Flow Visualization in Long-Neck Helmholtz Resonators with Grazing Flow

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Both oscillating and steady flows were applied to a single clear plastic resonator cavity with colored dyes injected in both the orifice and grazing flowfield to record the motion of the fluid. For oscillatory flow, the instantaneous dye streamlines were similar for both short- and long-neck orifices. The orifice flow blockage appears to be independent of orifice length for a fixed amplitude of flow oscillation and a fixed magnitude of the grazing flow. The steady flow dye studies showed that the acoustic and steady flow resistances do not necessarily correspond for long-neck orifices.

Introduction

DESPITE considerable research during the last decade, there is still much unknown concerning the mechanism of acoustic energy dissipation by a resonator in the presence of grazing flow. More detailed information is needed regarding the physical flow interaction process occurring near the mouth of a Helmholtz resonator in the presence of grazing flow. To ascertain the nature of the flow process for resonators, a visual study of the effect of grazing flow on the oscillatory flow in both short- and long-neck orifices has been performed in a clear plastic flow channel with a single side-branch Helmholtz resonator. Water is used as the fluid medium and colored dyes trace the fluid motion.

In this investigation, both oscillatory and steady flow were applied to the back cavity of the resonator. The motion of the dyes, and thus of the fluid, are recorded by a high-speed camera. Individual motion-picture frames are presented in this report to illustrate the flow regimes.

Apparatus and Procedure

Figure 1 is a schematic diagram of the test apparatus. The apparatus is essentially a once-through water flow system. The main channel is 90-cm long with a rectangular cross section 2.54 × 5 cm. Details of the short-neck resonator cavity are shown in Fig. 2, while details of the long-neck resonator cavity are shown in Fig. 3. For both cases, the orifice hole is a square 1.27 × 1.27 cm. The square geometry rather than a circular one was chosen for ease in photographing the flow. The short-neck resonator has a length-to-width (hydraulic) ratio (L/W) of 0.5 while the length to width ratio of the long-neck resonator is 4.

Three different color dyes can be injected into the flowfield (see Fig. 1). The dye flows under the action of gravity to the dry injection locations marked in Figs. 2 and 3. The needle valves shown in Fig. 1 were adjusted to prevent jetting of the dye so as to minimize any disturbance to the flowfield. Water soluble dyes were used.

Either oscillating or steady flow can be applied to the resonator through the valving shown in Fig. 1. The oscillatory flow was intended to simulate acoustic oscillations while the steady flow was intended to simulate a common method of measuring the resistive portion of the resonator impedance. The flow oscillations to the resonator cavity are driven by a servo-controlled hydraulically operated piston, as shown in Fig. 1. The piston could be oscillated from 0.1 to 50 Hz. For the purpose of these experiments, the frequency was set at 2 Hz. At higher frequencies (greater than 10 Hz), the equipment had a tendency to vibrate. At frequencies lower than 2 Hz, the resulting pulse was not sinusoidal. This latter effect was thought to occur because of resonance in the fluid lines.

For convenience, the oscillatory flow was applied to the resonator cavity rather than to the main stream. In this manner, the magnitude of the flow oscillation in the orifice could be precisely controlled by varying the stroke of the piston. It was found experimentally in Ref. 1 that the same type of flow profiles in the orifice occurred whether the flow oscillation was introduced in the back cavity or in the main stream. Use of this procedure allows the resonator cavity to be full of water with no need for an air bubble to provide compliance.

The grazing flow was measured with a turbine flowmeter and the frequency of the piston was also measured. The high-speed motion-picture camera was positioned adjacent to the resonator cavity. The velocity field in the orifice and in the main water channel can be determined from the high-speed motion pictures by following the movement of the dye.

In the entrance region of the main flow channel, a system of screens and baffles was added to produce an initially uniform velocity profile in the flow channel. According to the velocity profile measurements reported in Ref. 1, the boundary layer extends approximately 0.3 cm from the wall. This gives a ratio of boundary thickness to orifice diameter (hydraulic) of around 0.25, which is small compared to the corresponding ratio in actual flow ducts. Although this may change the

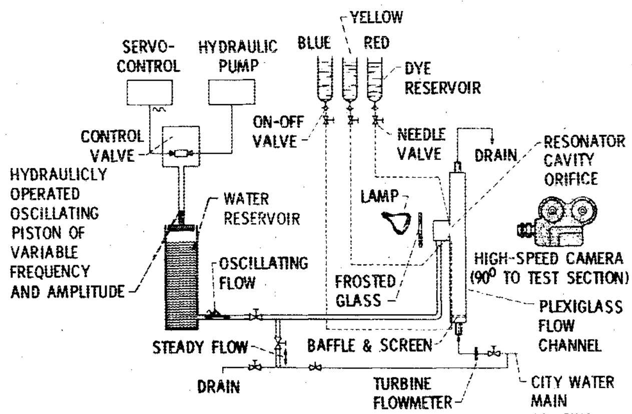

Fig. 1 Apparatus schematic for visualizing oscillatory flow in resonator orifice in presence of grazing flow.

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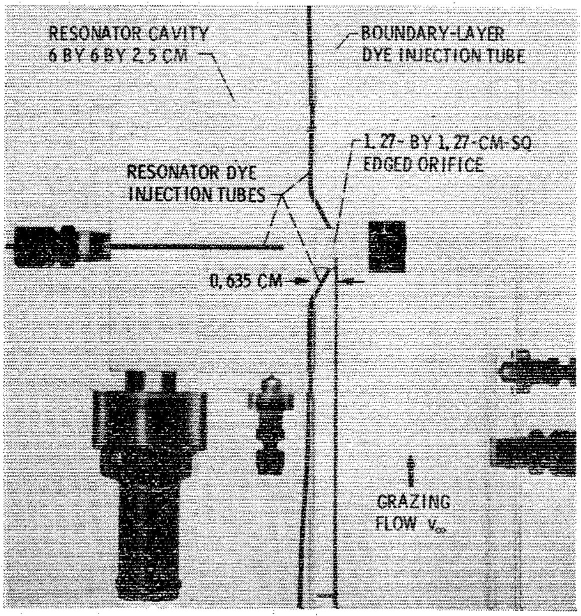

Fig. 2 Resonator cavity (short neck).

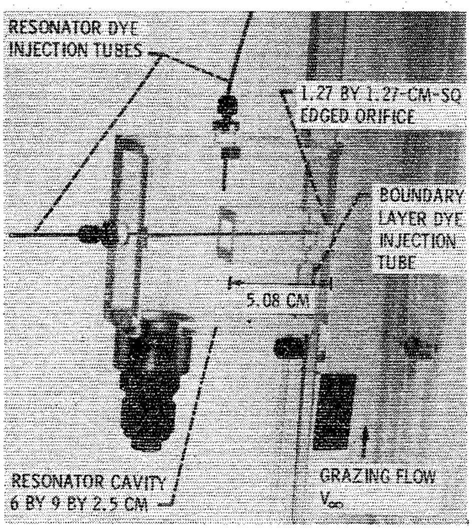

Fig. 3 Resonator cavity (long neck).

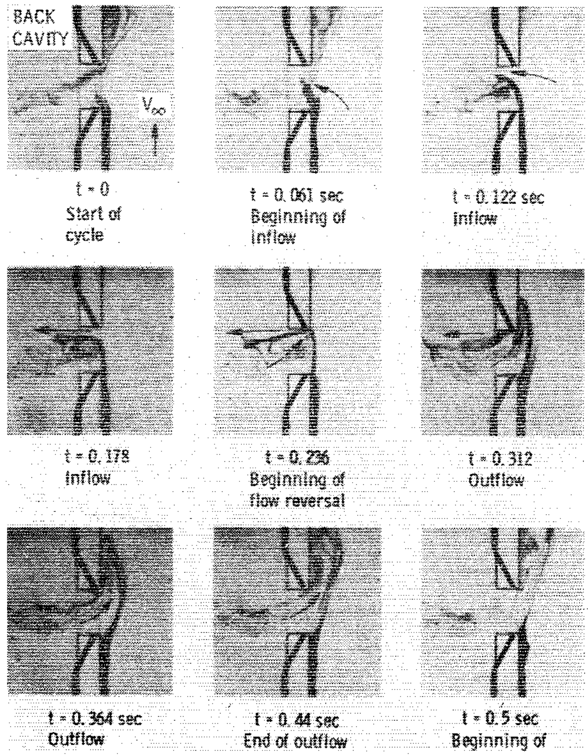

Fig. 4 Flow regimes with 0.3 m/s grazing flow and intermediate-amplitude oscillating orifice flow at 2 Hz.

magnitude of the resistance, it should not change the general characteristics of the flow regimes.

During a run, the grazing flow velocity in the main channel was set first. Next, the frequency (2 Hz) and amplitudes of the resonator flow perturbation were set. Finally, the valves to the dye reservoirs were opened. When desired, a high-speed motion-picture camera recorded the flow patterns. Generally, the camera was run at 500 frames/s.

Scaling Considerations

The intent of this study was to provide a visualization and hence a better understanding of the airflow process in a resonator orifice in the presence of a grazing steady flow. It is important to consider whether the water system simulates an air system. Based on the work of Thurston and Hargrove[2] and Ingard and Ising,[3] Hersh and Rogers[4] provide convincing evidence that air-water similitude exists for the resistance and reactance of flow in the orifice. Reference 1 also discusses this topic, as well as presenting some numerical examples.

Outside the hole, similarity of the air-water system with grazing flow may be inferred because grazing flow Reynolds numbers based on the diameters of the orifices are similar. Finally, the orifice to grazing stream momentum ratios are similar, thus implying dynamic force similarity.

Orifice Flow Visualization

The following figures summarize the oscillatory flow and steady flow regimes for a simulated resonator orifice. The figures contain single frames taken from a motion picture study. All the photographic sequences are for orifice flow in the presence of a grazing flow. Photographs of oscillating flow in the absence of grazing flow can be found in Ref. 1.

Photographs of oscillatory flow for short- and long-neck orifices will be presented and compared. Next, photographs of steady flow into both the short- and long-neck orifice will be presented and related to the oscillatory flow. The steady flow is of interest since measurements on a steady flow system are a practical way of estimating the orifice resistance to an oscillating flow.[5]

Oscillatory Flow Regimes

The oscillatory flow regimes are illustrated in Figs. 4 and 5, which show one cycle with both inflow and outflow to a short- and a long-neck orifice. As documented in Refs. 1 and 4, the resistance due to grazing flow may be viewed qualitatively as an orifice blockage effect. This fact is evident in the sequences shown in Figs. 4 and 5.

For the short-neck orifice (Fig. 4), during the inflow portion of the cycle ($t = 0\text{-}0.236$ s) the axial momentum (vertical) of the grazing flow makes it difficult for the fluid to negotiate the turn into the orifice. This results in a large separation or "dead flow" region at the lower side of the orifice which effectively reduces the area of inflow. The inflow region is seen to be limited to the small channel at the top of the orifice. For a long-neck orifice (Fig. 5), similar results are found during the inflow portion of the cycle ($t = 0\text{-}0.228$ s).

In the short-neck orifice, the kinetic energy of the entering jet of fluid is dissipated in the back cavity. At the beginning of flow reversal in Fig. 4 ($t = 0.236$ s), new flow from the resonator cavity is pushed outward through the lower or

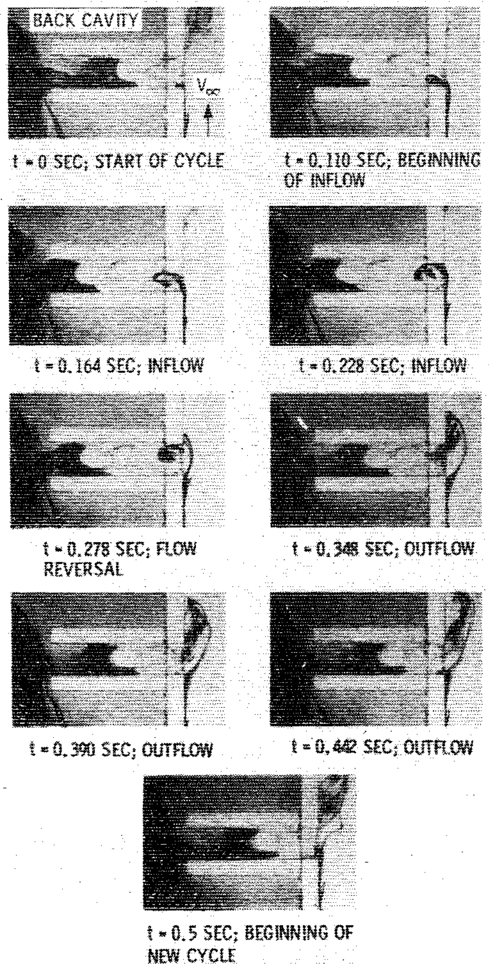

Fig. 5 Flow regimes with 0.3 m/s grazing flow and moderately high-amplitude oscillating flow at 2 Hz.

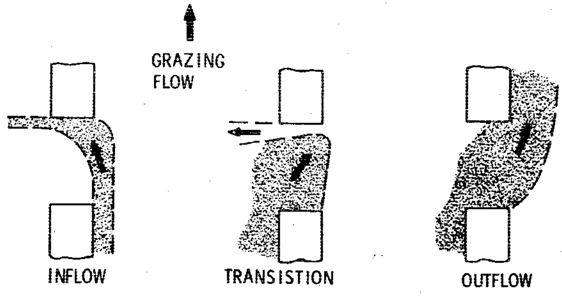

Fig. 6 Oscillatory orifice flow regimes with grazing flow.

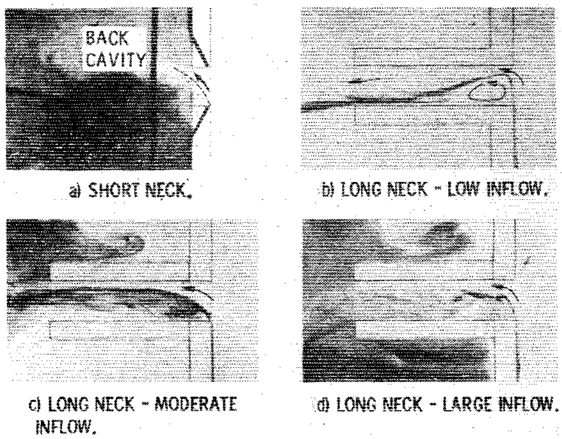

Fig. 7 Steady flow into short- and long-neck resonator cavities.

"dead water" portion of the orifice area while the inertia of the fluid, which has just entered the orifice near the upper surface, continues to carry that fluid back into the resonator cavity. Therefore, for short-neck orifices, the resonator cavity acts as the source of fluid for the outflow portion of the flow oscillation cycle. The flow patterns shown in Fig. 4 depend somewhat on the amplitude of flow oscillation. For large-amplitude oscillations, the amount of orifice blockage is reduced. This is also true of the long-neck orifice to be discussed next.

In the long-neck orifice (Fig. 5), the entering fluid at the top of the orifice is directed downward by the action of a small eddy formed at the lower lip of the orifice. Partial dissipation occurs during the turning process; however, some of the kinetic energy will be directed back into the main stream of the grazing flow during the outflow cycle. Remember that in the short-neck orifice all the kinetic energy was dissipated in the back cavity. Therefore, the acoustic resistance may be a function of the L/D of the orifice.

On the outflow portion of the cycle, the orifice flow is seen to encounter the large axial momentum of the grazing flow, which must be displaced before the orifice flow can emerge. In both the short- and long-neck resonator, the outflow streamlines look similar. The streamlines leaving the orifice turn downstream in parallel with the grazing flow.

One striking difference between the oscillating flow in the short- and long-neck orifice is the presence of an oscillating slug in the neck of the long orifice. In the motion-picture study of this oscillating slug, a red dye was used to mark the position of the slug as a function of time. To make this slug visible in a black and white photograph, a large concentration of the red dye was added in the rear of the orifice, as shown in Fig. 5. The inertia of the slug accounts for the increase in reactance that theory predicts for the long-neck orifice.

Steady Flow Regimes

Zorumski and Parrott[5] found for short-neck orifices that the instantaneous resistance is independent of frequency and is, therefore, equivalent to the flow resistance of the orifice. The flow resistance is defined as the ratio of the steady pressure drop across a material to the steady velocity through the material. Feder and Dean[6] also show a close correspondence between the acoustic and steady flow resistances in the presence of a grazing flow.

Short Neck

Using Fig. 4 as a basis for modeling the flowfields of a short-neck resonator, Fig. 6 presents schematics of the three flow regimes associated with one oscillation cycle. The flowfields of the steady inflow and outflow from the resonator closely approximate the instantaneous flowfields of the resonator due to an oscillatory flowfield, as seen in Fig. 4. Figure 7a shows a photograph of the flowfield for a typical inflow setting. In Fig. 7a the back cavity was filled with dye and the inflow is shown by the clear region near the top of the orifice. The streamline represented by the outer edge of the dye closely approximates the dye streamlines seen in Fig. 4 at $t = 0.122$ and 0.178 s. Therefore, the steady flow visualization confirms the earlier observations made by Zorumski and Parrott[5] for inflow to the orifice. Similar results occur for outflow.

Unfortunately, the streamlines associated with oscillatory flow near transition from inflow to outflow cannot be duplicated with a steady flow experiment. The advantage of oscillating flow visualization over that of steady flow can be seen by the sequence $t = 0.178$-0.312 s in Fig. 4. At $t = 0.178$ s, high-velocity inflow enters at the top of the orifice while a dead region occurs at the bottom. As time progresses the pressure drop across the orifice changes to a higher pressure on the left of the orifice than on the right (i.e., it favors outflow). The high-velocity jet regions cannot be immediately stopped and reversed. The dead region, however, can be more quickly accelerated to form an outflow. Thus there is an instant in the cycle where inflow exists on the top of the orifice and outflow exists on the bottom such that the net flow through the orifice is zero. Around this zero flow condition, a resistance-time (or net flow) history should be produced which is continuous. In effect, the two-dimensional quality of the dynamic flows will remove the discontinuity of resistance at zero through flow which was observed by Budoff and Zorumski[7] and Rogers and Hersh.[8]

Long Neck

The steady streamlines in a long-neck orifice do not match, in general, the instantaneous, dye-trace patterns in the same orifice under the conditions of an oscillatory flow. This is seen by comparing the dye traces in Fig. 7b, c, and d to the dye lines in Fig. 5. For relatively low inflow, as shown in Fig. 7b, the flow reattaches to the lower orifice wall. Consequently, the steady flow resistance measurement cannot be assumed equal to the instantaneous, oscillatory flow resistance. For the larger inflow rates (Fig. 7c and d), separation occurs in the long neck and the resonator back pressure is felt at the upstream entrance of the orifice. Under these conditions, the steady flow resistance might approximate the instantaneous inflow resistance.

The length at which an orifice can be considered long is not answerable with any certainty at the present time. However, to speculate, for an orifice to be considered long, it should be of sufficient length such that a standing vortex of the type shown in Fig. 7b could exist. Roughly, for a square orifice, the ratio of length to height should be equal to or greater than one for the vortex to occur.

Summary of Results

By means of colored dye traces, photographic sequences illustrate the detailed structure of an oscillating orifice flow with and without the presence of a grazing flowfield. Specifically, the following major results were found:

1) For flow into the resonator with grazing flow, the area of orifice flow blockage appears to be independent of orifice length for a fixed amplitude of flow oscillation and a fixed magnitude of grazing flow. For short-neck resonators, all the entering kinetic energy is dissipated in the resonator cavity; however, long-neck resonators return some of the entering kinetic energy back to the grazing flowfield. Therefore, the acoustic resistance may be a function of the L/D of the orifice.

2) As shown in the photographic sequences, at the crossover from inward to outward flow, flow simultaneously exits inward and outward in different parts of the orifice. Thus, no discontinuity in resistance will exist in an oscillating system when the average jet velocity approaches zero from either the inflow or outflow directions.

3) For long-neck resonators, the instantaneous fluid streamlines for oscillatory flow do not, in general, match the steady streamlines in the same orifice. Therefore, the acoustic and steady flow resistance do not necessarily correspond.

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