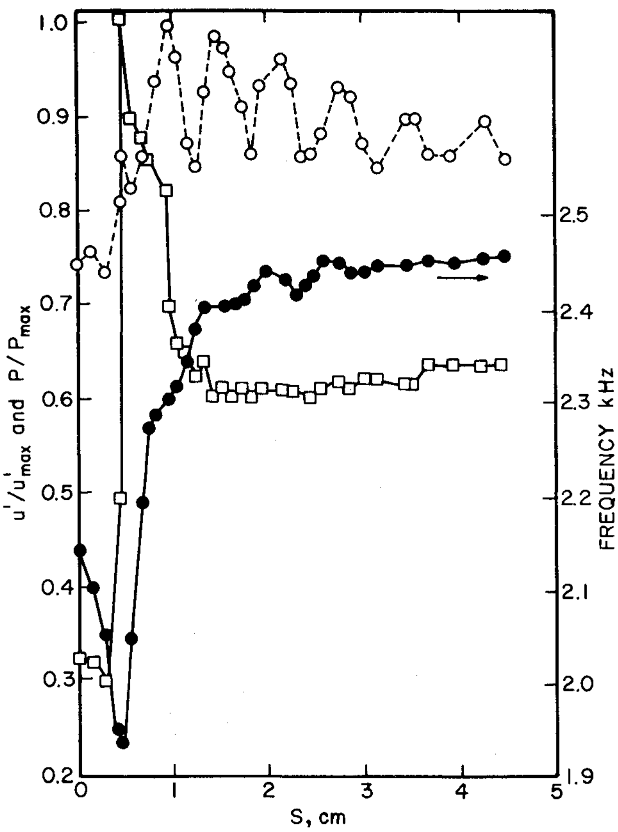


**Fig. 3 Frequency ●, dimensionless sound pressure level ○, and amplitude of the velocity fluctuations □ for flow over a pair of aluminum plates at $U = 16.8$ m/s, $P_{max} = 79$ dB, and $u'_{max} = 0.88$ m/s.**

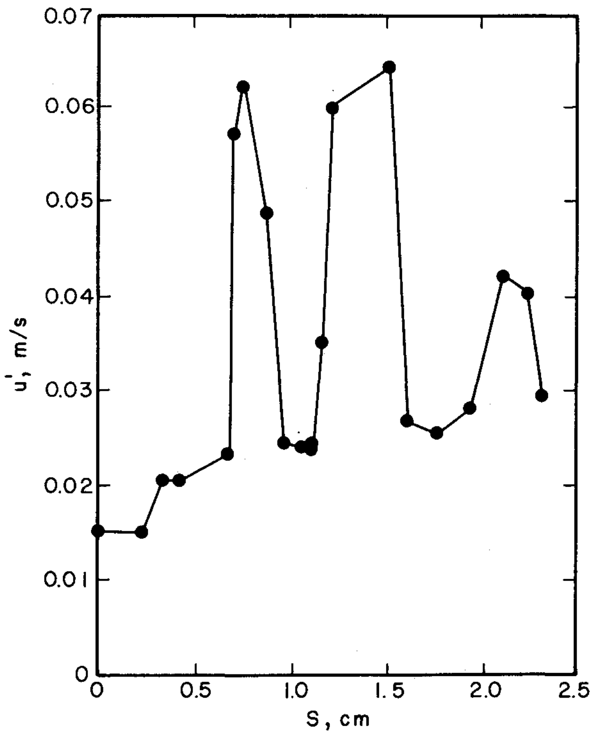


**Fig. 4 Amplitude of velocity fluctuations for flow over a pair of plates with streamlined upstream plate at $U = 3.4$ m/s.**

downstream blunt aluminum plate is consequently higher than that for the flow between two aluminum plates. However, the character of the two flows at the critical velocity is similar. The variation in the amplitude of the velocity fluctuations with the spacings is plotted in Fig. 4. The periodic component disappears between the peaks. The frequency of the periodic component is almost constant within each peak, but increases from 225 Hz in the first peak at the smallest spacing to 255 Hz in the second peak and 275 Hz in the third. At higher mean velocities, the flow downstream from the streamlined plate is qualitatively different from that downstream from the separated plate. The classic edge-tone staging characteristic evolves as shown in Fig. 5. The general trend of increasing frequency with increasing spacing observed in the flow between aluminum plates is still apparent, but this increase takes place in stages. For spacings beyond about 1 cm, the frequency drops continuously with increasing spacing

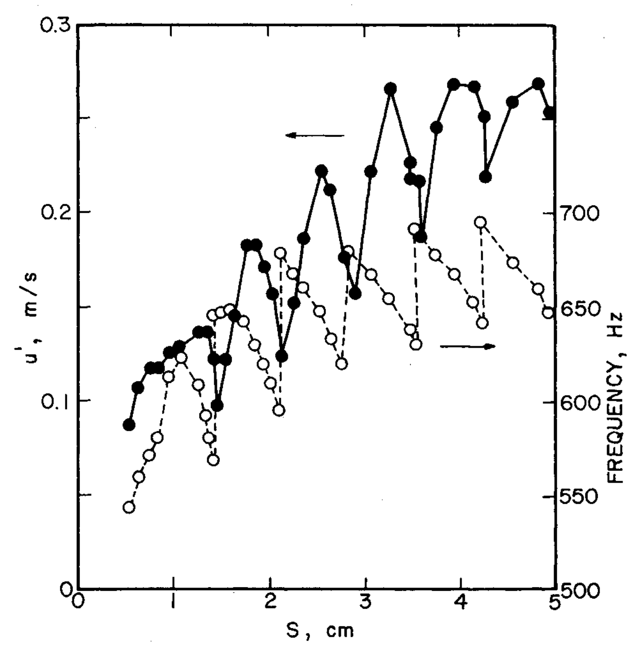


**Fig. 5 Amplitude and frequency of velocity fluctuations for flow over a pair of plates with streamlined upstream plate at $U = 6.1$ m/s.**

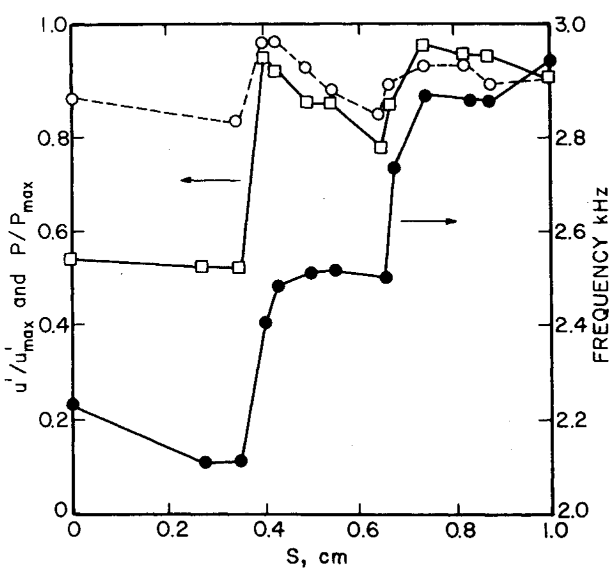


**Fig. 6 Frequency ●, dimensionless sound pressure level ○, and amplitude of the velocity fluctuations □ for flow over a pair of plates with streamlined upstream plate at $U = 17.5$ m/s, $P_{max} = 69$ dB, and $u'_{max} = 0.48$ m/s.**

until the end of a stage is reached, at which point a sudden jump in frequency occurs. The frequency of the tone (which was audible at this velocity, but not measurable with the instrument available) could be heard to follow the staging in velocity.

Both pressure and velocity were measured at a higher mean velocity and are plotted in Fig. 6. The frequency of the velocity fluctuations is the same as that of the pressure fluctuations. A staging is still detectable at this mean velocity and it is apparent in the changes in amplitude of both $u'$ and $P$. At this velocity, the tone was not as loud or as pure as that produced by the flow over two aluminum plates at the same velocity. The range of spacings over which amplitude and frequency modulation could be detected was limited at this highest velocity. This is why Fig. 6 is truncated at a spacing of 1 cm.

Tests with the thin steel plates revealed that staging can be obtained in the flow between plates even though the upstream plate has blunt leading and trailing edges. However, this behavior was noted only at low Reynolds numbers. No staging could be detected at Reynolds numbers above 130 for these plates.

The flow over the blunt and streamlined plates was visualized using the smoke/wire technique. Measurements made from photographs of the unsteady flow and with hot-wire probes show that the wavelength of the flow oscillations between the aluminum plates does not change as the plate spacing is changed. The wavelength of the oscillations in the wake of the streamlined plate does change with the spacing. A continuous increase in wavelength is observed as the spacing is increased within a stage and an abrupt decrease is noted when a new stage is entered by increasing the spacing.

These measurements and observations of the flow downstream from a streamlined plate and downstream from plates with blunt trailing edges at low Reynolds numbers are consistent with the following model of the edge-tone phenomenon.[9] A laminar shear layer, in this case a wake, unstable to perturbations within some frequency band is excited by small disturbances in the flow at the trailing edge of the upstream plate. These disturbances grow as they are carried downstream by the mean flow and interact with the downstream edge where they produce periodic pressure fluctuations. The pressure fluctuations travel upstream, causing flow disturbances at the trailing edge of the upstream plate and completing a feedback loop. As the spacing between the upstream plate and the edge or downstream plate is changed, the wavelength of the oscillations in the unsteady wake changes to maintain the phasing conditions required for positive feedback. The changing wavelength gives rise to a changing frequency. The jumps in frequency between stages are required to keep the oscillations within the most sensitive range of the unstable wake. At the critical velocity, the bandwidth of unstable frequencies is small and positive feedback cannot be maintained at all spacings. In low turbulence-level streams, this leads to situations where the wake alternates between steady and unsteady as the spacing is changed. This is the case for the flows shown in Figs. 2 and 4.

The flow at high Reynolds numbers downstream from plates with trailing-edge separation does not conform to this model. Staging in the frequency of the flow oscillations is not observed as plate spacing is changed. The feedback of small disturbances from the downstream edge does not appear to be an essential feature of this flow. The oscillations may be associated with an imbalance of entrained and return flow in the separated wake as suggested by Rockwell.[9]

## Conclusions

In absence of separation at the leading edge of the upstream plate, the unsteady flow between closely spaced pairs of plates is characterized by relatively pure, sinusoidal, two-dimensional velocity fluctuations over a wide range of Reynolds numbers. The critical Reynolds number for the onset of unsteady flow was found to be in agreement with the measurements of Roadman and Loehrke.[5]

Two distinctly different kinds of flow were observed between pairs of plates: those that exhibited evidence of upstream feedback of unsteady disturbances from the downstream plate and those that did not. The primary indication of feedback was the variation with plate spacing of the frequency and amplitude of the velocity fluctuations measured at the leading edge of the downstream plate. The feedback phenomenon was observed over a wide range of freestream velocities when the upstream plate was streamlined, over a narrow range of velocities starting at critical for a thin flat upstream plate, and only at the critical velocity for the thickest plate tested with a blunt trailing edge. A conclusion consistent with these observations is that feedback influences the character of the flow only when the unsteadiness arises from the instability of a laminar wake. It does not influence the shedding frequency of a separated wake.

Resonance peaks in the far-field sound pressure level were detected with changes in the spacing between pairs of thick plates. The distance between locations of successive peaks is in agreement with the criterion given by Morse and Ingard[4] for flow over a pair of cylinders. The lack of corresponding changes in the amplitude of the velocity fluctuations at the leading edge of the downstream plate indicates that the pressure variations are not due to feedback effects, but rather represent the interaction of multiple sound sources.

## Acknowledgment

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