Self-excited oscillation study in grille-cavity flow on floating nuclear power platform

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Abstract. In order to investigate the self-excited oscillation characteristic of flow past the inlet and outlet of cooling water systems on floating nuclear power platform, a numerical study in grille-cavity flow with suction and drain is carried out. A back pressure condition is set on the side wall of the cavity to simulate the suction and drain conditions. By varying the incoming flow boundary layer thickness and back pressure value, the self-excited oscillation characteristic in grille-cavity flow with suction and drain is studied. As calculations show, the boundary layer thickness has little influence on the oscillation frequency. The strength of self-excited oscillations gradually decreases with the decrease of back pressure, but the frequency does not change much. When the back pressure reduces to a critical value, the self-excited oscillation phenomenon disappears finally.

1. Introduction

Cooling water system inevitably exists in new energy and future energy systems, such as floating nuclear power platform. The inlet and outlet of the system can be regarded as a grille-cavity structure. As the fluid flows past the suction and drain hole, the flow can be seen as the viscous flow problems over a grille-cavity with suction and drain. The oscillation is generated by the self-excitation of the flow system, and is called self-excited oscillation. From the engineering point of view, when self-excited oscillation occurs, it may cause flow obstruction at the inlet and outlet, and may also cause a series of problems such as structure vibration and noise, so the research has important practical value.

The self-excited oscillation problem of the shear layer can be traced back to the study of Krishnamurty [1] and Roshko [2]. They found that the cavity flow does not require an external excitation source, and self-sustained oscillation occurs. Rockwell [3] divided the flow into three forms according to the reason of the flow induced cavity oscillation: hydrodynamic oscillation, fluid-acoustic coupled oscillation and fluid-elastic coupled oscillation. Rossiter [4] proposed a fluid-acoustic resonance feedback model for cavity oscillation, and a semi-empirical formula for estimating the oscillation frequency is given. Based on the linear feedback loop model, Kook and Mongeau [5] established a nonlinear feedback loop model for the self-excited oscillation of the cavity flow to predict the oscillation frequency and amplitude.

Summarizing the research results of the predecessors, there are four important steps in the formation of the self-excited oscillation of the shear layer: 1) The separation point produces an ordered forward disturbance propagating in the direction of the main flow. This disturbance mainly refers to the ordered vortex generated by the separation of the free shear layer. 2) The vortex has an impact on the impact point. 3) Propagation of reverse disturbances. The reverse disturbance, that is, the...
disturbance whose propagation direction is opposite to the main direction, has three main sources, one is the reverse flow disturbance caused by the vortex motion (fluid dynamic disturbance), and the second is the reverse pressure wave generated by the vortex impact (acoustic disturbance), the third is the disturbance caused by the action of the fluid and the elastic wall (elastic wall disturbance). 4) The gain effect of the reverse disturbance on the disturbance of the separation zone. In the low Mach number flow, the fluid flow velocity is much smaller than the local sound velocity. The influence of the pressure wave caused by the vortex impact on the flow field oscillation is negligible. The reverse disturbance is mainly the fluid dynamic disturbance. Self-excited oscillation phenomenon caused by such reverse disturbance is studied in detail. When the reverse disturbance is transmitted to the flow separation region, it is coupled with the forward disturbance of the separation region, and the forward disturbance is amplified, so that the entire flow field continues to oscillate. Therefore, the reverse disturbance is the direct cause of the self-excited oscillation of the flow field.

The study of grille-cavity flow is relatively late. Rockwell et al [6-11] conducted a series of studies on this issue. At the beginning, Rockwell [6] used the PIV method to study the shear layer oscillation along a perforated surface under laminar flow conditions in the water tunnel, and observed the phenomenon of self-excited oscillation. Subsequently, Ozalp et al [7] conducted a more detailed study of the problem. On the basis of Rockwell, turbulent flow is used instead of laminar flow. The experimental results show that under the condition of turbulent flow, the self-excited oscillation of the flow field can also be formed near the perforated plate. Ekmekci and Rockwell [8] first studied the grille-cavity flow. It is shown that it is difficult to form a rolled shear layer in the flow field due to the obstruction of the grille structure, but there is still obvious self-excited oscillation in the flow field. Celik and Rockwell [9] believe that the flow on both sides of the perforated plate has a coupling effect, and the outer disturbance propagation along the main direction is closely related to the cavity flow inside the plate. For the first time, they analyzed the circulation in the cavity and found large-scale vortexes formed in the cavity, but the direction of motion was opposite to that of classical cavity flow (without a perforated plate). In the cavity with a perforated plate, the direction of flow inside the plate is opposite to the main flow, so it is called reverse flow. This reverse velocity pulsation allows the disturbance to propagate through the gap and is closely related to the propagation of disturbances on the outside of the plate. Sever and Rockwell [10] again set the study object to grille-cavity flow. Under different grille lengths and inflow conditions, the Strouhal numbers of the oscillation are all about 0.5. They believe that this oscillation is caused by the Kelvin-Helmholtz instability. The study done by Celik, Sever, and Rockwell [11] compared the cavity spoiler characteristics with a perforated plate and a grille cover, and studied the effect of cover thickness on the self-excited oscillation characteristics of the flow field. By comparison, it is found that the flow field near the two kinds of cover plates exhibits the same oscillation characteristics when the flow state and the geometric parameters are similar. They suggested that the strength of the reverse flow inside the cover can be used to measure the strength of the self-excited oscillation. When there is a strong self-excited oscillation in the flow field, an apparently ordered reverse flow occurs inside the cover plate. When the self-excited oscillation is not obvious, there is no obvious reverse flow inside the cover Zhang et al [12] studied the critical conditions of self-excited oscillation of the grille-cavity flow. It is believed that the length-to-height ratio of the grille spacing plays a major role in the transition of the flow state. As the aspect ratio increases, the flow becomes easier to enter the self-excited oscillating state.

However, the inflow and outflow fields are not introduced into the cavity of the grille-cavity flow of the above study, but the problem is widespread in the inlet and outlet structure of the cooling water system in ship and other offshore structure. Therefore, based on the analysis of the self-excited oscillation characteristics of the grille-cavity flow, the relationship between the intensity of suction and drain in the cavity and the self-excited oscillation is further explored.

2. Simulation case
In this paper, the medium is simulated as water, and the problem of self-excited oscillation of the grille-cavity with cooling water inlet and outlet is studied.
Simulation domain

The existing research show that the main difference between the two-dimensional and three-dimensional simulation results is reflected in the identification of low-frequency oscillation components [13]. When considering the effect of the span length, the model can reflect the flow period of the span, which is much larger than the self-excited oscillation period of the cavity, not caused by the self-oscillation of the flow field. Despite this, many studies have shown that the use of two-dimensional simulation methods can still reflect the main features of the self-oscillation phenomenon of the cavity [14-17]. Therefore, the grille-cavity flow in this paper uses two-dimensional simulation.

The grille-cavity flow simulation domain consists of three parts: the incoming fluid domain (upper part), the grille channel (middle) and the cavity flow domain (bottom). As shown in figure 1, the fluid of the incoming fluid domain and the cavity flow domain can exchange each other through the grille passage, and the right side of the cavity flow domain is the inlet and outlet passage of the cooling water system. The grille channel has a length of 1 m, a grille height of 50 mm, a width of 6 mm and a spacing of 50 mm. It is specified that the flow direction is the x direction and the vertical direction is the y direction.

![Simulation domain diagram](image)

**Figure 1.** Simulation domain diagram.

Simulation method

According to the grille-cavity flow characteristics, the core of the study is the shear layer oscillation and the near wall flow. According to this, the SST k-ω model with good adaptability to the shear layer and near-wall flow is selected.

Boundary condition

Inlet: In cavity flow studies, the boundary layer is generally characterized by an inflow boundary layer at the leading edge of the cavity. In this paper, the study of the influence of boundary layer thickness requires different boundary layer velocity distributions at the leading edge. Therefore, the method is adopted to set different thickness turbulent boundary layers at a certain distance upstream of the leading edge of the cavity, so that the velocity distribution of different boundary layer thicknesses at the downstream development is made. The turbulent boundary layer velocity profile is given at the inlet using a 1/7 power law [18], ie:

\[
V = \begin{cases} 
V_\infty (y / \delta)^{1/7} & 0 < y < \delta \\
V_\infty & \text{else}
\end{cases}
\]

Where A is the inflow velocity and B is the boundary layer thickness.

Outlet: Set to the pressure outlet boundary condition and set the pressure to 0.
System inlet and outlet: Set to the pressure outlet boundary condition as the back pressure. The rest is set as no slip wall.

- Mesh construction

![Meshing diagram](image)

**Figure 2.** Meshing diagram.

Due to the shape of the simulation domain is simple, the quadrilateral is used for meshing. As shown in figure 2, the flow field changes in the upper and lower parts of the calculation domain are small, and the mesh size of the area is large. The flow state near the grille and its upstream and downstream shear layer is complex, and it is the area we are most concerned about, thus the area is mesh-encrypted. The minimum mesh size in this area is $1 \times 10^{-4}$ m which is about one percent of the thickness of the boundary layer and considered that the calculation accuracy requirements are met.

- Monitoring position

Simulation results of typical locations are monitored. As shown in figure 3, three monitoring points (the middle, the end and the wake point of the grille) and 20 lines were set during calculation. Set the leading point is the coordinate origin, the Pm coordinate of the middle point of the grille is $(0.475, 0.025)$, the Pe coordinate of the end point is $(0.975, 0.025)$ and the Pw of the wake point is $(1.5, 0)$. The monitoring line is placed at the vertical centerline of the grille spacing.

![Monitoring position diagram](image)

**Figure 3.** Monitoring position diagram.

- Time step

The size of the time step directly affects the accuracy and time cost of the numerical results. Since the full implicit calculation is used, the selected time step can satisfy the following conditions: in the flow complex region, the CFL number of the calculation result is not more than 20-40. The CFL number expression is:

$$CFL = \frac{\mu \Delta t}{\Delta x}$$

Whether the grille-cavity flow calculation is accurate depends mainly on whether the shear layer and grille interaction are simulated accurately. The mesh size near the grille is $A$. Simulation cases cover the incoming flow velocity of three values, which are 2.5, 5 and 10 m/s respectively, so the time
steps of the corresponding cases are $1 \times 10^{-3}$ s, $5 \times 10^{-4}$ s, and $2.5 \times 10^{-4}$ s.

- Nondimensionalization

The following analysis are nondimensionalized by incoming dynamic pressure $\frac{\rho v_0^2}{2}$, velocity $v_0$ and cavity length $L$. The main dimensionless parameters are expressed as:

$$C_p = \frac{p - p_0}{\rho v_0^2 / 2}, \quad St = \frac{f L}{v_0}, \quad T = \frac{t}{L / v_0}$$

3. Self-excited oscillation

In order to analyze the self-excited oscillation characteristics of the grille-cavity flow, the incoming velocity is set as 5 m/s, the system inlet and outlet are set to the wall surface and the thickness of the boundary layer is 0.01 m. From the pressure oscillation analysis (time-domain and frequency-domain analysis) of different monitoring points, the self-excited oscillation is analyzed, as shown in figures 4-6.

As shown in figure 4, a first-order frequency $St$ and its double frequency appear at middle point,
and the first-order frequency dominates, called the dominant frequency, and the corresponding dimensionless pressure oscillation amplitude is 0.25. As shown in figure 5, the dominant frequency \( St_1 \) also appears at end point. The dominant frequency corresponds to an amplitude of about 0.3. As shown in figure 6, wake point also has the dominant frequency and its double and triple frequency, and the dominant frequency corresponds to an amplitude of 0.27.

Comparing the dominant frequencies of the three monitoring points, the values of the three are very close, and the amplitude of the end monitoring points is the largest, the trailing points are second, and the central points are slightly weak. It can be seen that the grille-cavity flow exhibits a strong self-excited oscillation, which is characterized by: the oscillation frequency of each position is the same and three obvious peaks appear, and the oscillation amplitude increases first and then decreases along the flow direction.

4. Influence of boundary layer thickness
The shear layer K-H instability also causes the shear layer to oscillate. Under laminar flow conditions, the frequency has the following relationship with the momentum thickness of the boundary layer.

\[
St = \frac{fL}{V_w} = St_n \cdot L / \theta, \quad St_n = 0.064
\]

Where the dimensionless frequency \( St_n \) based on the boundary layer momentum thickness is a constant. As seen from above expression, the natural oscillation frequency is inversely proportional to the thickness of the boundary layer.

As shown in figures 7-10, the effect of boundary layer thickness on the characteristics of self-excited oscillation is analyzed in this section. Since the inlet boundary condition is a velocity inlet, the boundary layer thickness can be directly set as 0.005, 0.01, 0.02 and 0.03 m.

![Figure 7. Pressure oscillation at 0.005 m BL thickness.](image1)

![Figure 8. Pressure oscillation at 0.01 m BL thickness.](image2)
Combining the above results, figure 11 can be obtained as shown below.

**Figure 9.** Pressure oscillation at 0.02 m BL thickness.

**Figure 10.** Pressure oscillation at 0.03 m BL thickness.

It can be seen from figure 11 that the thickness of the inflow boundary layer is not related to the frequency and amplitude of the self-excited oscillation. However, the oscillation caused by the K-H instability of the free shear layer is directly related to the thickness of the boundary layer, indicating that the association between the self-excited oscillation of grille-cavity flow and the free shear layer instability oscillation is small.

5. **Influence of back pressure**

The self-excited oscillation characteristics of the grille-cavity flow have been described above. Considering the actual engineering problem, the inlet and outlet of the cooling water system are installed in the cavity. Therefore, this section sets the back pressure at the inlet and outlet, simulates the function of the cooling water system pump, and focuses on the influence of the inlet and outlet back pressure on the self-excited oscillation characteristics of the grille-cavity flow.
In order to analyze the influence of back pressure, the incoming velocity of this example is fixed at 2.5 m/s, the boundary layer thickness is set as 0.01 m, and the system inlet and outlet back pressure is gradually reduced from 1000 Pa to -1000 Pa.

The self-excited oscillation characteristics of the grille-cavity flow under different back pressures are given below, as shown in figures 12-18.

**Figure 12.** Pressure oscillation at 1000 Pa back pressure.

**Figure 13.** Pressure oscillation at 500 Pa back pressure.

**Figure 14.** Pressure oscillation at 300 Pa back pressure.

**Figure 15.** Pressure oscillation at 200 Pa back pressure.
Figure 16. Pressure oscillation at -50 Pa back pressure.

Figure 17. Pressure oscillation at -200 Pa back pressure.

Figure 18. Pressure oscillation at low back pressure. (a)-500 Pa and (b)-1000 Pa.

Figure 19. Pressure oscillation at different back pressure.
Based on the above figures, figure 19 can be obtained.

As can be seen from figure 19, when the back pressure is greater than -50 Pa, the oscillation frequency is stable between from 0.35 to 0.5, but the oscillation amplitude decreases with the decrease of back pressure; when the back pressure is reduced to -200 Pa, two oscillation frequency peaks appear in the flow and the amplitude of the oscillations are decreased to about 0.12; when the back pressure is further reduced, the self-excited oscillation phenomenon disappears.

To find out why the oscillation disappears, the velocity field of the flow is studied. The relationship between the reverse velocity and the self-excited oscillation is shown in the flow velocity distribution of the flow field as shown in figure 20.

![Figure 20. Streamwise velocity contour at different back pressure. (a)-50 Pa, (b)-200 Pa, (c)-500 Pa and (d)-1000 Pa.](image)

As figure 20(a) shows, when back pressure is -50 Pa, the reverse velocity value is close to the inflow velocity, and an ordered large-scale reverse flow channel appears below the grille. At this time, the flow field exhibits a strong self-oscillation phenomenon.

As figure 20(b) shows, when back pressure continues to reduce to -200 Pa, the reverse velocity value is still close to the inflow velocity, but two independent large-scale reverse flow channels appear below the grille, with two dominant frequencies appearing along the flow field.

Finally, as shown in figures 20(c) and 20(d), when back pressure is reduced to below -500 Pa, the reverse velocity value is significantly smaller than the inflow velocity, and there is no ordered large-scale reverse flow channel. At this time, the flow field does not exhibit self-excited oscillation.

In short, when the grille-cavity flow exists in the system inlet and outlet, as the back pressure of the inlet and outlet of the system decreases, the oscillation intensity gradually decreases under the premise that the self-excited oscillation frequency is basically unchanged. When it is reduced to a certain value, the self-excited oscillation phenomenon disappeared.

6. Conclusions

Through the above study, we can draw the following conclusions:
- When the self-excited oscillation occurs in the grille-cavity flow, the self-excited oscillation frequency of different monitoring positions is the same, and a dominant frequency with its
double and triple frequency appear at each position, and the oscillation amplitude increases first and then decreases along the flow direction.

- The thickness of the incoming boundary layer has little relationship with the self-excited oscillation characteristics, as the oscillation frequency accompanying the K-H instability of the free shear layer is inversely proportional to the thickness of the boundary layer, indicating that the self-excited oscillation is not directly related to the oscillation caused by the instability of the shear layer.
- The system inlet and outlet back pressure can significantly change the characteristics of the self-excited oscillations. As the back pressure decreases, the strength of the self-excited oscillation gradually decreases, but the frequency does not change much. When the back pressure is reduced to a critical value, the flow field no longer exhibits self-excited oscillation.

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