Study on the Influence of Grilles on the Flow-Noise Generated by the Cavity

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Abstract. The two kinds of cavities, respectively with opening hole and slotted hole, numerically simulated based on the theory of large eddy simulation and acoustic analogy were performed. Firstly, according to the differences between vorticity and pressure magnitude contours of the flow filed around the slotted hole and opening hole, the influences on the flow field of the baffles were illustrated. Secondly, by analysing the power spectrum density of the monitoring points, the main noise source of these two models was found. Lastly, the flow-noise frequency spectrum of slotted hole and opening hole indicated that the grilles play an significant role in reducing the radiation of the flow-noise generated by the cavity with hole.

1. Introduction
Flowing over cavities is often a source of pure tone noise, it has been studied by many investigators. Xu Jun, Li Xiao-dong, Liu Cong-wei and Chen Can studied on the control of cavity flow tone by adding a plate in the cavity, altering the thickness of the boundary layer, changing the bottom slope of the cavity and the length to depth ratio [1-4]. In underwater vehicles, the use of slats is a common control strategy to improve the acoustic radiation. Zhang Nan concluded that the resistance performance caused by the baffles is better than by the longitudinal holes [5]. S Arunajatesan brought forward that the presence of the grilles obstruct the vortex to the cavity, but had little impact on the control of fluctuating pressure inside the cavity [6]. Dai Shao-shi et al pointed out that the fluid pattern is more complex, and the fundamental frequency of the first model of the shear layer increases due to the existence of the grids [7]. Xiao Zhi-xiang concluded that the grilles can decrease the thickness of the shear layer, restrain the fluctuating force and reduce the far field sound radiation intensity [8]. The flow field and acoustic field of the cavity with opening hole and slotted hole will be simulated in this dissertation, then between the two situations the difference of the SPL spectrum and the flow field force will be analyzed to study the mechanism of the grill influence the sound generation and radiation.

2. Model of cavity with two kinds of holes
A schematic of the cavities are shown in figure 1 and figure 2, the length, width and depth of the cavities are L=400mm, W=300mm, H=500mm, while the length and width of the holes are L_{hole}=300mm, W_{hole}=200mm, and the height of the hole neck is H_{hole}=20mm, which can be classified as deep cavity, according to the classification criteria put forward by Sarohia [9]. The computational domain is shown in figure 3, which extends over 5000mm×1800mm×1500mm. The upstream and side boundaries are respectively 2000mm and 900mm far away from the center of the hole.
The software Solidworks was used to modelling, then the model was imported into ICEM CFD to mesh. The meshes and the boundary conditions of the cavity are shown in figure 4 and figure 5, the CFD meshes include 2307220 meshes and 1676229 meshes of the cavity with opening hole of non-uniform size. The first layer scale near the wall was 0.05mm in order to catch the viscous stress change. In view of the distribution of the flow field parameters, the much coarser mesh size can be used in the places away from the hole. At the inlet boundary, a uniform normal velocity was defined with $u=10\text{m/s}$, whereas the outflow boundary condition was used with a relative pressure $p_{\text{ref,static}}=0\text{Pa}$ at the outlet. Along the solid walls, the non-slip condition was applied to the cavity wall, and the free-slip condition was imposed to the other walls.

The calculation was carried out in Fluent, containing the simulation of flow field and acoustic radiation. In the calculation, LES module was firstly used, FW-H acoustic module was set to perform the computation of sound radiation until the flow field is stabilized. In order to facilitate the analysis of the simulation results, serials of monitor points, receiver and slice which were assigned to detect the pressure changes on the wall of cavity and holes, pick up the sound pressure of the sound field and display the vorticity and pressure counters of the field are shown in figure 1 and figure 2.
3. Results and discussion

3.1. Flow field results
The diagram of three-dimensional steady streamline of the cavity with slotted hole was shown in figure 5. Due to the baffles function, the velocity of the flow was significantly reduced when flowing through the grid, and the fluid outside the grid area was not obviously affected. The diagrams of two-dimensional steady streamline on xOy slice of the two kinds of cavities are shown in figure 7 and figure 8. The velocity of the fluid flowing through the hole into the cavity was lower than the fluid outside the cavity. Only two eddies are found around the opening hole, both are near the rear wall of the opening hole. While the vortices are formed between each of two baffles and the rear wall. It indicates that the grids result in more vortices structure generation, which means that the baffles make the flow field more complex. Points A–E are the velocity monitoring points during both the simulation of two cavity models, the velocity of these points are shown in table 1. It obviously shows that the velocity of the slotted hole monitoring points are smaller than the points of the opening hole.

| Table 1. The velocity of monitoring points A–E. |
|-----------------------------------------------|
|                                              |
| A, B, C, D, E                                |
| Opening (ms⁻¹)                               |
| 5.7, 5.1, 3.8, 5.3, 8.1                      |
| Slotted (ms⁻¹)                               |
| 5.2, 4.1, 3.1, 4.7, 3.6                      |

One period of velocity invariant Q contours of the slotted hole is shown in figure 9, velocity invariant Q is used to display the vorticity distribution of the slotted cavity. As the fluid flowing through the grilles, the boundary curvature mutation caused by the existence of hole leads to the flow separation, a series of vortices are generated in the first grid hole. As the vortices moving backward and collapsing with the baffles, the vorticity magnitude is increased and the vortices structures
continue migrating to the downstream, until the vortices move to the last grid hole. The vortices collide with the rear wall of the hole, and derive from the hole, then gradually annihilate in the flow field. In the upstream, the vortices generated by the flow separating and collision is drove to the downstream to supplement the vortices in the downstream, which results in the repeated process of generation, motivation, collision and annihilation. It can be saw from the figure 9 that the vortices migration process is mainly from the top edge of the baffles, because the low speed fluid in the cavity and the acoustic feedback caused by the collision cannot decelerate the fluid outside the cavity to make the fluid move inside the cavity. Only a handful separated vortices caused by the collision motivates into the cavity and blends with the low speed fluid existed in the cavity.

![Figure 9](image.png)

**Figure 9.** One period of velocity invariant Q contours of the slotted opening.

### 3.2 Pressure analysis

The pressure distribution contours of the slotted hole in one period are shown in figure 10. The region of high and low pressure varies with time. As shown in figure 11, the pressure time sequence of the monitoring points 1~20 in one period illustrate that the cycle of each point is approximately the same, around 0.033s, while the phase between the points are slightly different.

In the process of the vortices motivation, the different phase between the points may be caused by the concentration of the vortices. On the one hand, the acoustic feedback and vortices collision with the baffle will cause the vortices to move toward the upper or lower edge of the baffle. The pressure of the center of the vortices is descended, due to the centrifugal action of vortex motion, therefore when the vortices concentrates on the different region, then the pressure will be descended. When the vortices collapses with the baffle may cause the vortices separating into two parts, one will flow over the upper edge of the baffle and the other one will be drove into the cavity. The pressure of the monitoring point will be at a low value approach to the upper (lower) edge of the baffle and the pressure of the upper (lower) monitoring point will be at a low value, when the vortices concentrates on the upper (lower) edge of the baffle. On the other hand, as the vortices motivates from the upstream to the downstream, the vortices will concentrate at each grid hole successively as time goes by. Once the vorticity concentrates in a grid hole, the pressure of this region will be decreased, and the pressure of the other region will be at a relatively higher value.
Figure 10. One period of pressure distribution contours of the slotted hole.

Figure 11. Pressure time sequence of the monitoring points.

The pressure power spectrums density of the monitoring points of the two kinds cavities are shown in figure 12 and figure 13, the values of the opening cavity are significantly higher than the slotted cavity. The main frequencies of the variant points are basically the same, with the fundamental frequency 17.5Hz of the opening cavity, and the fundamental frequency 30Hz and the second order frequency 59.99Hz of the slotted cavity. As shown in the figure 13, the value of the power spectrum density of the variant points is higher, as the location of the point is closing to the downstream, where the value of point 19 on upper edge of the rear wall of the hole is the highest. It is caused by the increasing vorticity magnitude, which resulted from the generation, motivation and collision with more baffles of the vortices.

Figure 12. The diagram of pressure power spectrum density of the monitoring points of the opening cavity.
Figure 13. The diagram of pressure power spectrum density of the monitoring points of the slotted cavity.

3.3. Acoustic analogy

The flow-induced noise frequency spectrum of slotted hole and opening hole is shown in figure 14. It indicates that as the baffles installed to the opening hole, the fundamental frequency increases from $f_{ol} = 17.5\, \text{Hz}$ to $f_{ol} = 30\, \text{Hz}$, and the SPL of the slotted hole model at the fundamental frequency of $30\, \text{Hz}$: $124.2\, \text{dB}$, is lower than the SPL of the opening hole model at the fundamental frequency of $17.5\, \text{Hz}$. Due to the existence of the baffles, the stroke between fluid and the cavity is cut from $300\, \text{mm}$ to $60\, \text{mm}$, therefore the period of the vortices motivation is shortened, and the fundamental frequency is increased. The velocities of the five points of the slotted cavity are significantly decreased by the baffles compared to the model of cavity with opening hole, which results in the excited force between fluid and baffles reducing, and furthermore makes the SPL at the fundamental frequency reduced. For the problem of the flow over the open cavity of an underwater structure, a semi-empirical formula by Rossiter can be used, where the frequency is obtained as [10].

$$f_n = \frac{U_\infty}{L_{hole}} \left( M_\infty + \frac{1}{k} \right)^{\frac{n-\alpha}{\nu}}$$

where $U_\infty$ is the velocity of the far field fluid, $L_{hole}$ is the stream direction scale of the cavity hole, $M_\infty$ is the Mach number, $\alpha = 0.25$ and $k = 0.57$. Using the above equation, the fundamental frequency of the opening hole is $f_{ol} = 14.29\, \text{Hz}$, at $L_{hole} = 0.3\, \text{m}$, $U_\infty = 10\, \text{m/s}$ the result of the calculation

Figure 14. The flow-noise frequency spectrum of the cavity with slotted hole and opening hole.
$f_{os1} = 17.5\text{Hz}$ is closed to $f_{os} = 14.29\text{Hz}$, while the fundamental frequency of the slotted hole is $f_{os} = 70.98\text{Hz}$, $L_{sh} = 0.3\text{m}$, $U_{in} = 10\text{m/s}$, the result of the calculation $f_{os} = 30\text{Hz}$ is far different from $f_{os} = 70.98\text{Hz}$. The reason for the case of the Rossiter formula does not apply to the slotted hole model is that the presence of the baffles destroy the effect of acoustic feedback.

4. Conclusion

(1) The presence of the baffles can decrease the velocity of the fluid, can be reduce the fluctuating force between the fluid and the wall, and play a salient role in controlling the flow noise radiation generated by the cavity with hole.

(2) The upper edge of the rear hole wall and the up-water surfaces of the baffles are the main source of the flow noise generation, therefore, the chamfer or fillet should be performed in engineering.

(3) The flow field near the slotted hole is much more complex than the flow field near the opening hole. Rossiter formula is only suitable to the prediction of the simple flow field. Rossiter formula can be used to predict the fundamental frequency of the model of the cavity with opening hole, but can not be applied to the model of the cavity with slotted hole.

Reference

[1] Xu J, Tang K F and Zhang X 2014 Chinese J. Hydrodyn. 29(05) 618-29.
[2] Li X D, Liu J D and Gao J H 2006 Chinese J. Theoretic. Appl. Mech. 38(5) 599-604.
[3] Liu C W, Wu F L, Li H, Peng Y L and Li W P 2014 Chinese J. Hydrodyn. 29(2) 218-24.
[4] Chen C, Wu F L, Li H, Zhang Z G and Liu C W 2015 Chinese J. Hydrodyn. 3 272-8.
[5] Zhang N, Shen H C, Yao H Z, Gao Q X and Gu M 2004 J. Ship Mech. 8(01) 1-11.
[6] Arunajatesan S and Sinha N 2005 Modeling Approach for Reducing Helmholtz Resonance in Submarine Structure. 11th AIAA/CEAS Aeroacoustics Conference.
[7] Dai S S, Yao X L, Yang G J and Li Z. 2010 J. Vibr. Shock, 29(04) 207-12.
[8] Xiao Z G and Zhu J G 2015 Study on the influence of grilles on cavity noise. The Chinese Congress of Theoretical and Applied Mechanics.
[9] Sarohia V 1977 AIAA J. 15(7) 984-91.
[10] Rossiter J E. 1964 Aeronaut. Res. Council Rep. Memoranda, 3438 8-12.