Dynamic Response of Circular, Hexagonal and Rectangular Shaped Floating Fish Cage in Waves

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Abstract: A three dimension (3D) model of floating fish cage in both regular and irregular waves is investigated by numerical simulations. The model vary in the geometry of circular, hexagonal and rectangular/square shaped. Main purpose of this research is to develop a comparison of floating fish cage responses between the models. Frequency domain analysis is performed to investigate the responses in both regular and irregular waves. The fish cage model comprises floating collar with two concentric HDPE tubes and held together by the horizontal and vertical braces. The benchmark model of circular fish cage is adopted from Shen [1], OD fish cage = 60m, then it is modified into hexagonal and rectangular shaped with nearly dimension from circular shaped. The model was assumed in rigid state and excluding flexible nets in order to simplify the computation. Dynamic analysis was performed in free-floating condition by calculating the hydrodynamic properties i.e. added mass, damping and wave oscillation forces in three-dimensional diffraction theory. The corresponding analysis reveal that the response of circular fish cage has the largest amplitude in heave and pitch motion than hexagonal and rectangular model. The following condition is emerged in accordance of viscous damping of each geometry.

1 INTRODUCTION

In recent years the development of marine aquaculture located in offshore progressively increases due to limited nearshore. The fish farms are being moved by industry from nearshore to more exposed sea region where waves and current are stronger. Indonesia, which is 75% of it's territory, comprises of the seas, it contributes the huge opportunity in marine culture/mariculture development such as marine aquaculture as known locally as Keramba Jaring Apung (KJA). The model of KJA is in the form of floating cage in circular shaped comprised of two concentric HDPE tube commonly used nowadays.

A numerous research has been done to investigate the dynamic responses of floating cage by model tests and simulations. Endersen (2011) evaluate the loads and responses of floating fish farm in circular collar. The hydrodynamic behaviors of multiple net cages in waves and current were investigated numerically by Xu et al. (2012, 2013b). Shen et al. (2018) provide numerical and experiment investigations on mooring loads of a marine fish farm in waves and current.

This research is focused to investigate the motion characterstics of floating collar fish cage in various shapes : circular, hexagonal and rectangular/square. The floating collar comprises with two concentric tubes and were held together with both horizontal and vertical braces. In order to simplify the calculation, the model was simulated in rigid state and exclude the modeling of flexible nets cage and mooring system. Thus, in this paper we neglect the effect of nonlinierity. Dynamic analysis was performed in free-floating condition by calculating the hydrodynamic properties i.e. added mass, damping and wave oscillation forces in three-dimensional diffraction theory.

The models were investigated in both regular and irregular seas to obtain the comparison of the motion characteristic of each model. JONSWAP wave spectra is conducted to develop the dynamic analysis in irregular seas, vary from wave height, H, 1.00 to 10.00 meters.

In summary, the present paper organized as follows. First, a general description of methodology used in this research, next a brief description model simulation in three shapes : circular, hexagonal and rectangular. Second chapter is elaboration of waves configuration and analysis basic concept in regular

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and irregular waves. Next, generating the governing equation of motion behaviour. And finally, performing result and discussion, consist of motion characteristic on regular wave, responses on irregular waves and comparing statistical response of each model.

2 RESEARCH METHODOLOGY

2.1 General

This research began with determining the fixed variable of fish cage principal dimension. Based on model generated by Shen (Shen & Faltinsen, 2018), we kept the dimension of Outer Diameter = 60 m for circular model, then adopted the OD into the diagonal length with the exact dimension to the other model. With this fixed dimension, we generate the model of fish cage into circular, hexagonal and rectangular shaped (Figure 2). The model generated in 3D surface model, based on 3D diffraction concept. Next, finding the equilibrium position of each model and computing the dynamic analysis in regular wave to obtain the motion characteristic of each model and presented into Response Amplitude Operator (RAO) graph, then investigating the motion in irregular waves by tabulating the squared RAO and multiply by wave spectra to obtain the response spectra. Finally, stochastic analysis is performed to generate the statistical responses and compared the response to each model. (Show Figure 1)

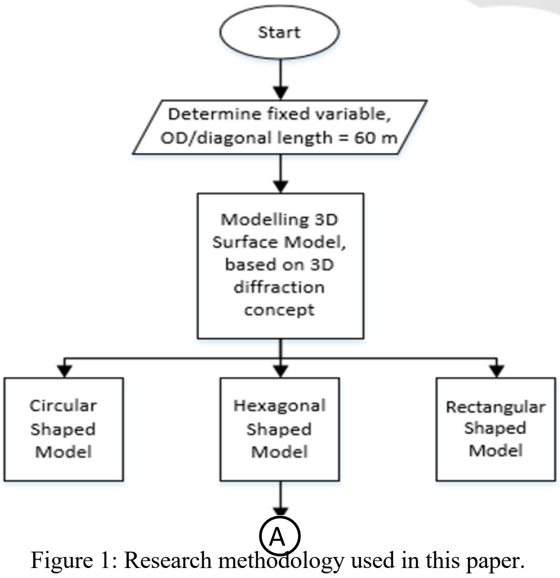

Figure 1: Research methodology used in this paper.

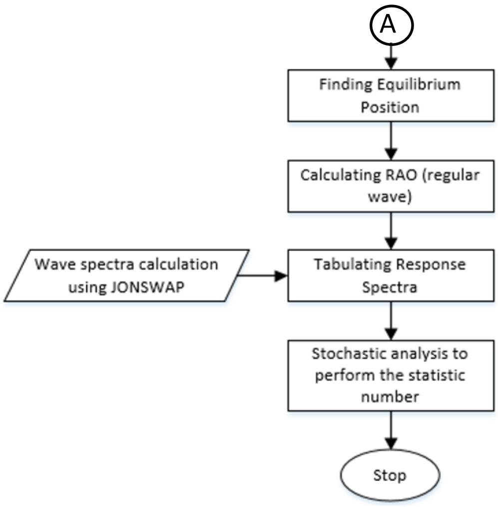

Figure 1: Research methodology used in this paper. (next)

2.2 Model Simulation

The floating collar composed of two concentric HDPE tubes with outer cross sectional diameter, odtube = 0.44 m, and wall thickness, wttube = 0.04 m. The diameter of the center line of the outer tube, ODouter = 60 m. The inner tube was positioned with the distance, l = 2.22 m inside the outermost, leading to the center line diameter, Odinner = 55.56 m. The tubes were held together by both horizontal and vertical braces with the length of lhorbrace = 2.22 m and lverbrace = 2.78 m. Those braces has cross sectional diameter, odbrace = 0.25 m and wall thickness, wtbrace = 0.02 m. Material properties of HDPE tube used in this present paper is given in Table 1.

The model of circular fish cage is adopted from Shen (Shen & Faltinsen, 2018), Figure 2 (top-left), then it is modified into hexagonal and rectangular/square shaped with the near-dimension from circular model, see Figure 2. The model was simplified in rigid state and excluding flexible nets in order to simplify the computation. Dynamic analysis was performed in free-floating condition by calculating the hydrodynamic properties i.e. added mass, damping and wave oscillation forces in three-dimensional diffraction theory.

Table 1: Material properties of HDPE.

Parameter	Total	Unit
Specific gravity	0.953	-
Material density	4299.88	N/m³
Young's Modulus	10800	MPa
Poisson's Ratio	0.45	-
Coefficient of Thermal Expansion	1.52	1/ºC
Yield stress	29.5	Mpa

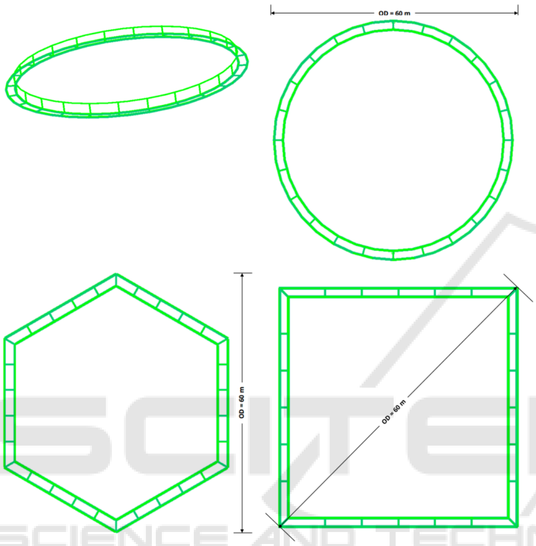

Figure 2: Floating fish cage geometry : isometric view (top-left); top view : circular, hexagonal and rectange shaped.

2.3 Waves Configuration and Analysis

The responses of floating fish cage in both regular and irregular waves are to be evaluated. Linear theory is adopted to compute the regular wave. According to Djatmiko (Djatmiko, 2012), the floating structure exposed to the external force, such as wave excitation force, then the structure moves with the steady amplitude and frequency, as known as steady state oscillation. This state can be performed in the equation 1.

$$\zeta_z = \zeta_{z0} \sin (\omega t - \varepsilon_z) \qquad (1)$$

Where ζ_{z0} denotes oscillating motion amplitude and ε_z is the phase degree between motion and the propagating wave force. The function of Equation 1 gives the oscilating sinusoidal graph with x-axis of time (s), and y-axis of wave elevation (ζ_z).

The wave excitation forces are the diffraction force due to added mass and water particle acceleration and the Froude-Kriloff pressure force due to the undisturbed dynamic pressure over the wetted surface of the structure. The diffraction force will be calculated according to linear theory.

Besides, an irregular waves simulation is evaluated by computing JONSWAP wave spectra, suggested by DNV (DNV, 2010), as follows :

$$S_j(\omega) = A_\gamma\, S_{PM}(\omega)\gamma^{\left(exp\left(-0.5\left(\frac{\omega-\omega_p}{\sigma\,\omega_p}\right)\right)^2\right)} \qquad (2)$$

where,
S_{PM} = Pierson-Moskowitz spectrum

$$= \frac{5}{16}\, H_S^2\, .\, {\omega_p}^4 . \omega^{-5} . exp\left(-\frac{5}{4}\left(\frac{\omega}{\omega_p}\right)^{-4}\right) \qquad (3)$$

H_s = significant wave height
ϖ_p = 2π/Tp (angular spectral peak frequency)
γ = non-dimensional peakedness parameter
σ = *spectral width parameter*
σ =0.07 for $\varpi \leq \varpi_p$
σ =0.09 for $\varpi > \varpi_p$
A_γ = 1- 0.287 ln(γ) as the normalizing factor

Spectral response analysis is conducted by computation on the basis of H_s intensities for the long-term occurence varying from 1.00 to 10.00 m. The responses of floating fish cage are obtained by multiplying the square of RAO and wave spectrum considered in this analysis. The stokhastic parameter can be generated using the varians of the statistical method, as follows:

$$m_n = \int_0^\infty \omega^n S_\zeta(\omega) d\omega \qquad (4)$$

where m_n denotes varian nth and $S_\zeta(\omega)$ is the wave spectra.

2.4 Motion Behaviour of Floating Fish Cage

In the first stage, the analysis of floating fish cage motions is conducted in the numerical model based on frequency domain. The formulation of the dynamic for the equation of floating structure motion, in vertical axis may be written as follows (Endersen, 2011):

$$m\frac{\partial^2 w(s,t)}{\delta t^2} + c_{33} w(s,t) + EI\frac{\partial^4 w(s,t)}{\delta s^4} = f_3^D(s,t) + f_3^{FK}(s,t) + f_3^{added\ mass} + f_3^{damping} \qquad (5)$$

The vertical velocity and acceleration is $\frac{\partial w(s,t)}{\partial t}$ and $\frac{\delta^2 w(s,t)}{\delta t^2}$. The unit for each term in the equation is N/m. m is the mass of the floater per unit length. m is not varying in space and is therefore a constant. c_{33} is the general hydrodynamic restoring coefficient. EI is the bending stiffness. $f_3^D(s,t)$ and $f_3^{FK}(s,t)$ are the diffraction and Froude-Kriloff force. $f_3^{added\ mass}$ is the added mass force because of vertical acceleration of the floater section. $f_3^{damping}$ is the damping force, and contains contributions from potential damping, skin friction, vortex shedding and structural damping.

Output of the analysis is presented in the form of RAO curves which exhibit fluctuation of the ratio of the motion amplitude and the wave amplitude as a function of wave frequency increment from 0.1 up to 4.0 rad/s. In this analysis a comparison is performed between the motion behaviors of circular, hexagonal and rectangular shaped inheave and pitch motion. Analysis of the motion behaviors in random waves is obtained from the computation of the squared RAO multiplied by the wave spectra, which yields the stochastic data of significant motion responses as the output.

3 RESULT AND DISCUSSION

3.1 Motion Characteristic on Regular Wave

In the following section, we present results from the numerical simulation in the form of RAO curve in heave and pitch motion (Figure 4 and Figure 5). The floating fish cage is exposed with the regular wave in head seas direction (180 deg).

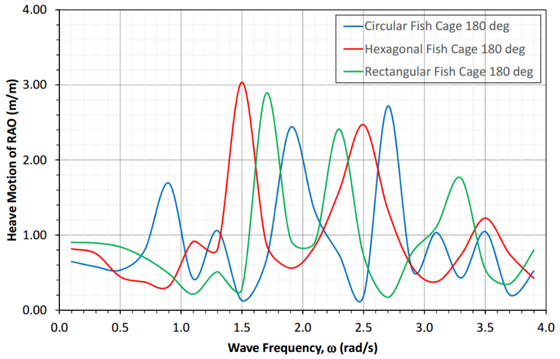

Figure 3: Comparison of heave motion RAO between models.

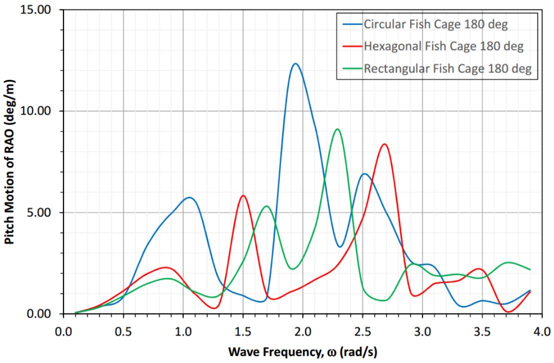

Figure 4: Comparison of pitch motion RAO between models.

According to Figure 4 the resonance of heave motion for circular model occurs several times at 0.9, 1.3, 1.9 and 2.7 rad/s with the highest magnification of heave amplitude through wave amplitude is 2.7 times. The resonance of hexagonal model can be found at 1.5, 2.5 and 3.5 rad/s. While the rectangular model gave the resonance at 1.7, 2.3 and 3.3 rad/s. Observing the graph, we find the first resonance of circular model occurs at 0.9 rad/s with the wave (JONSWAP) occurence probability is 14% at the same frequency. This condition will generate the high response of heave at irregular wave.

Meanwhile the pitch motion of each model shown at Figure 5 yields the highest RAO at wave frequency 2.0 rad/s, 2.7 rad/s and 2.3 rad/s for circular, hexagonal and rectangular respectively.

3.2 Fish Cage Response on Regular Wave

Having accomplished analysis of the motions in regular waves, the next stage is directed towards the examination of floating fish cage motions in irregular waves. In this regards the fish cage motions is estimated by performing the spectral analysis using the JONSWAP spectrum as shown in Figure 5. The peak curve occurs at wave frequency, ω = 0.95 rad/s. The spectrum is derived for the wave height, H from 1.00 to 10.10 m. Results of the spectral analysis of each model presented in Figure 6 to Figure 11, then the stochastic analysis yields significant response and compared to each other as given in Figure 12 and Figure 13 for heave and pitch motion respectively.

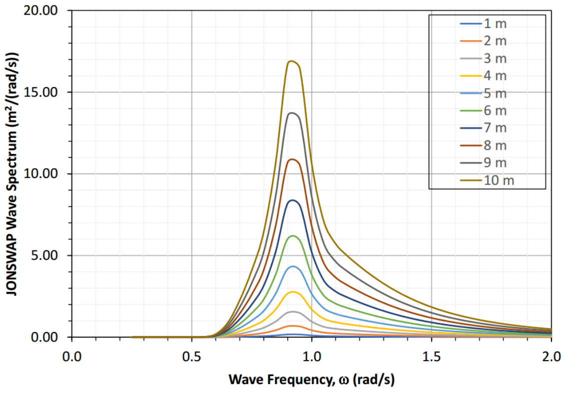

Figure 5: JONSWAP wave spectrum from H = 1.00 to 10.00 m.

3.2.1 Circular Shaped

Based on Figure 6 and Figure 7, the density of circular floating cage responses of heave and pitch has several peaks, first at ω = 0.90 rad/s that is caused by the superposition of first resonance of motion and by wave excitation. Then at ω = 1.30 rad/s and ω = 1.90 rad/s are caused by the superposition with second and third resonance of motion.

3.2.2 Hexagonal Shaped

According to the Figure 8 and Figure 9, the peak spectra response of heave motion found at ω = 0.95 and 1.50 rad/s, while in pitch motion found at ω = 0.90 and 1.50 rad/s, The first peak is generated from wave excitation for heave, and superposition of both motion and wave excitation for pitch.

3.2.3 Rectangular Shaped

Observing to the Figure 10 – 11, the density of rectangular floating cage responses of heave motion, has several peaks at ω = 0.90, 1.30, 1.70 and 2.30 rad/s. The first peak is affected by wave excitation while the second, third and forth peak are generatef from resonance of heave motion. The peak of pitch responce located at ω = 0.90, 1.70 and 2.30 rad/s, the first peak is generated from superposition of wave excitation and motion, while the other two is influenced by its motion.

3.2.4 Significant Responses Comparison

The stochastic number i.e. significant responses can be derived from the computation of spectral response accomplished before by identifying the variant of data analysis. Significant responses of each motion are shown at Figure 12 and Figure 13. According to the graphs, the responses of floating cylinder on irregular wave with the circular shaped has the largest amplitude than the hexagonal and rectangular shaped in vertical motion. The following condition is emerged in accordance of viscous damping of each geometry. The circular model has a smallest viscous damping than hexagonal and rectangular model. Thus the response of circular shaped yields larger than other model.

The difference of heave responses of circular shaped yields 1.26 times larger than hexagonal, and 1.71 times larger than rectangular shaped. While in pitch, the circular responce significantly escalated 2.1 times larger than hexagonal and 2.34 times larger than rectangular. The pitch response between hexagonal and rectangular shaped remain the same.

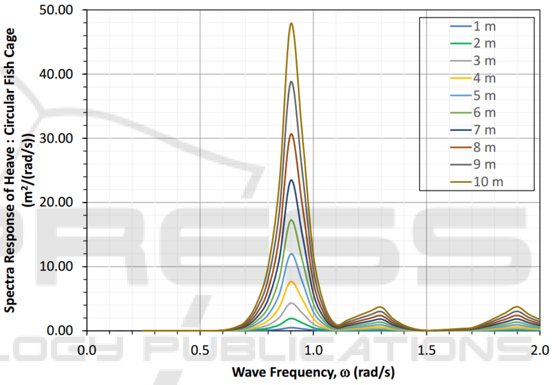

Figure 6: Spectra response of heave : circular shaped fish cage.

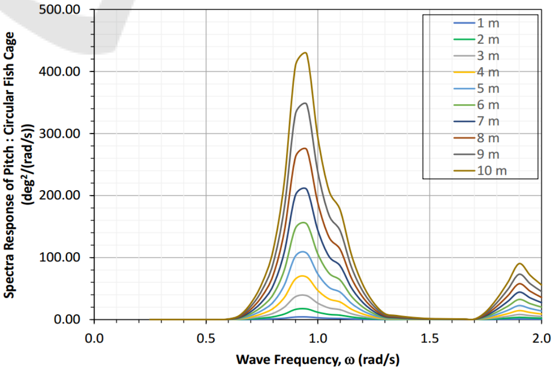

Figure 7: Spectra response of pitch : circular shaped fish cage.

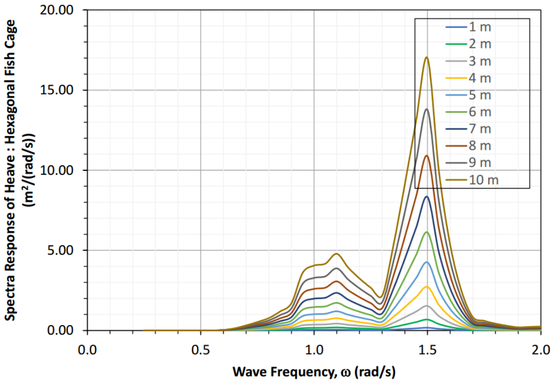

Figure 8: Spectra response of heave : hexagonal shaped fish cage.

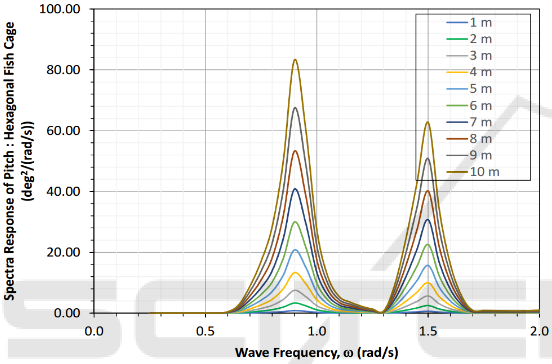

Figure 9: Spectra response of pitch : hexagonal shaped fish cage.

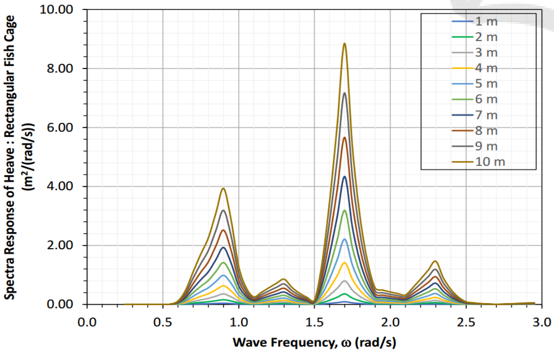

Figure 10: Spectra response of heave : rectangular shaped fish cage.

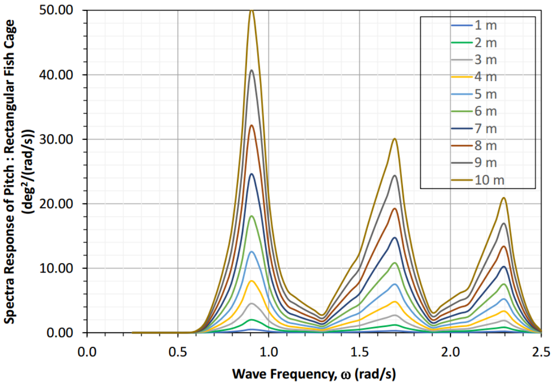

Figure 11: Spectra response of pitch : rectangular shaped fish cage.

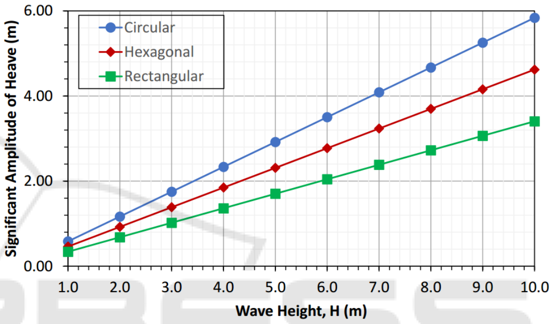

Figure 12: Significant response of heave on irregular waves, Hs = 1.0 to 10 m.

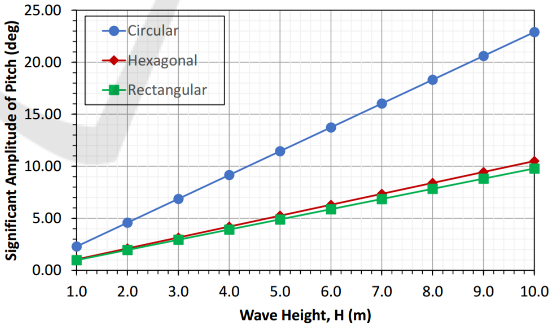

Figure 13: Significant amplitude of pitch on irregular waves, Hs = 1.0 to 10 m.

4 CONCLUSIONS

A numerical simulation has been performed to investigate the responses of floating fish cage in circular, hexagonal and rectangular/square shaped. The simulation conducted in both regular and irregular waves. This analysis yields some conclusions as follows:

- The motion characteristic on regular wave of circular shaped has the peak RAO curve in the wave frequency appear in accordance to the peak of irregular wave frequency. The following condition will generate a resonance.
- The responses of circular model on irregular wave has the largest amplitude than the hexagonal and rectangular shaped in vertical motion. The following condition is emerged in accordance of viscous damping of each geometry. The circular model has a smallest viscous damping than hexagonal and rectangular model. Thus the response of circular shaped yields larger than other model.

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