THE CHARATERISTICS OF DYNAMIC RESPONSE OF WATER IN AQUEDUCT BRIDGE UNDER LARGE AMPLITUDE SLOSHING*

Nie Liying[1], Chu Jiayi[2] and Zhang Liaojun[3]

[1]*Associate Professor, Civil engineering college of Hohai University, Nanjing . China*
[2]*Master, Civil engineering college of Hohai University, Nanjing . China*
[3]*Professor, Hydraulic engineering college of Hohai University, Nanjing . China*
Email:nly1972@hhu.edu.cn

ABSTRACT :
The seismic research of large scale aqueduct bridge is important part of the South to North Water Transfer Project. The huge water contained in duct is the predominant feature of aqueduct bridge. In isolation design of aqueduct bridge, if isolating bearing with significant shear deformation are adopted, the duct-water coupled components may be excited by wave, which include more richer long period impulse due to the filter action of bearing, under earthquake. Thus, the large amplitude sloshing of water may occur. Because this tendency has been observed in experiment, it is important to study the characteristics of water dynamic response in aqueduct bridge under the condition of large amplitude sloshing. Based on typical rectangular duct sections, following researches are carried out. (1) Checking the computational model with existed experiment data. (2) The nonlinear characteristics of water dynamic response due to large amplitude sloshing are illustrated through the relationship of exciting wave amplitude and water dynamic response such as wave elevation of free surface, water dynamic pressure, overturning force and overturning moment.(3) The relationship between varying exciting frequency and water dynamic response are investigated. These researches can provide the basis of conceptions and method for selecting parameter of isolation design of aqueduct bridge.
KEYWORDS: aqueduct bridge, isolation, dynamic response, large amplitude sloshing.

1. INTRODUCE

The seismic research of large scale aqueduct bridge is important part of the South to North Water Transfer Project[1]. Some isolation researches of aqueduct bridge have been made preliminarily[2,3,4]. The huge water contained in duct is the predominant feature of aqueduct bridge. In isolation design of aqueduct bridge, if isolating bearing with significant shear deformation are adopted, the duct-water coupled components may be excited by wave, which include more richer long period impulse due to the filter action of bearing, under earthquake. Thus, the large amplitude sloshing of water may occur. Because this tendency[4] has been observed in experiment, it is important to study the characteristics of water dynamic response in aqueduct bridge under the condition of large amplitude sloshing.

The essence of large amplitude sloshing of water in liquid viaduct is fluid-structure-integrated analysis. Presently, the researches of liquid large amplitude sloshing are active. There are Lagrange finite element method[5], ALE finite element method[6,7], boundary element method[8,9] and VOF finite difference method[10] and so on to solve this problem. The process of numerical solution is the process of solving the partial differential equations set. The numerical solution are always somewhat in error，such as numerical dissipation or numerical dispersion. That the analytical model is rational or not is usually identified by comparing with the experiment data[8,10,11].Therefore, the comparison result in this paper with existed experiment data is carried out at first.

In primitive stage of isolation design, isolated period and other control parameters need to be set by learning dynamic characteristics of structure. When duct is rectangular and small amplitude sloshing hypothesis is

*Nation Natural Science Fund Sustentation(50509006)

adopted, the multi-linear-spring Housner model[12,13] is wildly used and analytic solution can be obtained under harmonic wave exciting when water is non-cohesive and irrotational[12,13]. Moreover, it can be observed from Housner model or analytic solution that the amplitudes of the dynamic response waves are proportion to the amplitude of exciting wave and their frequencies are frequency of exciting wave. However, large amplitude sloshing is typical nonlinear phenomenon and the analyses for investigating nonlinear characteristics of dynamic responses due to large amplitude sloshing are carried out.

2 INTRODUCE AND CHECK OF ANALYTICAL MODEL

In present CFD , the numerical solution are always somewhat in error. That the analytical model is rational or not is usually identified by comparing the analysis result with the experiment data. According to the present status, the analytical model in this paper is selected from the experiment[8] directly. The analytical model which is shown in Fig1,is two-dimension duct with water. The duct width is 0.9m and the water depth is 0.6m, the gird dimension is 0.0125m*0.0125m and the viscous coefficient is 0.001 N.s/m2. The exciting wave is harmonic displacement wave, $X(t) = A\sin\omega t$, in which A=0.002m, $\omega = 0.9547\omega_1$ and ω_1 is the fundamental circular frequency of rectangular duct with water which is obtained from equation (2.1) as following , in which g is gravity acceleration, $2a$ is width of rectangular duct and D is the depth of water in duct.

$$\omega_n^{\ 2} = g\frac{n\pi}{2a}\tanh\left(\frac{n\pi}{2a}D\right) \tag{2.1}$$

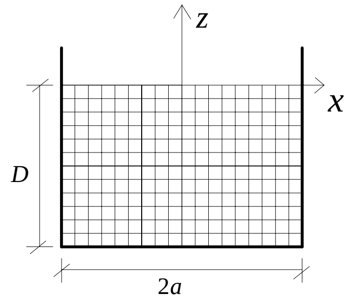


Fig1 Analytical model

To identify the computational accuracy in this paper, the elevation of free surface is compared by experiment data[8]. It can be seen from Fig2 that the elevation of free surface is agreed with the experiment data in period and amplitude.

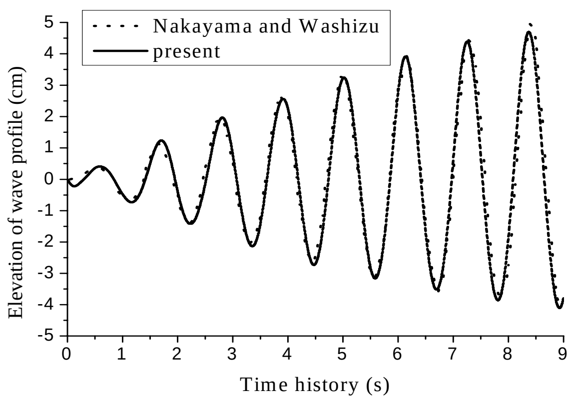


Fig2 The comparison about present results with experiment datas

3 NONLINEAR CHARACTERISTICS DUE TO LARGE AMPLIDUES SLOSHING

Under small amplitude sloshing hypothesis and harmonic wave exciting, the amplitudes of dynamic responses wave are proportion to the amplitude of exciting wave and their frequencies are frequency of exciting wave. However, large amplitude sloshing is a typical nonlinear phenomenon. Under the condition of harmonic displacement wave exciting, the nonlinear characteristics of water dynamic responses due to large amplitude sloshing are illustrated by investigating the relationship of amplitudes and frequencies between exciting waves and dynamic responses.

In the following results, the elevation of free surface is obtained at right side of the wall, and hydrodynamic pressure, overturning force and overturning moment is obtained from the bottom of the side wall.

3.1 Characteristics resulted from varying amplitudes of exciting wave

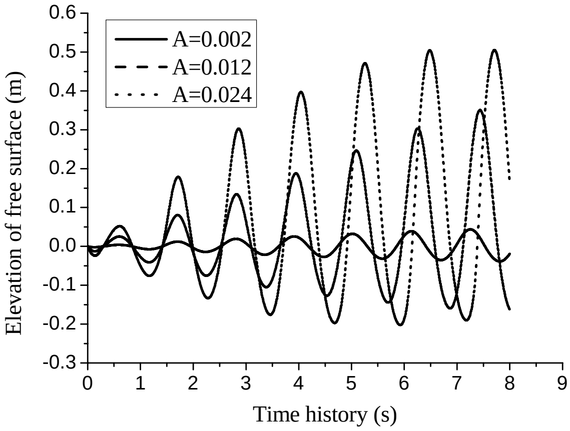
In the research of nonlinear characteristics of water dynamic response due to large amplitude sloshing under varying amplitudes of exciting waves, exciting waves is horizontal displacement $X(t) = A\sin\omega t$, in which $\omega = 0.9547\omega_1$ and ω is approaching the fundamental frequency ω_1. Under this condition, the dynamic responses of gradually enhanced amplitude can be excited. The range of A is from 0.002m～0.024m and the detail is illustrated in Table1.

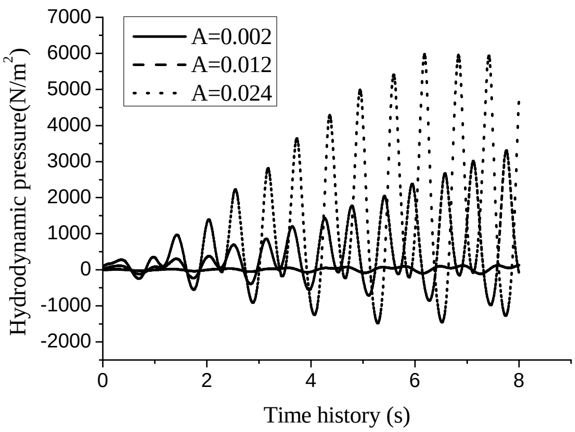
Table 1 The computational cases of various amplitudes of exciting wave

Cases of computation	1	2	3	4	5	6	7
Amplitude of exciting wave	0.002	0.004	0.008	0.012	0.016	0.020	0.024

To demonstrate the effects on period and amplitude of dynamic responses of duct-water coupled structure, the time history wave of elevation of free surface, hydrodynamic pressure, overturning force and overturning moment are illustrated in Fig3 when A equal 0.002m、0.012m and 0.024m. It can be shown from Fig3 that the wave profile of every dynamic response is analogical and sloshing periods are lengthened with the sloshing amplitudes heightening.

To illustrate the relationship between elevation of free surface, the first, the forth and the seventh peak of elevation of free surface of each case are shown in Fig4 and the ratios of them to case one are shown in Fig5 . Meanwhile, the line of y=x represent the linear increased relationship between dynamic response and exciting wave under small amplitude sloshing hypothesis.





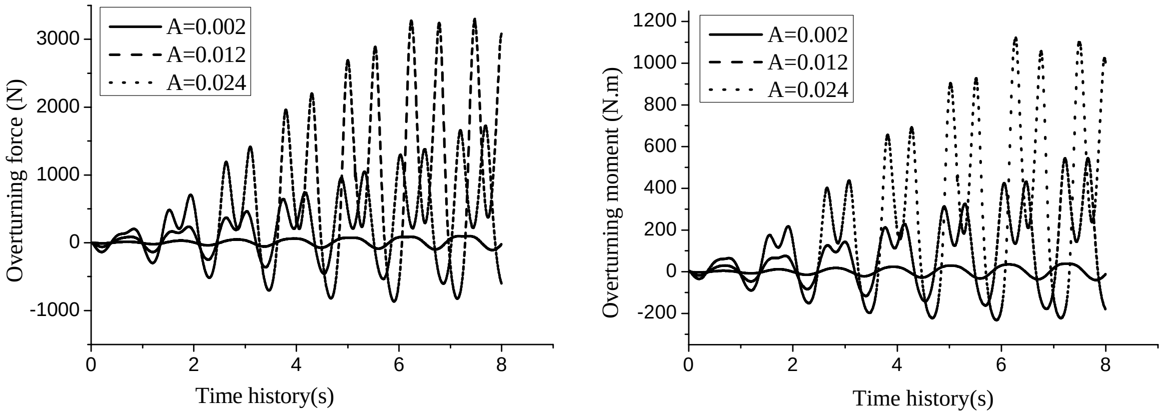


Fig3 Dynamic responses under cases of 1,4 and 7

The results form observing the Fig 4 and Fig 5 is following. (1) Small and the amplitudes of free surface increase linearly with the amplitudes of exciting wave in the first vibration period of each case. (2) The relationship between the amplitudes of free surface and the amplitudes of exciting wave is obvious nonlinear when amplitude of free surface are large, and the increment ratio of the elevation of free surface is apparently lower than the increment ratio of exciting wave amplitude, such as in the seventh vibration period of each case.

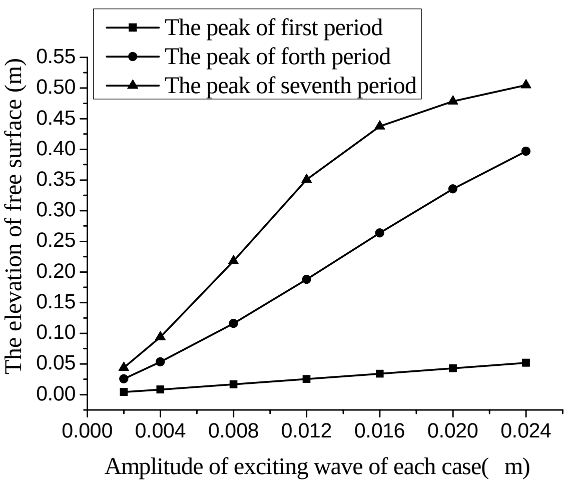


Fig4 Various elevation of free surface at right side of the wall with varying amplitudes of exciting wave

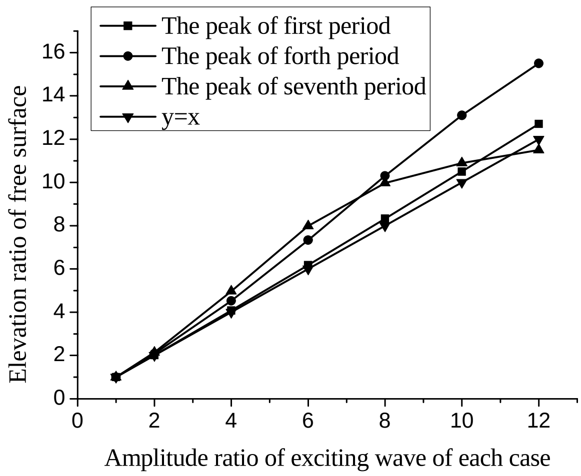


Fig5 Various elevation ratio of free surface at right side of the wall with varying amplitudes of ratio of exciting wave

Each peak value of dynamic response of the seventh period is the largest response in the whole time history during eight second. To illustrate the relationship between wave amplitude of hydrodynamic pressure, overturning force and overturning moment respectively, the ratio of the seventh peaks of these dynamic response waves of each case to case one are shown in Fig6. The characteristic of effects on period due to large amplitude sloshing is given in Fig7.

It can be shown from Fig6 that the amplitude increment of hydrodynamic pressure, overturning force and overturning moment are far higher than the amplitude increment of exciting wave and obvious nonlinear dynamic magnification exist. Together with Fig1, the conclusion can be obtained from Fig7 that the sloshing periods are lengthened with the sloshing amplitudes heightening.

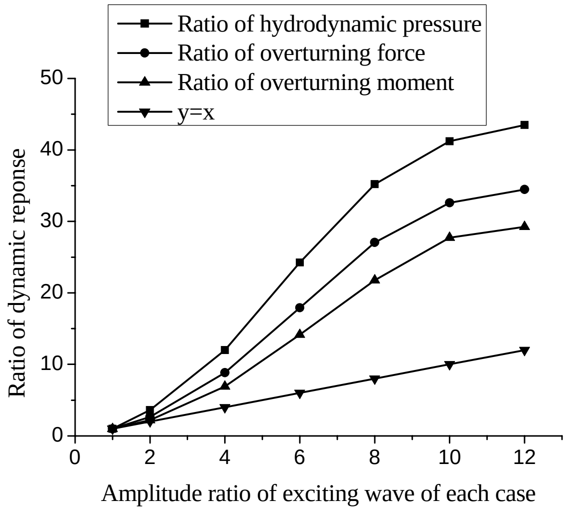


Fig6 Various dynamic responses ratio with varying amplitudes ratio of exciting wave

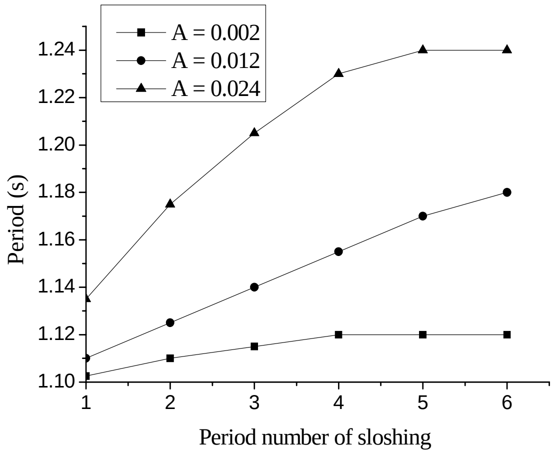


Fig7 The characteristics of effects on period due to amplitude heightening

3.2 Characteristics resulted from varying frequency of exciting wave

In the research of the relationship between frequency of exciting wave and the frequency of dynamic response, the exciting wave is horizontal displacement $X(t) = A\sin\omega t$, in which A=0.002m and $\omega = c\omega_1$. The range of circular frequency ratio c is from 0.5 to 2.0 and the detail is illustrated in Table2.

Table2 Different cases of varying frequency of exciting wave

Cases of computation	1	2	3	4	5	6
Circular frequency ratio	0.5	0.9	0.999	1.1	1.5	2.0
Frequency(Hz)	0.458	0.825	0.916	1.009	1.375	1.834

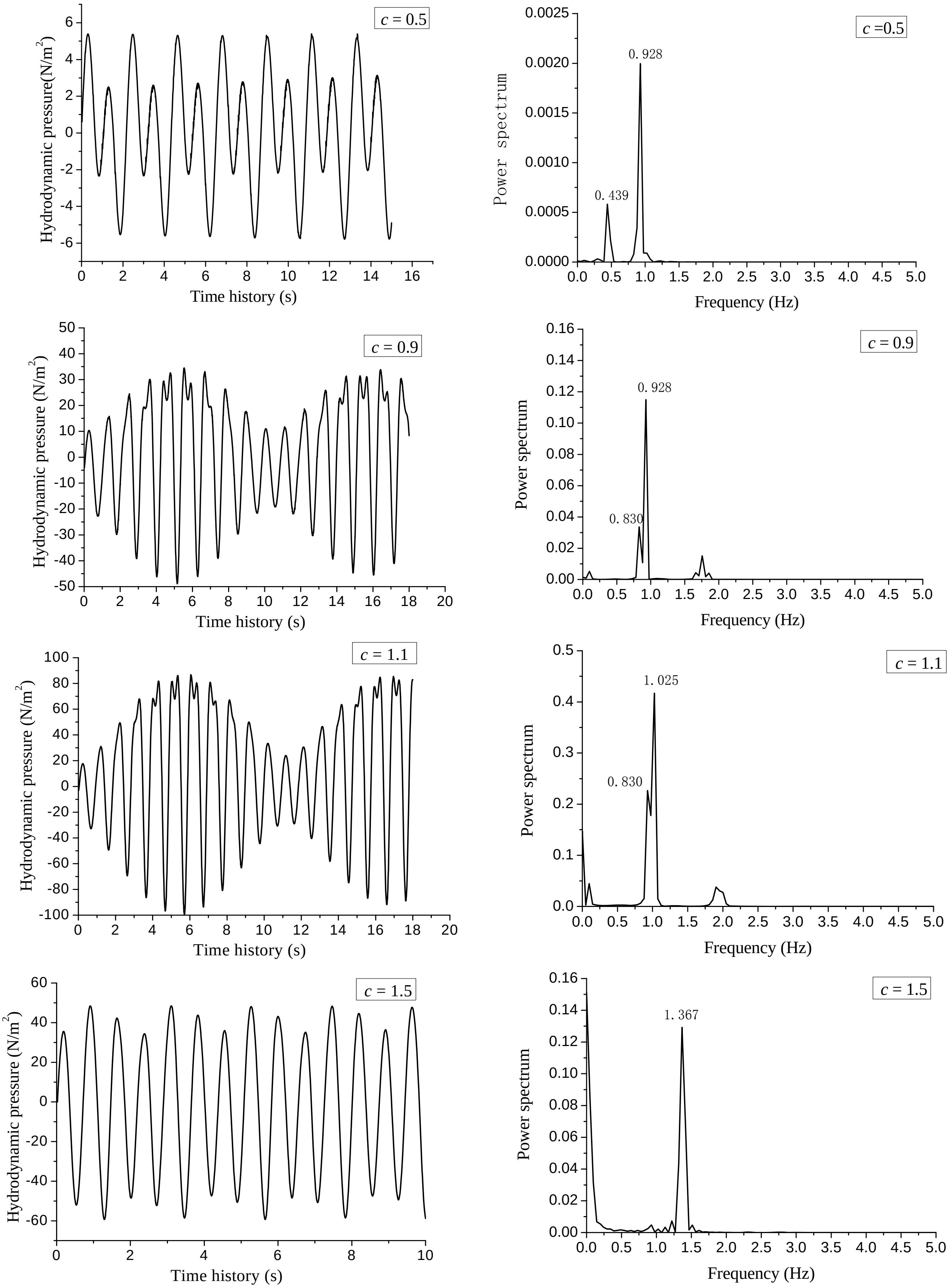
To learn the frequency component of dynamic response, FFT power spectrum analyses are carried out. And the main principal frequencies of dynamic response are compared with the frequencies of exciting wave and natural frequencies which are shown in Table3.

Table3 Natural frequency of water in rectangular duct

Number	Natural frequency(Hz)
1	0.917322
2	1.316811
3	1.613123
4	1.86268

It can be known from section 2.1 that the wave profiles of the elevation of free surface, hydrodynamic pressure, overturning force and overturning moment which are excited by same periodic displacement wave are analogical. So, only hydrodynamic pressure results are displayed in Fig8.

The results form observing the Fig 8 is following.(1)If c equal 0.5 or 0.9 , the frequency of exciting wave is lower than the fundamental natural frequency, the most dominant frequency of time history of dynamic responses is 0.928, which is very approaching the fundamental natural frequency, and the next main frequency is 0.439or 0.830, which is very near the frequency of exciting wave, 0.458 and 0.825. This illustrate that the most dominant frequency


c = 0.5
Hydrodynamic pressure(N/m2)
Time history (s)
c =0.5
0. 928
0. 439
Power spectrum
Frequency (Hz)
c = 0.9
Hydrodynamic pressure (N/m2)
Time history (s)
c = 0.9
0. 928
0. 830
Power spectrum
Frequency (Hz)
c = 1.1
Hydrodynamic pressure (N/m2)
Time history (s)
c = 1.1
1. 025
0. 830
Power spectrum
Frequency (Hz)
c = 1.5
Hydrodynamic pressure (N/m2)
Time history (s)
c = 1.5
1. 367
Power spectrum
Frequency (Hz)

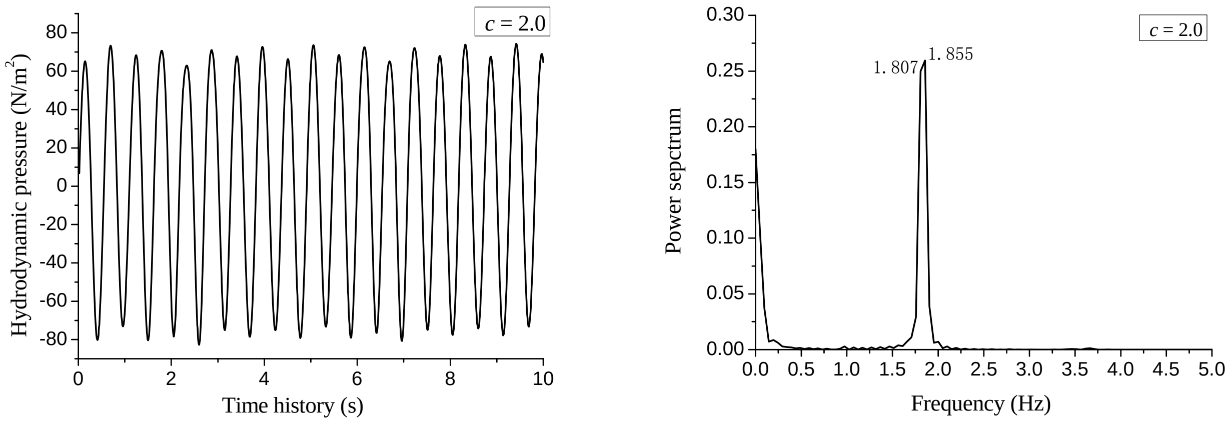


Fig8 Hydrodynamic pressure and corresponding power spectrum with varying exciting wave frequency ratio

of dynamic responses is the fundamental natural frequency, and next is the frequency of exciting wave when the frequency of exciting wave is lower than the fundamental natural frequency. (2) If c equal 1 .1, 1.5 or 2.0, the frequency of exciting wave is higher than the fundamental natural frequency, the most dominant frequency of time history of dynamic responses is 1.025, 1.367 and 1.832, the mean value of 1.807and 1.855, which are very near the frequency of exciting wave, 1.009，1.375 and1.8345. This illustrate that the most dominant frequency of time history of dynamic responses is the frequency of exciting wave when the frequency of exciting wave is higher than the fundamental natural frequency.

4 CONCLUSION

The parameter analyses of nonlinear characteristics of dynamic responses due to large amplitude sloshing are carried out under varying amplitudes and frequencies of harmonic displacement wave exciting. The main conclusions are following.

(1)Dynamic responses of gradually enhanced amplitude are excited when the frequency of exciting wave is close to fundamental natural frequency. The wave profile of each elevation of free surface, hydrodynamic pressure , overturning force and overturning moment are analogical respectively, meanwhile, sloshing periods are lengthened as the sloshing amplitudes are heightened.

(2)The amplitude increment of hydrodynamic pressure, overturning force and overturning moment are far higher than the amplitude increment of exciting wave and obvious nonlinear dynamic magnification exist when the large amplitude sloshing occur.

(3)The most dominant frequency of dynamic responses is the fundamental natural frequency, and next is the frequency of exciting wave when the frequency of exciting wave is lower than the fundamental natural frequency. The most dominant frequency of time history of dynamic responses is the frequency of exciting wave when the frequency of exciting wave is higher than the fundamental natural frequency.

REFERENCES

[1] Chen houqun .(2003).Seismic safety of the South-to-North Water Transfer Project，*Journal of China Institute of Water Resources and Hydropower Research*,**1:1**,17-21. (in Chinese).

[2] Zhang Junfa, Wang Kecheng.(1999).Seismic response reduction for aqueduct by using LRB. *JOURNAL OF HYDRAULIC ENGINEERING*. **10**,65-69. (in Chinese).

[3] LIU Yun he, CHEN Hou qun.(2003). Aseismic effect of lead rubber bearing for large scaled aqueduct . *JOURNAL OF HYDRAULIC ENGINEERING*.**12**,98-103. (in Chinese).

[4] Zhuang Zhong hua, Li Min xia.(2002).Basic theory on aqueduct bridge vibration control using lsolation

and energy dissipation hybrid system.*Noise and Vibration Control*.**2**,10-12. (in Chinese).

[5] Okamoto T, Kawahara M.(1990).Two-dimension sloshing analysis by Lagrangian finite element method[J].*International Journal for Numerical Methods in Fluids*.**11**,453-477.

[6] Ramaswamy B,Kawahara M. (1987). Arbitrary Lagrangian-Eulerian finite element method for unsteady,convetive, incompressible viscous free surface flow. *International Journal for Numerical Methods in Fluids*, **7** ,1053-1075.

[7] Wu Yi, Muo Haiou, Yang Cun.(2003) . ALE Simulation of Large Sloshing of Water in U-shaped Aqueduct.*Journal of South China University of Technology*, **31:9**,90-93. (in Chinese).

[8] Nakayama T,Washizu K. (1981). The boundary element method applied to the analysis of two-dimensional nonlinear sloshing problems.*International Journal for Numerical Methods in Engineering*,**17:11**,1631-1646.

[9] Yuchun,Lou Menglin. (2000) Bem simulation of nonlinear sloshing for aqueduct fluid.*Earthquake Engineering and Engineering Vibration*.**20:2**,51-56. (in Chinese).

[10] Hakan AKYILDIZ, M Serdar.(2002). Numerical Computation of Hydrodynamic Loads on Walls of a Rigid Rectangular Tank Due to Large Amplitude Liquid Sloshing. *Turkish J. Eng. Env. Sci.*.**26** , 429 -445.

[11] J R Cho, H W Lee.(2004).Numerical study on liquid sloshing in baffled tank by nonlinear finite element method. *Comput. Methods Appl. Mech. Engrg*.**193**,2581–2598.

[12] Housner G W. (1957).Dynamic pressure on accelerated fluid containers. *Bulletin of the seismological of America*, **47:1**,15-35.

[13] Housner G W. (1963).The dynamic behavior of water tanks. *Bulletin of the seismological of America*,**53:2**,381-387.

[14] Ju Rong chu.(1983).The coupled Vibration theory of elastic structure and fluid. Earthquake Publisher