Experimental Investigation on Shape Dependence for Flow past Shallow Cavities

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Abstract. Relative motion between a bluff body having a cavity and the fluid surrounding it causes the fluid flow gets modified due to the presence of the cavity. The properties of flows past cavities are analysed, and various control techniques are devised and employed over the years. The present study aimed at experimentally analysing the flows and their features past three different shapes of cavities i.e., rectangular, hemispherical as well as triangular cavities under similar boundary conditions. The study consists of experimental investigation carried on cavities for similar length-to-depth ratios and the visualization of flow characteristics using a two-dimensional water channel apparatus. In this technique, the free surface of the water stream in the test-section is used in visualizing and analysing the flow characteristics including the formation of vortices, through dye injection, around cavities. The comparative study performed at varying Reynolds number for different cavities indicated the suitability of hemispherical cavities towards creating maximum amount of boundary layer suction.

1. Introduction

A cavity in a structure is a sudden depression of the surface below the level of the surface of the body. When there is relative motion between a bluff body having a cavity and the fluid surrounding it, the fluid flow gets modified due to the presence of the cavity. Flow past cavities gives rise to coherent self-sustained oscillations that cause undesirable aero-acoustic resonance. These aero-acoustic vibrations cause fatigue and eventually damage in structures if not contained within a reasonable limit. Weapon bays, landing gears and wheel wells of aircrafts, depression of ship and submarine hulls, sunroof of cars, closed side branches of pipelines, pantograph recess of high-speed trains and high-speed aircrafts experience fatigue due to aero-acoustic resonance of vibrations due to flow past cavities. Flows past cavities can also be observed in nature in places like the veins in cacti or the flow of wind through suburban structures.

1.1. Nomenclature

The following nomenclature is used throughout the paper.

\begin{align*}
  l & = \text{length of cavity} \\
  d & = \text{depth of cavity} \\
  H & = \text{height of internal cylindrical cavity} \\
  D & = \text{diameter of cylindrical cavity} \\
  Re & = \text{Reynolds number} \\
  M & = \text{Mach number}
\end{align*}
1.2. Properties of cavity flows

Properties of flow past cavities are affected by the length and depth of cavities, position from leading edge, shape of cavity, Reynolds number, Mach number, temperature, viscosity and relative velocity of the fluid and bluff body.

A supersonic flow over a single cavity is characterized by many features, for example, leading-edge and trailing-edge vortices in the cavity, the diffusion of momentum and turbulent dissipation in the shear layer, the shear layer impingement on the downstream face of the cavity, recompression of the flow, and oscillation. These features are likely to be influenced by Mach number, cavity geometry, and the state of the oncoming boundary layer [1].

Cavity flows are divided into three categories: open cavity flow, transitional cavity flow and closed cavity flow based on their aspect ratio, length-to-depth ratio ($l/d$). Open cavity flow ($l/d < 9$) occurs in elongated cavities where the free shear layer attaches to the floor of the cavity and recirculates in the opposite direction. Closed cavity flow ($l/d > 13$) is when the reattachment of shear layer does not occur. Transitional cavity flow ($9 < l/d < 13$) is an intermediate flow between the two above states and exhibits the characteristics of them both.

1.3. Mechanism

Boundary layer of thickness $\delta$ separates at the upstream edge of cavity of length $l$ and depth $d$ and it rolls up into vortices since it is unstable due to Kelvin-Helmholtz instability. Kelvin-Helmholtz instability arises due to layers of fluid moving with a velocity relative to one another. Here, the two layers being the free shear layer and the fluid moving at freestream velocity. When those vortical structures collide with the downstream edge, they result in vorticity distortion and result in expansion waves at low Mach numbers, compression waves at higher Mach numbers and wavy patterns for hypersonic flows.

The relative position of the travelling vortices and the position of downstream corners determine the strength of the waves induced due to the instability. The acoustic waves travel to the upstream corner of the cavity and influence the initial amplitude and the phase of the instability waves in the shear layer as any slight disturbance caused at the upstream corner of the cavity affects the properties of the resulting vortical structures. When the process is coupled with an acoustic cavity resonance, intense aerodynamic tones are generated. Cavity resonance occurs by the Helmholtz resonator mechanism as illustrated in Figure 1 [2].

![Figure 1. Mechanism of cavity flow [2].](image_url)
1.4. Vortex formation in internal cavities
The presence of cavities in a fluid flow bounded by a surface can cause large fluctuations in pressure, velocity and density. Internal flow cavity configurations occur in many engineering applications from segmented rocket motors to dump combustors. The Reynolds number of the flow influences the vortices that are formed within the cavity. The flow that is generated is affected by the cavity shape. In the case of cylindrical cavities, the flow characteristics depend upon the aspect ratio $H/D$ [3].

1.5. Control techniques
Control techniques can be divided as active and passive means. Active means are those that prevent the cause for the noise production whereas passive means are those that reduce the noise once it has already been produced. Control techniques can also be classified based on the location at which they are employed: leading edge, downstream edge and cavity floor.

1.5.1. Active techniques. These introduce wavy patterns of velocity fluctuation and a phase change of 180 degrees is introduced in the flow. Since the pressure variation and thus the sound produced will be 180 degrees out of phase, the resulting noise will be cancelled out far away from the source even though the noise generation at the source will not be reduced.

1.5.2. Passive techniques. These techniques work directly on the rolled-up vortices as opposed to the active control techniques that control the cavity flows by changing only the timing of vortex rolling up using less energy. The passive control of cavity flow has been done by either using a static plate or by introducing a blockage on the floor of the cavity. Resonance inside a cavity may be damaged due to the presence of a large plate covering the cavity. The upstream plate discourages the rolling-up process of the shear layer, while the downstream plate weakens the feedback loop. Whereas the latter involves suppressing the cavity noise generation by controlling the recirculating fluid motions inside a rectangular cavity. The vortices are destructed due to the blockage in the cavity floor.

1.6. Gaps in existing research
Multiple studies of individual cavities as well as cavities in tandem [Zhang et al., 1992] with different flow regimes have been performed. In addition to experimental studies, several computational studies have been performed to predict the vibration and acoustics associated with cavity flows for various Mach numbers in rectangular cavities [4-7]. The noise generated by circular cavities, was also investigated by Marsden et al. [8] and Chicheportiche et al. [9]. Heat and mass transfer [10]; as well as vortical flow features in a hemispherical cavity on a flat plate were also studied [11].

The existing studies discuss in detail about the several types of flows and their characteristics past various geometries but a study that compares different geometries of cavities under similar boundary conditions and aspect ratios hasn’t been extensively researched upon. The present study aims to experimentally analyse the flows and their features past three different shapes of cavities i.e., rectangular, cylindrical as well as triangular cavities under similar boundary conditions, having same...
aspect ratios that result in open, closed and transitional cavities. The cavities to be tested are designed as well as manufactured and the process is described in the paper. The study consists of experimental investigation carried on cavities for different $l/d$ ratios and the visualization of flow characteristics is performed using a two-dimensional water channel apparatus.

2. Methodology
The present study aims to experimentally analyse the flows and their features past three different shapes of cavities i.e., rectangular, hemispherical as well as triangular cavities under similar boundary conditions and having same aspect ratios specifically focused on the analysis of Open Cavity of different shapes. The visualisation technique used for the qualitative analysis of flow features past cavities is water channel. The design and manufacturing of the cavities as well as the apparatus has also been discussed.

2.1. Apparatus
The experimental setup consists of an in-house manufactured water channel used with a hydraulic bench at the Fluid Mechanics Laboratory at BITS Pilani, Dubai Campus. The qualitative analysis of fluid flow features is done using a dye-injection unit with a camera placed at isometric angles. The cavities to be tested are also designed and manufactured and the process explained in the following sub-sections.

2.1.1. Water channel. A water channel facility is used to study the characteristics of flow of water around the cavities. The water channel is designed using AUTOCAD and is manufactured using laser cut Acrylic sheets of 6mm thickness, joined using chloroform whose design and dimensions are shown in Figure 4, and the schematic and experimental arrangements depicted in Figure 5-6.

![Figure 4. Design of water channel.](image-url)
Figure 5. Schematic of experimental setup similar to the arrangement investigated by Khurana et al. [13].

Figure 6. Experimental setup.

- An inlet pipe containing water will carry water into the water chamber. This water will collect behind the inclined plane. When the water quantity exceeds the height of the inclined plane, the water will start spilling over the inclined plane gaining some velocity.
A 3-D printed mesh, as shown in Figure 7, provided just after the inclined plane will streamline the water flow into the test section. The mesh was designed using Autodesk FUSION 360 software with the required dimensions and printed using the Markforged 3-D printer at the Creative Laboratory at BITS Pilani, Dubai Campus.

![Figure 7. Design of mesh.](image)

2.1.2. **Dye injection system.** Dye injection is used as a method of surface flow visualization. The dye will be released only on the free surface of the water and a camera mounted on top of the test section will record the changes in flow taking place. The dye is released into the water flow through narrow holes along the length of the dye injection unit. Care is to be taken to minimize any flow field disruption by the dye. Hence, the velocity of the dye must be equal to the velocity of the water flowing in the water channel. The dye injection unit is manufactured in-house by drilling 120, 2mm holes into a PVC pipe of 30mm diameter. A pipe is connected to the inlet of the dye injection unit from a beaker containing dye.

2.2. **Test cavities**
The cavities to be tested were designed on Autodesk FUSION 360 software and printed using the Markforged printer at the Creative Laboratory at BITS Pilani, Dubai Campus. The following table outlines the dimensions of all the cavities regardless of their shape. This is done to enable the same aspect ratio ($l/d$) for all the geometries. The cavities designed are open cavities with an aspect ratio of $l/d = 3 (<9)$. A representative model of a rectangular cavity is depicted in Figure 8 with the details about the dimensions presented in Table 1. Similarly, the hemispherical and conical cavity

![Figure 8. Rectangular cavity with different parameters.](image)
Table 1. Dimensions for open cavities.

| Parameter       | Length of Cavity | Depth of Cavity | l/d | Front Relief | Rear Relief | Angle of Inclination | Vertical Height |
|-----------------|------------------|-----------------|-----|--------------|-------------|----------------------|-----------------|
| **Dimension**   | 80 mm            | 30 mm           | 3   | 35 mm        | 25 mm       | 20 degrees           | 50 mm           |

Figure 9. 3-D printed test cavities.

3. Results and Discussions
The present study was performed on three shapes of open cavities with aspect ratio of l/d = 3 at three different Reynolds numbers 9827, 14089, 22031 for 0 degrees of angle of attack with the flow direction. The calculation of $Re$ was done by measuring the velocity of the water stream by using the floating particle technique. The following table shows the readings for the calculation of $Re$. The experiment was recorded by video camera at 60fps and images were processed using a frame-by-frame analysis of the recordings.

3.1. Flow performance with variation in cavity shape

3.1.1. Case 1. The first set of observations for flow features of water past cavities was made at $Re$ = 9827 with water flowing at a velocity of 0.1093 m/s. The three cavities were placed in the water channel one by one and the features were recorded.
As observed from Figure 10, one large vortex develops in the bottom right corner of the circular cavity and causes suction of the boundary layer to the floor of the cavity. The boundary layer detaches from the bottom at half length.

Figure 11 depicts the development of two vortices in a rectangular cavity, one at each bottom corner of the cavity, causing significant suction of the boundary layer into the cavity. The boundary layer, however, does not touch the floor of the cavity at any point.
Figure 12. Triangular cavity at \( Re = 9827 \) (flow direction from left to right).

Two small vortices form in the conical part of the triangular cavity sucking in the boundary layer, which does not touch the floor of the cavity at any point as clear from Figure 11.

Figure 13. (a) Circular (b) Rectangular and (c) Triangular cavities at \( Re = 9827 \).

In comparing all three cavity shapes it is noted that the suction done by the circular cavity is the most, where it touches the floor of the cavity whereas in the case with rectangular and triangular cavities, it does not.

3.1.2. Case 2. The second set of observations for flow features of water past cavities was made at \( Re = 14089 \) with water flowing at a velocity of 0.1567 m/s. The three cavities were placed in the water channel one by one and the features were recorded.
Figure 14. Hemispherical cavity at $Re = 14089$ (flow direction from left to right).

With increase in $Re$, as seen from Figure 14, the large vortex originates at the bottom right corner of the cavity, extending till beyond the centre point of the circular cavity. The suction caused by the vortex causes the flow to attach to the floor of the cavity. The vortex diminishes, and the flow is completely attached to the floor of the cavity with time.

In the case of the rectangular cavity, as shown in Figure 15, increase in $Re$ leads to the increase in the size of the vortex that spans the entire length of the cavity floor. The suction caused by a rectangular cavity has decreased due to the increase in Reynolds number.

Figure 15. Rectangular cavity at $Re = 14089$ (flow direction from left to right).
In the case of the triangular cavity (Figure 16), the size of the vortices decreased with increase in Reynolds number thus causing limited suction to the flow as seen in Figure 15.

![Figure 16. Triangular cavity at Re =14089 (flow direction from left to right).](image)

In comparing the three different shapes of cavities the hemispherical cavity again causes the most amount of suction to the flow, whereas the rectangular cavity causes the least amount of suction to the flow.

3.1.3. Case 3. The third set of observations for flow features of water past cavities was made at Re =22031 with water flowing at a velocity of 0.2451 m/s. The three cavities were placed in the water channel one by one and the features were recorded.

As seen from Figure 18, in a hemispherical cavity, one vortex originates in the center of the floor of the cavity, diminishes in size and leads to the suction of the flow towards the floor of the cavity. In a rectangular cavity, as shown in Figure 19, the two vortices at the two corners of the cavity become larger than the previous case with Re =14089. In this case, the vortices diminish in size, causing the flow to come very close to attaching to the floor of the cavity at the center. In a triangular cavity at Re =22031, shown in Figure 20, instead of two distinct vortices as in the previous cases for triangular cavities, there is one vortex occupying the bottom of the cavity. There is significant suction of flow due to this large vortex, but the flow doesn’t attach to the floor of the cavity at any point.
Figure 18. Hemispherical cavity at $Re = 22031$ (flow direction from left to right).

Figure 19. Rectangular cavity at $Re = 22031$ (flow direction from left to right).
Figure 20. Triangular cavity at \( Re = 22031 \) (flow direction from left to right).

Figure 21. (a) Circular (b) Rectangular and (c) Triangular cavities at \( Re = 22031 \).

Comparing the three cavity shapes in Figure 21, the hemispherical cavity is the one that causes maximum suction of the flow causing the flow to attach to the floor of the cavity, followed by the triangular cavity and lastly the rectangular cavity with the flow not attaching to the bottom of the cavities.

3.2. Flow performance with variation in Reynolds number

3.2.1. Hemispherical Cavity. The observations at the three different Reynolds numbers showed similar flow features.

Figure 22. Hemispherical cavity at (a) \( Re = 9827 \) (b) \( Re = 14089 \) (c) \( Re = 22031 \).
There is only one vortex in each hemispherical cavity at all three Reynolds numbers and they collapse upon themselves in due time. With change in Re, the point of origin of the vortex shifts from the bottom right corner to the bottom center of the cavity. The shape and position of the vortices corroborates with the observation made by Olsman et al. [14] in a study that aimed to visualize flow features in a hemispherical cavity on an airfoil.

3.2.2. Rectangular Cavity. The flow features past a rectangular cavity at different Re remained similar in shape and position. It can be seen in Figure 24, that there were two vortices at both the corners of the cavity with a narrow region along the base of the cavity. The size, however, increased with increase in Re.

The observation of the shape agrees with the observations made by Ortega et al. [15] in a numerical study over shallow cavity.

**Figure 23.** Flow visualization in the (a) water channel and (b) the numerical simulation of vorticity contour plot for the airfoil with a cavity at Re = 20000 [14].

**Figure 24.** Rectangular cavity at (a) Re = 9827 (b) Re = 14089 (c) Re = 22031.

**Figure 25.** Streamlines for the typical cavity l/d = 8 (open cavity) [15].
3.2.3. Triangular Cavity. The shapes and positions of vortices past triangular cavities varied to a small extent with change in \( Re \). However, with increasing \( Re \) the vortices became less defined as can be observed from Figure 26. In all cases, two vortices existed at the bottom of the cavity, one bigger compared to the other.

![Figure 26](image)

**Figure 26.** Triangular cavity at (a) \( Re =9827 \) (b) \( Re =14089 \) (c) \( Re =22031 \).

4. Conclusions and the way forward

An experimental investigation was performed for open cavities for three different shapes, namely hemispherical, triangular and rectangular, for the same aspect ratio, at three different Reynolds number, and a comparative performance provided significant insights into the suction created for the flow over shallow cavities, with the hemispherical cavity appearing demonstrating the maximum amount of suction created. The results from the current study were corroborated for hemispherical and rectangular cavities from previous works.

For the next step, the authors aim to study the effect of angle of attack with the freestream direction on the flow features around the current open cavities in consideration, followed by conducting a comparative investigation on closed cavities.

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