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The prediction of hydrodynamic damping characteristics of a hydrofoil with blunt trailing edge

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Abstract: Flow-induced vibration is a prevailing phenomenon in the operation of the hydraulic machinery system. Fluid-structure interaction (FSI) is an important characteristic of flow-induced vibration and must be taken into account in design phase of hydraulic machinery. FSI in the form of mass loading and damping, it has a major impact on the dynamic response of the structural. Hydrodynamic damping can reduce the vibration amplitude and improve the stability of the hydraulic machinery which is of great importance. The aim of this study is to prediction the hydrodynamic damping characteristics of a NACA 0009 hydrofoil by using three dimensional two-way fluid-structure interaction modeling. The first bending mode of the hydrofoil is excited to produce the deformation, then the deformation information is transmitted to the flow field through the fluid-solid coupling junction. In the numerical simulation, dynamic response is acquired by dynamic mesh deformation of flow field, and the hydrodynamic damping parameters are obtained by the logarithmic decay method. Turbulent viscosity is computed by using the two equation SST k-ω model and the effect of time step on the calculated results is eliminated. It was found that the hydrodynamic damping is significantly increased linearly as the flow velocity is increased, and this trend is consistent with the experimental results. The results of this research are compared with those obtained from experiments and the relative difference is around 50% by least squares linear regression, and it is essential to consider the effect of numerical damping and near-wall region processing on the results.

1. Introduction

During the operation of the hydraulic machinery system, flow-induced vibration is a prevailing phenomenon and it may lead to premature failure. Moreover, after the installation of hydraulic machinery it is difficult to rectify the vibration in high-speed rotation and high pressure environment [1]. Fluid-structure interaction (FSI) in the form of mass loading and damping, it has a major impact on the dynamic response of the structural. Hydrodynamic damping can reduce the vibration amplitude and has a significant effect in improving the stability of the hydraulic machinery, which is of great importance and must be taken into account in the design phase [2].

The acquisition of hydrodynamic damping parameters is the basis for the analysis of hydrodynamic damping characteristics. One way to accomplish such a goal is by experiments. Recently, some experimental investigations of hydrodynamic damping characteristics using three dimensional hydrofoil has been presented [3][4]. They excited the first bending mode of the hydrofoil to produce the deformation and obtained damping rate in different velocity. Yao et al. [4] found that for first bending mode the hydrodynamic damping is significantly increased linearly as the flow velocity is increased. When the structure is immersed in a fluid flowing at high speed, the hydrodynamic damping is much larger than the structural damping and material damping, but compared with the elastic force and inertia force is still much smaller [5]. Moreover, the internal flow of hydraulic machinery is complex turbulence and it is difficult to accurately measure hydrodynamic damping parameters. Another way to obtain hydrodynamic damping parameters is by numerical simulations. For hydrofoils, many investigations focus on hydrodynamic damping characteristics by using two-way FSI numerical simulation have been presented [1][6]. Liaghat et al. [1] eliminate the effects of calculation parameters such as force application, mesh, time step et al. The calculated results are less than 12% in comparison with the experimental values. Bernd et al. [7] combined finite element analysis (FEA) and computational fluid dynamic (CFD) and obtained the response by means of dynamic mesh deformation, the hydrodynamic damping characteristics has a good agreement with experimental results for first bending mode.

The aim of this study is to predict the hydrodynamic damping characteristics of a NACA 0009 hydrofoil by using three dimensional two-way iteratively implicit FSI modeling. The main contribution of this work is the prediction of hydrodynamic damping and amplitude of vibration at different flow rates on hydrofoil by using numerical simulations.

2. Mathematic methods

For numerical coupling, the fluid using finite volume method and the structure using finite element method. Generally, it is difficult to put two different algorithms together to solve the differential equation. Recently, the most popular coupling method is two-way iteratively implicit FSI numerical simulation. In this method, the fluid and solid equations are solved separately by implicit algorithms, and exchange data by fluid-solid coupling junction until the respective convergence is reached. For unsteady computational fluid dynamics calculations, the incompressible continuous equation and momentum equations can be written as

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho u_j\right)=0 \tag{1}$$

$$\frac{\partial\left(\rho u_i\right)}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho u_i u_j\right)=-\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}\left(\mu \frac{\partial u_i}{\partial x_j}\right)+\rho f_i \tag{2}$$

Where ρ is density of fluid, kg/m^3, p is pressure, Pa, μ is dynamic viscosity coefficient, Pa·s, u_i is i th component of the mean velocity, m/s, f_i is unit mass of fluid, m/s^2, t is time, s. Turbulent viscosity is computed using the two equation SST *k-ω* model, which applicable to the solution of the near wall of the hydrofoil.

When the hydrofoil is immersed in water, the additional parameters should been taken into account. The equation of the system for the transient dynamic analysis can be written as

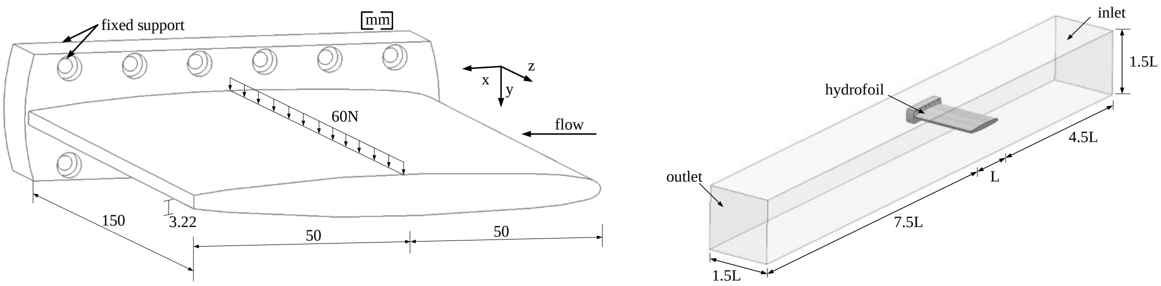
$$\mathrm{M\ddot{W}+C\dot{W}+KW=F(t)} \tag{3}$$

Where W, $\mathrm{\dot{W}}$ and $\mathrm{\ddot{W}}$ are displacements, velocity and acceleration, M, C and K are mass, damping and stiffness matrices, $\mathrm{F(t)}$ is the vector of externally applied load.

Two-way FSI numerical simulation combining finite element analysis (FEA) and finite volume analysis (FVA). The interaction between the two analysis usually takes place at the fluid-structure junction, the solid convey information to the fluid in the form of total mesh displacement and the fluid convey information to the solid in the form of total force.

3. Calculation model

3.1. Physical model
The geometry of the three dimensional hydrofoil used for numerical simulation is shown in figure 1(a). And it is the same as the experimental geometry presented by Roth et al. [3]. The channel in which water flows also has the same scale as the experimental test section. The material of the hydrofoil is aluminum and the properties of it are given as Young's modulus E =69 GPa, density ρ= 2700 kg/m^3 and Poisson ratio v =0.33. The chord length (L) of the hydrofoil is 100mm, the span of the hydrofoil is 150 mm.



(a) Geometry of hydrofoil (b) Boundary conditions

Figure 1. Physical model

One side of hydrofoil is fixed and an initial force is applied on the hydrofoil to excite its first order mode in the fluid.

3.2. Damping ratio identification
The force of 60 N is applied to the center line of the hydrofoil along the positive direction of the y axis as shown in figure 1. The hydrofoil will have a vibration response after removing the applied force, and the vibration response will gradually decrease due to the influence of hydrodynamic damping. For Two-way FSI modeling, the hydrofoil convey information to the fluid in the form of total mesh displacement, and then the vibration response is obtained by means of dynamic mesh deformation of fluid. The vibration response of hydrofoil takes the form of a time decay [8].

$$y(t) = y_0 e^{-\zeta\omega_n t} \sin \omega_d t \tag{4}$$

Where $y(t)$ is displacement, m, ζ is hydrodynamic damping radio, ω_n is natural frequency, Hz, $\omega_d = \omega_n \sqrt{1-\zeta^2}$ is damped natural frequency, Hz. If all the amplitude points are connected to a curve, then equation (4) can be simplified as,

$$y(t) = y_0 e^{-\zeta\omega_n t} \tag{5}$$

The function is fitted by MATLAB to obtain the hydrodynamic damping radio.

3.3. Calculate parameter
Three different meshes for the structure as coarse mesh, medium mesh and fine mesh were used for modal analysis in dry conditions. The corresponding natural frequencies for the first bending mode are 283.03Hz, 282.86Hz and 282.5Hz respectively, and the relative error is less than 0.2%. The experimental value is 288.2Hz, the relative error of numerical simulation is less than 2% compared with the experimental results. In order to reduce the computational time, coarse mesh are used for structural calculations. Finite volume analyses based on unsteady Computational Fluid Dynamics, the turbulent viscosity is computed by using the two equation SST *k-ω* model and the yplus of the flow field is less than 1. To achieve more precise results we need to use a smaller time step but need more

time to calculate. The influence of time steps also be taken into account in the Two-way FSI numerical simulation at v=20m/s.

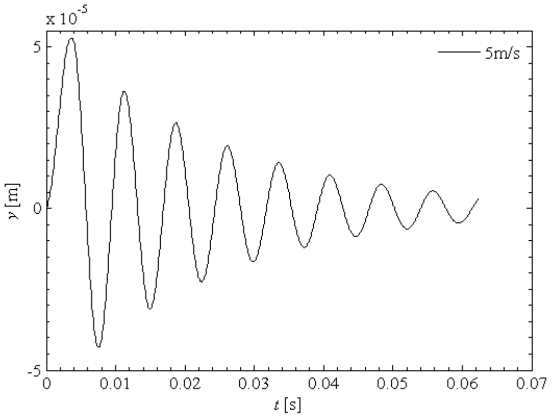
Table 1. Hydrodynamic damping ratio for different time steps

Time step [s]	5e-4	2e-4	1e-4	5e-5
damping ratio	0.254	0.216	0.198	0.201

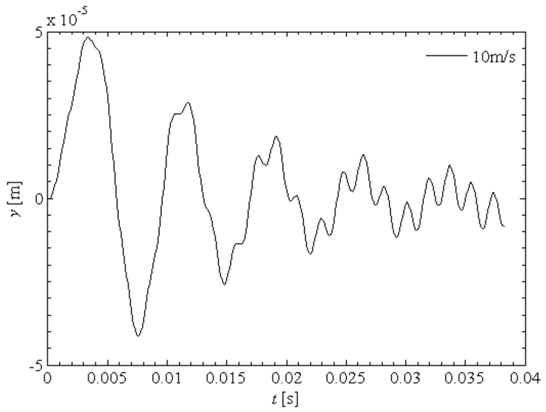
The table 1 shows that the time step has little effect on the result when the time step is less than 1e-4s, and such time step will use in subsequent calculations.

4. Result and discussion

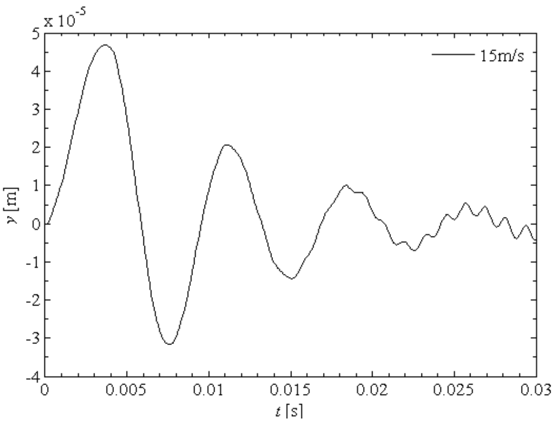
The experimental results show that the velocity of flow has a great influence on the hydraulic damping characteristics, and it is expected to explore the relationship between flow velocity and hydrodynamic damping also by numerical simulation method. In present study, the hydrodynamic damping characteristic associated with the first bending mode of a NACA 0009 hydrofoil was calculated numerically in different velocities. The vibration responses were clearly identified at four different flow rates of 5m/s, 10m/s, 15m/s and 20m/s as shown in figure 2.



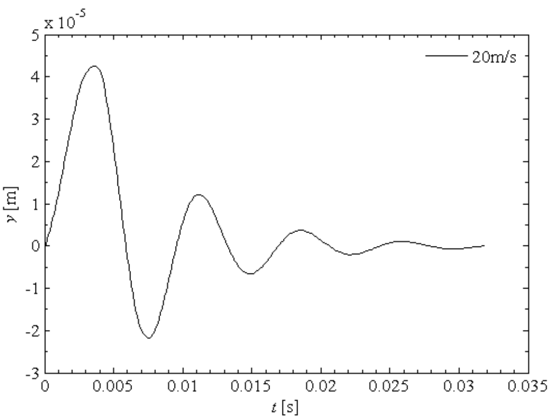
(a) v=5m/s



(b) v=10m/s



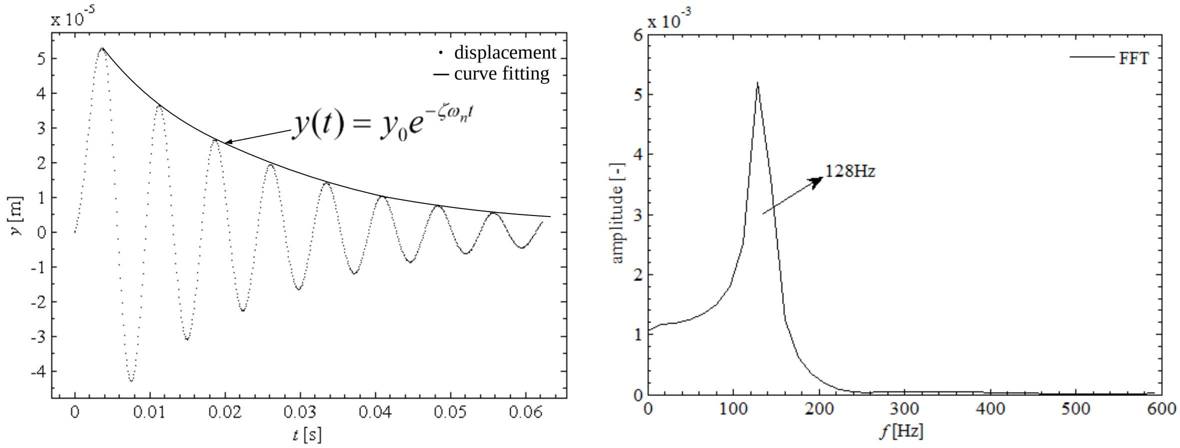
(c) v=15m/s



(d) v=20m/s

Figure 2. Response of y-displacement at different velocity

After obtaining the vibration response, the hydrodynamic damping rate is obtained by MATLAB fitting method. Fitting the amplitude of the vibration and obtain the hydrodynamic damping radio are carried out successfully. The fitting results is shown in figure 3(a).

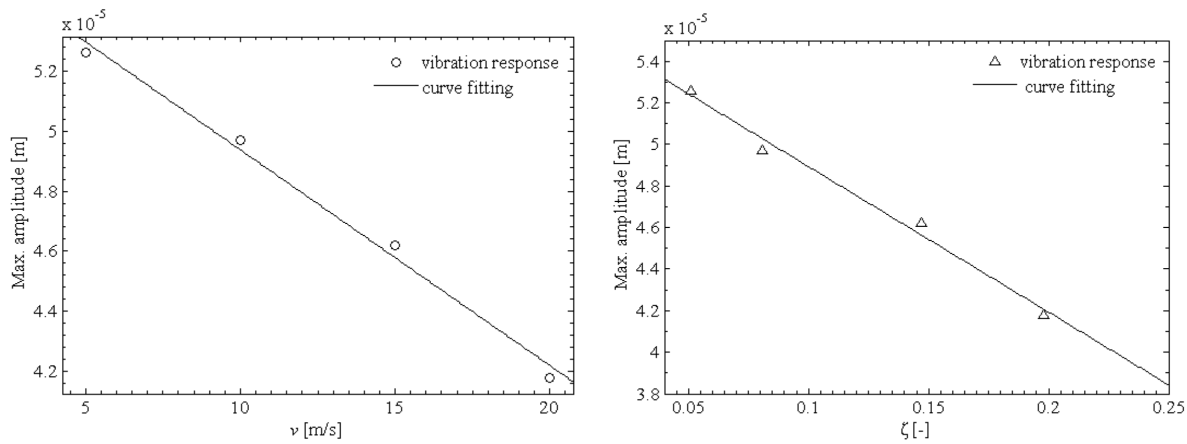


(a) Fitting for the vibration response (b) Spectrum of the vibration response

Figure 3. Post-processing of the vibration response at the condition v =5m/s

Figure 3(b) shows the spectrum of the vibration response by using FFT method, and the corresponding operating velocity is 5m/s. The figure 3(b) shows that only the first order mode is excited, and the frequency of bending hydrofoil in water is 128Hz. The experimental value of corresponding frequency is 123.8Hz, and the relative error is less than 3.5%, which means the accurancy is quite high.

The hydrodynamic damping ratios is obtained by fitting the vibration response data in different velocity as shown in figure 2. It can be seen from the current results that the velocity has a significant effect on the maximum vibration amplitude of the hydrofoil. The results show that the maximum amplitude of the hydrofoil vibration decreases when the fluid velocity is increased and as shown in figure 4(a).



(a) Max. amplitude vs velocity (b) Max. amplitude vs hydrodynamic damping ratio

Figure 4. Relationships among Maximum amplitude, velocity and hydrodynamic damping ratio

Hydrodynamic damping has a significant effect on limiting hydrofoil vibration and the maximum vibration amplitude is significantly reduced linearly as the hydrodynamic damping radio is increased by least squares linear regression as shown in figure 4(b).

The numerical simulation results are compared with the experimental observations presented by Roth et al. [3]. It was found that the hydrodynamic damping is significantly increased linearly as the flow velocity is increased, and the results of this research are compared with those obtained from experiments by least squares linear regression plotted in figure 5.

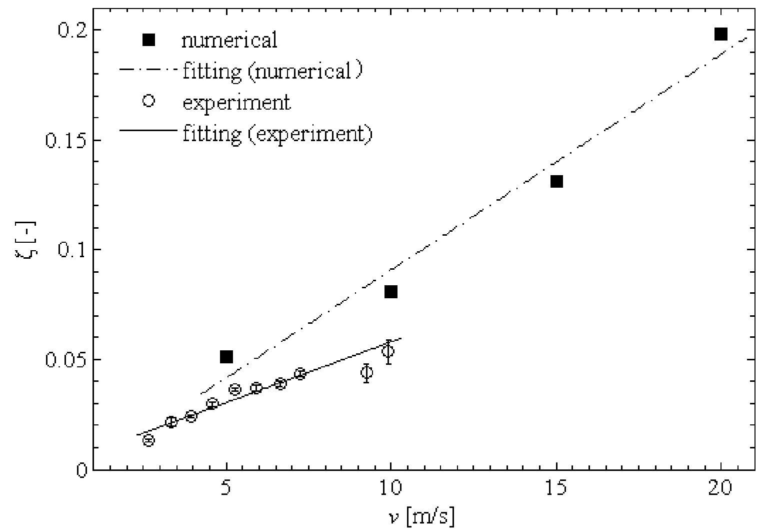


Figure 5. The damping radio of the first bending mode for different velocity

The results show that the numerical damping method can obtain the hydraulic damping ratio, but the results compared with the experimental values have a large error in the current stage. It is estimated that there are two factors that will have an effect on the results, but need further validation. (1) Influence of numerical damping. The default value for numerical damping in commercial software is 0.1, but this value may not be suitable for hydrofoil hydraulic damping calculations. (2) Influence of near wall processing mode. There will be a transition in the near wall of the hydrofoil, which may have an effect on the hydraulic damping parameters.

5. Conclusion

The following conclusion can be summarized:

- Two-way iteratively implicit FSI numerical simulation method is suitable for analyzing hydrodynamic damping characteristics, but the numerical damping and near-wall region processing should be taken into consideration in further investigation.
- The hydrodynamic damping radio is significantly increased linearly as the flow velocity is increased. The maximum vibration amplitude is significantly reduced linearly as the hydrodynamic damping radio is increased.
- Numerical simulation results show that hydrodynamic damping has a significant impact on the vibration characteristics. Increasing the hydrodynamic damping can limit the vibration and improve the stability of the hydraulic mechanical system.

Reference

[1] Liaghat T, Guibault F, Nennemann B, et al. Two-way fluid-structure coupling in vibration and damping analysis of an oscillating hydrofoil[C]. ASME 2014 International Mechanical Engineering Congress & Exposition. 2014.

[2] Seeley C, Coutu A, Monette C, et al. Characterization of hydrofoil damping due to fluid structure interaction using piezocomposite actuator. Smart Mater Struct, 2012, 21: 35027-

35029.
[3] Roth S, Calmon M, Farhat M, et al. Hydrodynamic damping identification from an impulse response of a vibration blade[C]. In: 3rd IAHR International Meeting of the Workgroup on Cavitation and Dynamic Problems in Hydraulic Machinery and Systems. Brno, Czech Republic. 2009.
[4] Yao Z, Wang F, Dreyer M, et al. Effect of trailing edge shape on hydrodynamic damping for a hydrofoil[J]. Journal of Fluids & Structures, 2014, 51:189–198.
[5] Liang C C, Liao C C, Tai Y S, et al. The free vibration analysis of submerged cantilever plates[J]. Ocean Engineering, 2001, 28(9):1225-1245.
[6] Liu X, Luo Y, Karney B W, et al. Virtual testing for modal and damping ratio identification of submerged structures using the PolyMAX algorithm with two-way fluid–structure Interactions[J]. Journal of Fluids & Structures, 2015, 54:548-565.
[7] Nennemann B, Monette C, Chamberland-Lauzon J. Hydrodynamic damping and stiffness prediction in Francis turbine runners using CFD[J]. 2016, 49(7):072006.
[8] De Silva C W. Vibration: fundamentals and practice[M]. CRC press, 2006.