SHEAR LAYER COUPLING WITH SIDE-BRANCH RESONATORS

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INTRODUCTION

High velocity flow past the junction of a side branch with a pipe can result in the excitation of depth-mode standing waves in the branch. The shear layer separating the main stream flow and the cavity provides coupling between the driving and the driven flow. Photographic evidence indicates that large scale vortex structures develop at the shear layer. The vortex formation process involves strongly non-linear instability of the shear layer and may be characterized as a non-linear fluid mechanical oscillator. The standing wave system formed in the cavity is essentially an acoustic wave system of nearly linear character. The principle interaction takes place through the excitation of a quarter wavelength standing wave in the cavity. Apparently, the shear layer oscillator drives the acoustic oscillator which, in turn, has the ability to drive the shear layer through a presently unknown feedback mechanism. The system exhibits bandwidth synchronization in that the shear layer frequency is captured by the depth-mode resonance of the cavity.

The purpose of this paper is to present experimental results obtained from side branch cavity resonance studies utilizing a three-dimensional junction geometry. The investigation involved studies of cavity sound pressure level as a function of frequency for a variety of cavity depths and main pipe velocities. Flow visualization techniques were employed to reveal the vortex formation process and organization as a function of shear layer mode. The significance of these analyses were two-fold. First, the visualization studies revealed a correlation between the number of vortices simultaneously populating the shear layer and the mode of shear layer instability. Second, the interface geometry studied was unique with respect to similar experimental investigations which in the past have considered two-dimensional junction geometries exclusively.

EXPERIMENTAL APARATUS

Experiments were performed using a specially designed apparatus consisting of a centrifugal blower whose exhaust was connected to a dissipative muffler which, in turn, was connected to a 15 cm diameter flow pipe. Velocity measurement was achieved with an ASME standard specification high beta ratio flow nozzle. Flow control was achieved with a manually adjustable gate valve at the inlet of the blower so that air speeds up to 40 m/s were available. The flow pipe was designed to accommodate a removable test section which for the tests reported herein consisted of a 15 cm diameter flanged pipe, 45 cm long, with a 6 cm diameter side branch mounted perpendicular to its axis. The side branch was fitted with a piston such that the cavity depth could be varied up to 60 cm. Two test sections were used; one test section was fabricated of grey PVC and used exclusively for sound studies, the other test section was fabricated of clear PMMA plastic to facilitate flow visualization. Figure 1 is a schematic of the flow apparatus.

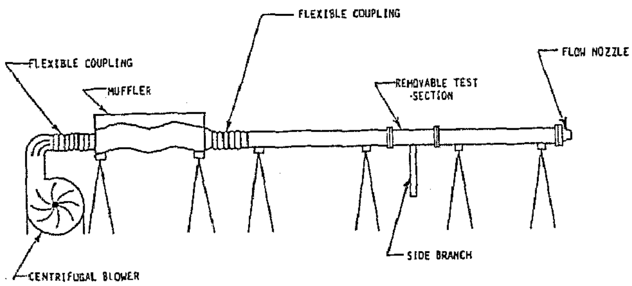

Figure 1. Test Apparatus

To facilitate flow visualization, a hot plate type smoke generator was used to produce kerosene vapor in a nitrogen atmosphere. The smoke generator was physically located near the upstream cavity edge such that maximum smoke flux could be delivered to a small hole in the flow pipe wall upstream of the cavity. Shear layer illumination was provided with a high intensity strobe system incorporating slit filters and cylindrical lenses to produce a 6 mm thick sheet of light perpendicular to the side branch junction. A TTL circuit/microcomputer system

was used to detect zero crossings of the signal produced from the resonant cavity and trigger a 35 mm camera and strobe system with preselected delays. This system enabled photographs to be taken at known phases in the cycle of the oscillating shear layer.

Sound pressure levels were measured at the bottom of the cavity with a piezoelectric microphone mounted flush with the face of the cavity piston. The microphone output was amplified with a differential amphlifier and processed using a dynamic signal analyzer. The analyzer was connected to a plotter so that permanent records of the power spectra could be obtained.

METHODOLOGY

The sound studies were conducted by fixing the cavity at selected lengths and varying the free stream velocity. The selected cavity depths ranged from 15 cm to 40 cm with intermediate depth increments of 5 cm. The free stream velocity was varied from 26 m/s to 40 m/s with intermediate velocity increments of approximately 2 m/s. Power spectra, consisting of sound pressure level (SPL) versus frequency were obtained for each cavity depth over the specified velocity range. Suitable non-dimensionalization of the measured data to pressure coefficients and Strouhal numbers resulted in the collapse of all data to a single curve. The pressure coefficient, $Cp = 2Prms/\rho V^2$, related the root mean square (RMS) cavity pressure fluctuation at peak resonant frequency, to the dynamic pressure of the free stream in the main duct. The Strouhal number, $S = fd/V$, was referenced to the inner diameter of the cavity and the mean velocity of the free stream.

Flow visualization studies were conducted for two cavity depths, 18 cm and 38 cm. A free stream velocity of approximately 33 m/s was utilized which allowed adequate kerosene vapor visualization with maximum SPL for the quarter mode pipetown frequency. The vapor was drawn through a 3 mm diameter hole in the flow pipe wall, 6 mm upstream of the cavity edge. Sequential photographs of the shear layer during the oscillation cycle were obtained from 0 degrees phase, delayed in increments of 45 degrees phase, to a final 315 degrees phase.

RESULTS

With fixed cavity lengths, the resonant sound pressure level would rise with increasing velocity, achieve a maximum, and thereafter decrease. This trend was observed to occur in two ranges of velocity within the limitations of the flow apparatus. The dominant observed frequency of cavity resonance was the quarter mode fundamental for the velocity range used. Thus, at fixed cavity length, the frequency did not vary as the velocity was increased. The measured sound pressure levels, thus, typically exhibited periodic behavior with increasing velocity such that two maxima occur on a plot of Cp versus S. Figure 2 illustrates the variation of the pressure coefficient with the Strouhal number showing two distinct response peaks. The first, occurring in the range of Strouhal number from 0.35 to 0.55, corresponds to the lowest mode of shear layer instability. In this mode a single vortex exists on the shear layer at any given time. The second maxima occurs in the range of Strouhal numbers from 0.80 to 1.0, where the higher mode of shear layer instability is observed to occur. In this mode two vortices exist on the shear layer at any given time. The intensity of the cavity resonance was observed to achieve a maximum of 150 decibels in sound pressure level for S = 0.45 in the lowest mode.

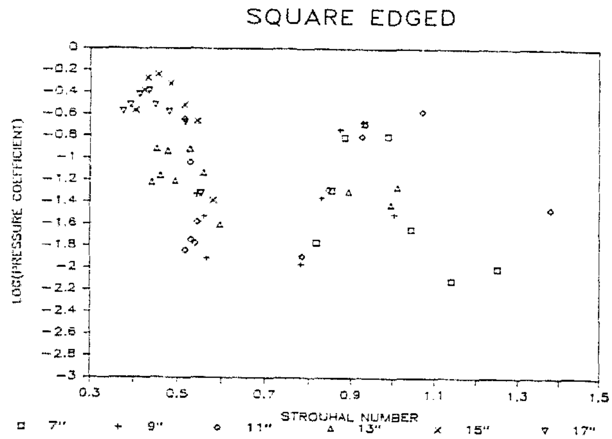

Figure 2. Pressure Coefficient vs. Strouhal Number for PVC Test Section from reference (1).

The flow visualization results for the 38 cm cavity are depicted by the sequence of photographs in Figure 3. This sequence of events correspond to one cycle of oscillation of the shear layer in the lowest mode. Each photograph is spaced at even increments of 45 degrees phase through the cycle. Initially, it is apparent that the vortex structure forms as the shear layer is deflected into the cavity. The vortex grows in diameter as it is convected downstream and is eventually expelled from the cavity as the shear layer completes one cycle of oscillation. This cycle of events correspond to a Strouhal number of 0.38 or a cavity frequency of 210 hertz.

Figure 4 is a typical photograph of vortex formation on the shear layer for the 18 cm cavity depth. In this case the higher mode of instability is present. The Strouhal number was S = .78 and the frequency was f = 425 hertz. Individually, multiple vorticies follow a history similar to the single vortex mode.

CONCLUSIONS

High velocity flow in a pipe with a side branch causes substantial tone generation by virtue of the interaction of the shear layer with the resonant cavity. The frequency of the oscillation is determined by the fundamental mode (quarter wavelength) of the cavity. The amplitude is determined by the speed of flow in the pipe. Apparently the feedback mechanism is such that for lower velocities a double vortex structure exists on the shear layer which drives the cavity flow at its resonant frequency. The coupling is such that strong reinforcement of the shear layer mode occurs. At higher velocities it is evident that strong feedback from the resonant cavity occurs such that a single vortex structure exists on the shear layer. This is the lower shear layer mode and typically results in the strongest coupling.

NOMENCLATURE

Cp	Pressure coefficient
d	Cavity diameter
f	Frequency
P_{rms}	RMS fluctuating pressure
ρ	Fluid density
S	Strouhal number
V	Free stream velocity

REFERENCES

1) C. F. Maguire III, "An Experimental Investigation of Self Sustaining Cavity Oscillations in a Pipe Mounted Side Branch", April, 1985 Masters Thesis, Worcester Polytechnic Institute, Worcester, MA.

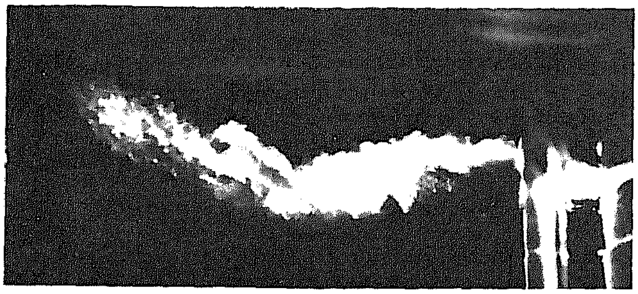

Fig. 3.a Single Vortex Formation, $\phi = 0°$

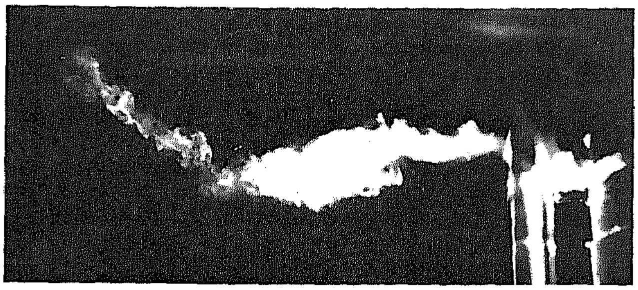

Fig. 3.b $\phi = 45°$

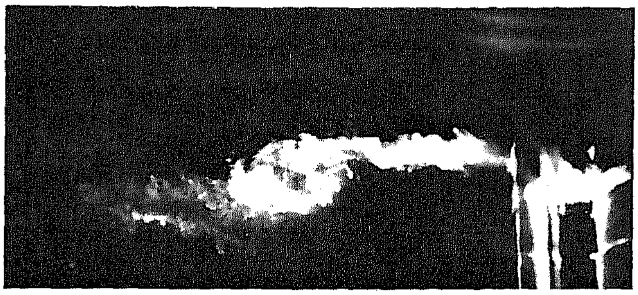

Fig. 3.c $\phi = 90°$

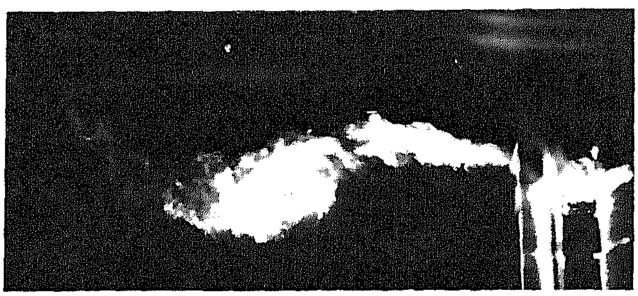

Fig. 3.d $\phi = 135°$

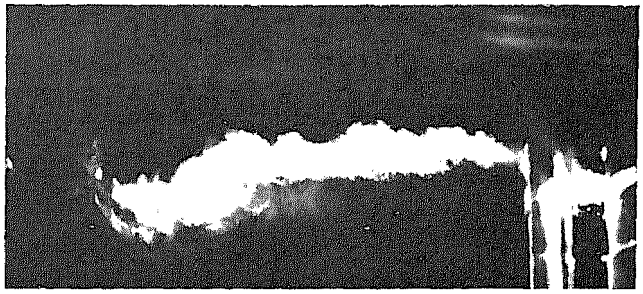

Fig 3.e $\phi = 180°$

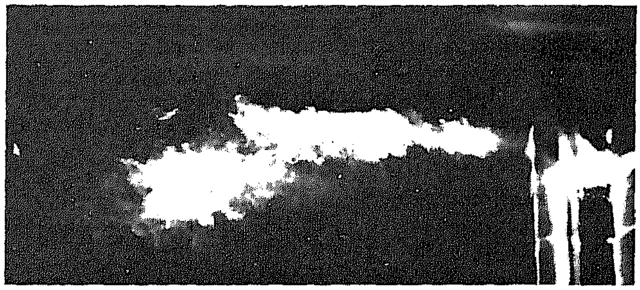

Fig. 3.f $\phi = 225°$

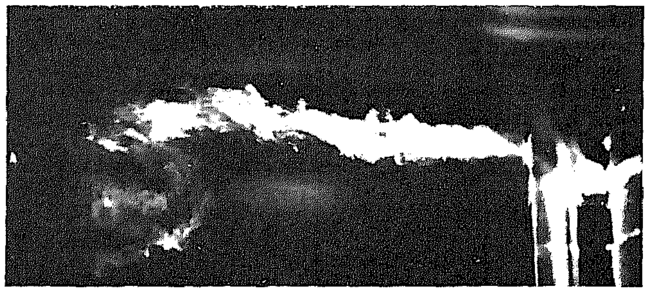

Fig. 3.g $\phi = 270°$

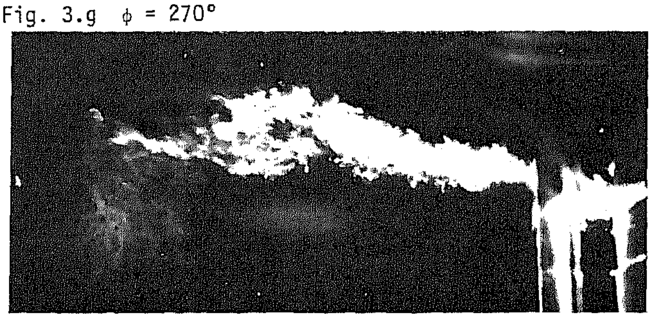

Fig. 3.h $\phi = 315°$

Fig. 4. Double Vortex on Shear Layer