# ACOUSTIC MODE ANALYSIS OF ENCLOSE FLUID WITH INTERNAL FLEXIBLE STRUCTURE

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The vibro-acoustic coupling of enclose fluid with internal flexible boundary is studied using strong-interaction method. By changing the thickness of the flexible structure, a curve which describes the relationship between acoustic mode frequencies and structure parameter can be found. Further-more, acoustic mode frequency of enclose fluid is studied with opening in the internal flexible structure. The hole will make the modal frequency greatly reduced. With the opening area increasing, the modal frequency will gradually converge in the case of no baffle plate. The position and shape of the opening has little effect on the fluid modal frequency. The study will provide references for optimization design and numerical boundary selection of cavity structure as well as water tank.
Keywords: enclose fluid, flexible structure, acoustic characteristic

## 1. Introduction

Fluid tank is one of the most common structures in the ship, such as oil tank, water tank, etc. Most scholars [1-3] focus on the influence of the structural dynamic characteristics when the liquid filled in the tank. Scholz[4] and Gabbai[5] research the numerical method to solve the fluid-solid coupling problem. In practice, with a structure, fluid flow characteristics will also change, and the fluid modal frequency and vibration mode will change too. When hull subjected to mechanical equipment or fluid incentive, structure vibration and noise will increase at the frequency near the structure natural frequency[6]. Similarly, the hull vibration noise maybe increase significantly when fluid resonance occurs. Therefore, in order to suppress the vibration of the tank, to reduce the vibration noise, it is necessary to change the fluid natural frequency through the optimization design of the tank structure or changing the fluid movement.

This paper is focus on the modal characteristics of fluid tank with a flexible baffle plate. The influence on the hydrodynamic characteristics of the thickness of the plate, the size of the opening, the position and the shape of the hole was studied. The result can be used in optimization of the tank and the change of the fluid natural frequency.

## 2. Structure model

In order to simplify, the modal characteristics of the fluid in the presence of rigid baffles are studied firstly. The geometric model is given in Fig.1. Three cases are mainly studied, one is no baffle plate, the second has an *x*-direction plate, and the third has a *y*-direction plate.

The length, width and height of the water tank are $l$=8m, $h$=3m and $b$=2m. The mass density and sonic velocity of the water are $\rho_f$=1000kg/m$^3$ and $v_f$=1450m/s. To avoid the influence of the dynamic response of the tank structure, assuming the face of the tank is thick enough, thus the boundary of water can be treated as rigid. For a simple rectangular flow channel, the modal frequency of the fluid has an analytical solution as shown in Eq. (1).

$$f_{n_x n_y n_z} = \frac{c_0}{2}\sqrt{\left(\frac{n_x}{l}\right)^2 + \left(\frac{n_y}{b}\right)^2 + \left(\frac{n_z}{h}\right)^2} \quad (1)$$

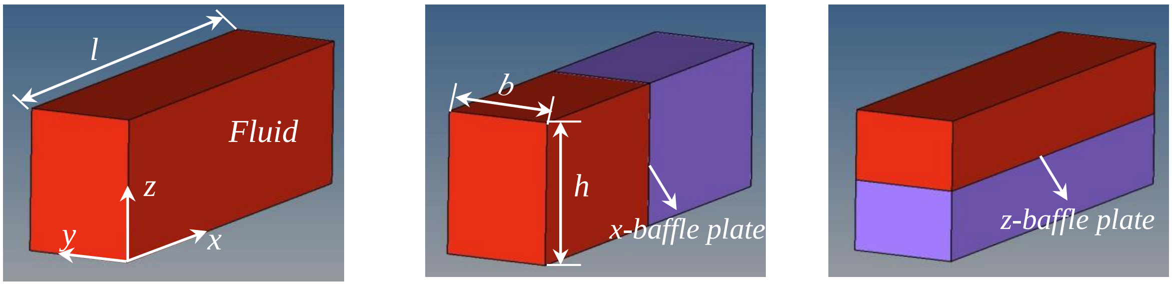
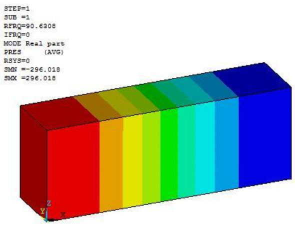
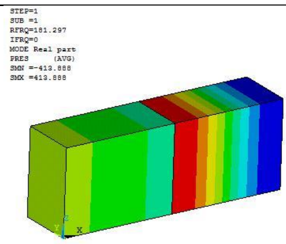
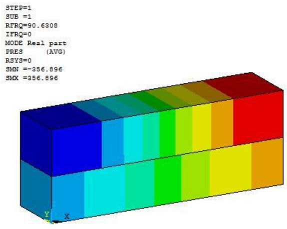
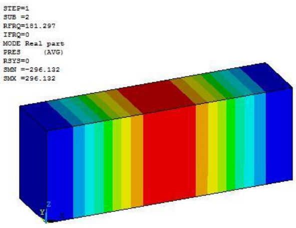
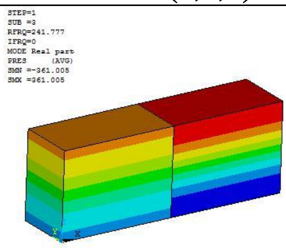
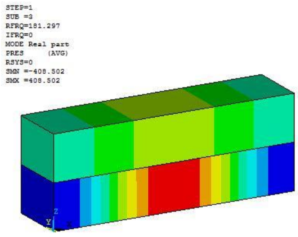
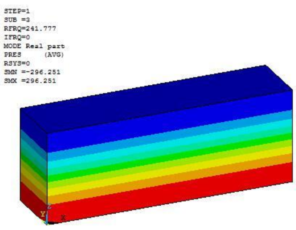
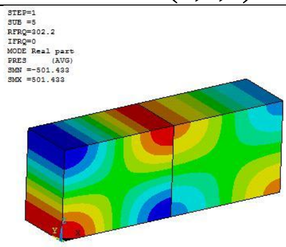
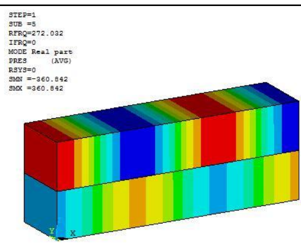
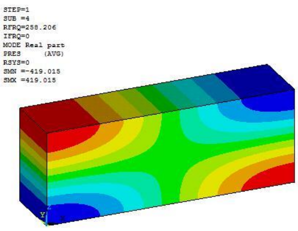
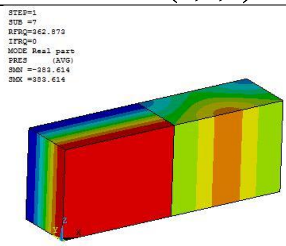
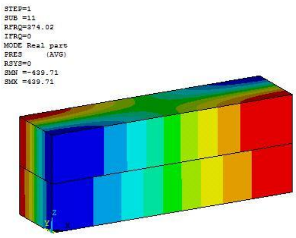



Figure 1: Geometry and finite element model.

The fluid modal frequency and vibration mode of the three cases calculated by the finite element method are given in Table 1.

Table 1: Acoustic model of the three cases

| | No baffle plate | *x*-baffle plate | *z*-baffle plate |
|---|---|---|---|
| Mode 1 |  90.6Hz(1,0,0) |  181.3Hz(1,0,0) |  90.6Hz(1,0,0) |
| Mode 2 |  181.3Hz(2,0,0) |  241.8Hz(0,0,1) |  181.3Hz(2,0,0) |
| Mode 3 |  241.8Hz(0,1,0) |  302.2Hz(1,0,1) |  272Hz(3,0,0) |
| Mode 4 |  258.2Hz(1,0,1) |  362.9Hz(0,1,0) |  374.0Hz(1,1,0) |

As can be seen from Table 1, the $x$-baffle plate only has effects on the fluid mode that moves in $x$-direction, and so was the $z$-baffle plate. Therefore, before the tank structure is modified, it is necessary to know in advance which order of the fluid mode need to be focused on. By comparing natural frequency obtained by the analytical solution and finite element method, we can see that the finite element method is correct and can be used to solve complex structures.

A baffle plate exists in the middle of the tank normal to $x$-direction with thickness of $t$. The plate boundary is fixed and the equation of motion is:

$$D\left[\frac{\partial^4 w}{\partial y^4}+2\frac{\partial^4 w}{\partial y^2 \partial z^2}+\frac{\partial^4 w}{\partial z^4}\right]+\rho_s \ddot{w}=F(t) \tag{2}$$

where the flexural stiffness of the plate is $D=Et^3/\left(12\left(1-\nu^2\right)\right)$ with Young's modulus $E$, Poisson's ratio $\nu$, thickness $t$, and mass density $\rho_s$.

The boundary condition of baffle plate is:

$$\begin{aligned} at \quad x=\frac{l}{2}, y=0 \quad and \quad x=\frac{l}{2}, y=h: w=0; \frac{\partial w}{\partial y}=0 \\ x=\frac{l}{2}, z=0 \quad and \quad x=\frac{l}{2}, z=b: w=0; \frac{\partial w}{\partial z}=0 \end{aligned} \tag{3}$$

Solving the problem with using the FEM, the coupling equation of the fluid and the structure is:

$$\begin{bmatrix} M_s & 0 \\ \rho_f R & M_f \end{bmatrix}\begin{Bmatrix} \ddot{U} \\ \ddot{P} \end{Bmatrix}+\begin{bmatrix} C_s & 0 \\ 0 & C_f \end{bmatrix}\begin{Bmatrix} U \\ P \end{Bmatrix}+\begin{bmatrix} K_s & -R^T \\ 0 & K_f \end{bmatrix}\begin{Bmatrix} U \\ P \end{Bmatrix}=\begin{Bmatrix} F_s \\ 0 \end{Bmatrix} \tag{4}$$

where: $M_s$, $C_s$ and $K_s$ are the mass matrix, damping matrix and stiffness matrix of structure, $M_f$, $C_f$ , $R$ and $\rho_f$ are mass matrix, damping matrix, coupling matrix and the density matrix of fluid.

## 3. Numerical result

In practical, the baffle plate has a finite thickness, and both sides are in contact with the liquid, which always performs as an elastic structure. In the following, we will discuss the interaction of the baffle plate with fluid. Without losing generality, only the $x$-baffle plate is added. The changing of first order fluid mode frequency is discussed with the variation of the thickness, the area, the location and the shape of the opening in the baffle plate.

### 3.1 Influence of the thickness of the baffle plate

Consider the baffle plate is steel and its material parameters are Young's modulus $E$=210GPa, Poisson's ratio $\nu$=0.33 and density $\rho_s$=7850kg/m$^3$. The thickness changes from 1mm to 1m. The first mode frequency of different thickness is shown in Fig. 2.

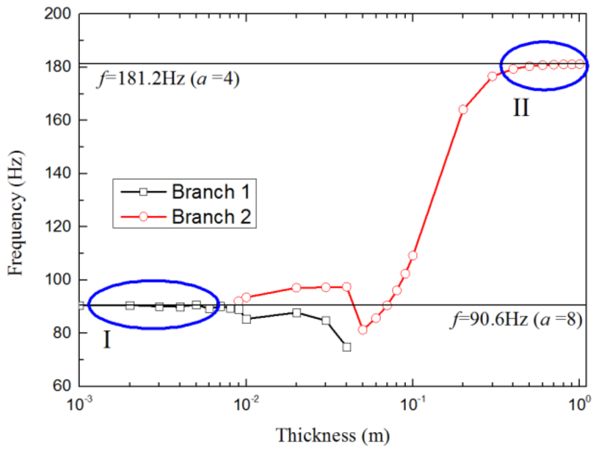



Figure 2: First mode frequency when the thickness changes.

As can be seen from Fig. 2, the modal frequency of the fluid is almost between 90.6Hz and 181.2Hz, corresponding to the fluid with a feature size *l*=4m and *l*=8m respectively.

In region II, the panel is very thick and exhibits a rigid characteristic that blocks the transfer of fluid motion on both sides. The modal frequency of the fluid depends on the characteristic size of each cavity after partitioning. In the middle part between I and II, the panel exhibits elastic properties. The movement of the panel and the fluid is coupled each other. When the thickness of baffle plate is larger, the movement of the plate strong affects the fluid, so that the first-order natural frequency of the fluid decreases gradually as the thickness decreases.

With the further reduction of the thickness of the baffle plate, the energy of the fluid and the plate movement is nearly equivalent. There will be two modal frequencies corresponding to the first-order mode. This is due to the strong coupling between the structure and the fluid, and cannot be distinguished primary and secondary. Thus the fluid itself has a first-order mode of movement, while the appropriate structural movement also promotes the fluid to move with a similar style as the first-order vibration mode. These two frequencies will not be superimposed directly, and the whole system will find a new balance. After reallocating, the two frequencies are with a certain offset from each other as shown in Fig.2.

When the thickness is small enough, the baffle plate has little effect on the movement of the fluid, and the flexible panel moves with the fluid. As shown in region I, the wall almost does not exist, and the modal frequency of the fluid is determined by the length of the entire tank.

### 3.2 Influence of the area of the opening

To avoid the coupling of the thin plate and the fluid movement, fluid mode frequency variation is discussed influenced by the opening in the thick baffle plate (*t*=0.5). The curve in Fig.3 shows the mode frequency variation with the opening ratio, which is defined by $A_{hole}/A_{plate}$ (area of opening/ the whole area of baffle plate). In the Region I, the area of the cavity on the plate gradually increases in the *y* direction as shown in Fig 3(a). In other regions, the open area on the plate increases in the *z*-direction as shown in Fig 3(b), keeping the width unchanged in the *y*-direction.

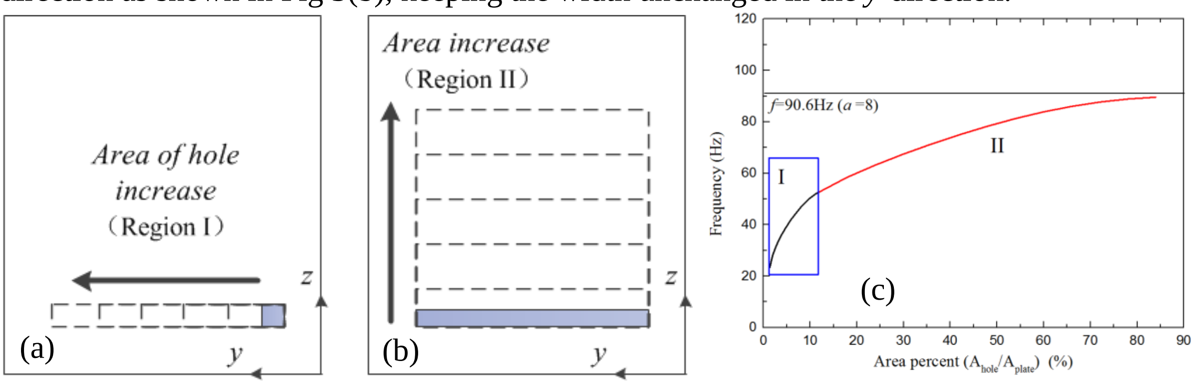



Figure 3: First modal frequency with different opening ratio.

As can be seen from Fig. 3, although the panel exhibits nearly rigid properties, once the opening exists, the first-order frequencies of the fluid are greatly reduced and less than 90.6 Hz. This is because the fluids on both sides of the baffle plate are connected through the opening, so that the average feature size of the fluid is longer than the original one. With the area of the opening increasing, the characteristic size of the fluid gradually decreases, and will eventually be consistent with the size of the cavity. Then the first-order natural frequency of the fluid will converge to 90.6Hz.

### 3.3 Influence of the location and shape of opening

The effect of the opening position is discussed with three kinds of thickness of the baffle plate. The opening area keeps 0.5m$^2$, and the opening gradually translates from the bottom to upwards along the *z*-axis (Fig. 4a). A curve about the fluid natural frequency changing with the *z*-coordinate of the opening bottom boundary is shown in Figure 4b.

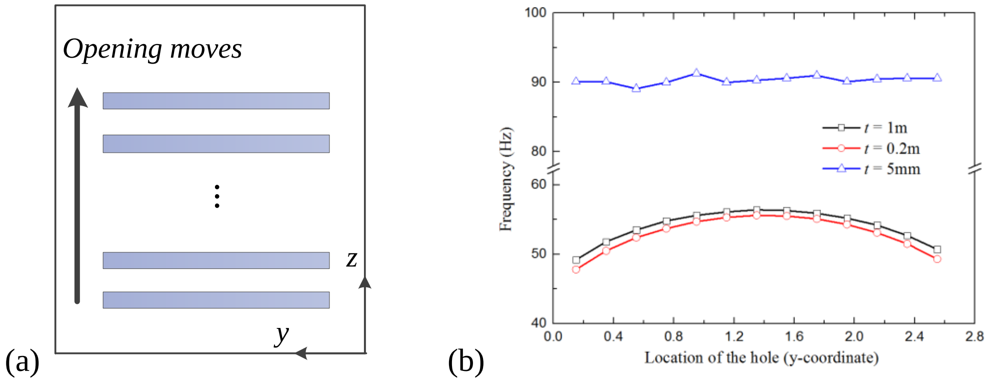



Figure 4: First mode frequency with different location of the hole.

We can know that the natural frequency of the fluid will change slightly as the opening position changes. When the hole exists in the middle of the baffle plate, the natural frequency of the fluid will have a maximum value. In other cases, the natural frequency will be slightly reduced. Likewise, when the baffle plate is thin enough (for example *t*=5mm), the location of the openings has little effect on the natural frequency of the fluid.

The effect of the opening shape will be discussed for the baffle plate with a thickness *t* =0.5 m. The three openings are shown in Fig.5, respectively, with the size of 0.2m×0.8m, 0.4×0.4m and 0.8×0.2m. The fluid modal frequencies are given in Table 2. It can be seen that the natural frequency of the fluid is not sensitive to the shape of the opening. When the aperture area is equal, only make the shape changing, the modal frequencies of the fluid are almost constant.

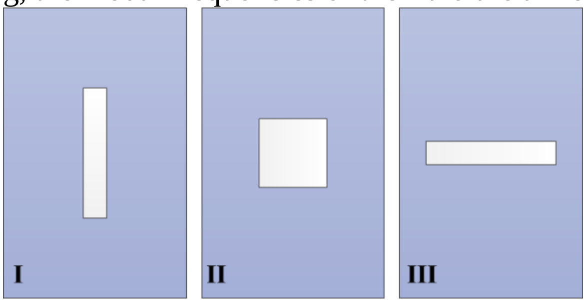



Figure 5: Three kinds of opening hole.

Table 2: Fluid mode frequency of three kinds of hole

| | Shape 1 (Hz) | Shape 2 (Hz) | Shape 3 (Hz) |
|---|---|---|---|
| Mode 1 | 34.4 | 34.6 | 34.5 |
| Mode 2 | 171.8 | 173.2 | 173.3 |
| Mode 3 | 181.3 | 181.3 | 181.3 |
| Mode 4 | 237.2 | 236.7 | 236.1 |
| Mode 5 | 241.8 | 241.8 | 241.8 |
| Mode 6 | 284 | 289.9 | 288.5 |

## 4. Conclusions

In this paper, the fluid mode frequency influenced by the baffle plate in the water tank is discussed. It is found that with the change of the thickness of the baffle plate, the fluid will show three different response modes. One is the fluid only moves in the cavity after partition; the second is that the fluid appears the overall movement mode as the baffle plate not exists, and the third is coupled with the movement of the structure. The hole in the baffle plate will make the modal frequency greatly reduced, and with the opening area increases, the modal frequency will gradually converge in the case of no baffle plate. But the position and shape of the openings have little effect on the fluid modal frequency. The research can be used to avoid the fluid resonance and to improve the design of the fluid tank, thereby diminishing the vibration or noise caused by fluid resonance.

## ACKNOWLEDGMENT

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