J. Marine. Sci. Appl. (2008) 7:77-81
DOI: 10.1007/s11804-008-7040-x

Fluid-structure coupled analysis of underwater cylindrical shells

AI Shang-mao* (艾尚茂), **SUN Li-ping** (孙丽萍)

College of Shipbuilding Engineering, Harbin Engineering University, Harbin 150001, China

Abstract: Underwater cylindrical shell structures have been found a wide of application in many engineering fields, such as the element of marine, oil platforms, etc. The coupled vibration analysis is a hot issue for these underwater structures. The vibration characteristics of underwater structures are influenced not only by hydrodynamic pressure but also by hydrostatic pressure corresponding to different water depths. In this study, an acoustic finite element method was used to evaluate the underwater structures. Taken the hydrostatic pressure into account in terms of initial stress stiffness, an acoustical fluid-structure coupled analysis of underwater cylindrical shells has been made to study the effect of hydrodynamic pressures on natural frequency and sound radiation. By comparing with the frequencies obtained by the acoustic finite element method and by the added mass method based on the Bessel function, the validity of present analysis was checked. Finally, test samples of the sound radiation of stiffened cylindrical shells were acquired by a harmonic acoustic analysis. The results showed that hydrostatic pressure plays an important role in determining a large submerged body motion, and the characteristics of sound radiation change with water depth. Furthermore, the analysis methods and the results are of significant reference value for studies of other complicated submarine structures.

Keywords: underwater structure; fluid-structure coupled analysis; initial stress; natural frequency; sound radiation

CLC number: U661.44 **Document code:** A **Article ID:** 1671-9433(2008)02-0077-05

1 Introduction

The coupled vibration analysis of underwater structures has been of great interest and a challenging task. Numerous factors affect the motions of underwater structures. The prediction of such motions requires various hydrodynamic coefficients including the added mass, damping, and water depth is also an important factor. In this paper, to easily demonstrate the method, a simple and useful cylindrical structure is analyzed, and the influence of fluid on the natural frequencies and sound radiation has been taken into account. The method can be used for reference in the analysis of complicated submarine structures.

Cylindrical shells are the main elements of many types of engineering structure, such as aerospace, marine, petrochemical, nuclear and power generation, etc. Thus its vibration problem is an important topic in engineering and many methods have been employed to study the vibration problem by many previous authors for decades. The vibration problem of a cylindrical shell in vacuum has been fully studied by many authors. Vibration analysis of cylindrical shells immerged in water is the fluid-solid interaction problem indeed. Vibrations of a solid body caused by the interaction between the body and the surrounding fluid frequently make noise. Underwater cylindrical shells have also been extensively investigated, both theoretically and experimentally. Reviews of this research include those by XU M.B.[1]. Additionally, the published literature on finite element modeling has usually cancelled out initial stresses in the models of the acoustic vibration analysis.

In this study, the fluid effect on vibration characteristics of an underwater cylindrical shell has been evaluated by commercial FEM software Ansys. The fluid effect mainly causes hydrostatic pressure and hydrodynamic pressures. The hydrostatic pressure has been taken into account in terms of initial stress stiffness. For natural frequency analysis, by comparisons with the frequencies obtained by the present method and by the added mass method in Ref.[2], attempt is made to conclude whether the present method is reliable or not. And for acoustic analysis, the effect of hydrostatic pressure on the

Received date: 2007-05-25.
Foundation item: Supported by China National 111 Project Under Grant No. B07019.
***Corresponding author Email:** isomer007@163.com

characteristics of sound radiation is analyzed with different water depths. At last, a harmonic acoustic analysis using a frequency sweep between 500 Hz and 1 500 Hz has been performed with a complicated underwater stiffened cylindrical shell considering water depth h=50 m.

2 Theory of acoustic fluid-structure coupled analysis

In this paper, the finite element approach for both structure and fluid domain has been used to deal with the coupled fluid-solid interaction problem. The hydrodynamic pressure acting on the shell is developed under dynamic interfacial coupling conditions.

2.1 Equations of acoustic fluid matrixes

In acoustical fluid-structure interaction problems, the structural dynamic equation needs to be considered along with the Navier-Stokes equations of fluid momentum and the flow continuity equation. It assumes that the fluid is compressible, but allows only relatively small pressure change with respect to the mean pressure. Also, the fluid is assumed to be non-flowing and inviscid (that is, viscosity causes no dissipative effects). Uniform mean density and mean pressure are assumed, with the pressure solution being the deviation from the mean pressure, not the absolute pressure. After the wave equation is discredited, the acoustic wave equation is written in matrix notation

$$\boldsymbol{M}_{\mathrm{e}}^{p}\ddot{\boldsymbol{P}}_{\mathrm{e}}+\boldsymbol{K}_{\mathrm{e}}^{p}\boldsymbol{P}_{\mathrm{e}}+\rho\boldsymbol{R}_{\mathrm{e}}^{\mathrm{T}}\ddot{\boldsymbol{U}}_{\mathrm{e}}=\boldsymbol{0}, \tag{1}$$

where $\boldsymbol{M}_{\mathrm{e}}^{p}=\frac{1}{c^{2}}\int_{v}\boldsymbol{N}\boldsymbol{N}^{\mathrm{T}}\mathrm{d}v$ is fluid mass matrix, $\boldsymbol{K}_{\mathrm{e}}^{p}=\int_{v}\boldsymbol{B}\boldsymbol{B}^{\mathrm{T}}\mathrm{d}v$ is fluid stiffness matrix, $\boldsymbol{R}_{\mathrm{e}}=\int_{s}\boldsymbol{N}\boldsymbol{n}^{\mathrm{T}}\boldsymbol{N}'^{\mathrm{T}}\mathrm{d}s$ is coupling mass matrix, $\boldsymbol{P}_{\mathrm{e}}$ is nodal pressure vector, $\boldsymbol{N}$ is element shape function for pressure, c is speed of sound in fluid medium, ρ is mean fluid density, and $\boldsymbol{n}$ is normal at the fluid boundary.

2.2 Acoustic fluid-structure coupling matrixes equations

As we know, the structural equation is rewritten as

$$\boldsymbol{M}_{\mathrm{e}}\ddot{\boldsymbol{U}}_{\mathrm{e}}+\boldsymbol{K}_{\mathrm{e}}\boldsymbol{U}_{\mathrm{e}}+\boldsymbol{C}_{\mathrm{e}}\dot{\boldsymbol{U}}_{\mathrm{e}}=\boldsymbol{F}_{\mathrm{e}}+\boldsymbol{F}_{\mathrm{e}}^{\mathrm{pr}}, \tag{2}$$

where $\boldsymbol{M}_{\mathrm{e}}$, $\boldsymbol{C}_{\mathrm{e}}$ and $\boldsymbol{K}_{\mathrm{e}}$ are the structure element mass matrix, structural element damping matrix and structural element stiffness matrix respectively, $\boldsymbol{F}_{\mathrm{e}}^{\mathrm{pr}}$ is the fluid pressure load acting on the interface in order to completely describe the fluid-structure interaction problem

$$\boldsymbol{F}^{\mathrm{pr}}=\int_{s}\boldsymbol{N}'\boldsymbol{N}^{\mathrm{T}}\boldsymbol{n}\mathrm{d}s\boldsymbol{P}_{\mathrm{e}}=\boldsymbol{R}_{\mathrm{e}}\boldsymbol{P}_{\mathrm{e}}. \tag{3}$$

Eqs.(2)~(3) describe the complete finite element discretization equations for the fluid-structure interaction problem and are written in assembled form as

$$\begin{bmatrix}\boldsymbol{M}_{\mathrm{e}} & 0\\ \boldsymbol{M}^{\mathrm{fs}} & \boldsymbol{M}_{\mathrm{e}}^{P}\end{bmatrix}\begin{bmatrix}\ddot{\boldsymbol{U}}_{\mathrm{e}}\\ \ddot{\boldsymbol{P}}_{\mathrm{e}}\end{bmatrix}+\begin{bmatrix}\boldsymbol{C}_{\mathrm{e}} & 0\\ 0 & \boldsymbol{C}_{\mathrm{e}}^{P}\end{bmatrix}\begin{bmatrix}\dot{\boldsymbol{U}}_{\mathrm{e}}\\ \dot{\boldsymbol{P}}_{\mathrm{e}}\end{bmatrix}+$$

$$\begin{bmatrix}\boldsymbol{K}_{\mathrm{e}} & \boldsymbol{K}^{\mathrm{fs}}\\ 0 & \boldsymbol{K}_{\mathrm{e}}^{P}\end{bmatrix}\begin{bmatrix}\boldsymbol{U}_{\mathrm{e}}\\ \boldsymbol{P}_{\mathrm{e}}\end{bmatrix}=\begin{bmatrix}\boldsymbol{F}_{\mathrm{e}}\\ 0\end{bmatrix}. \tag{4}$$

If $\boldsymbol{F}_{\mathrm{e}}$ equals zero, the Eq.(4) will be changed into a modal analysis equation.

2.3 Effect of initial stress stiffed matrixes

Taking the effect of initial stress into account, the tangent matrix in Eq.(2) has the following form

$$\boldsymbol{K}=\boldsymbol{K}_{\mathrm{e}}+\boldsymbol{K}_{G}, \tag{5}$$

where $\boldsymbol{K}_{\mathrm{e}}$ is the usual stiffness matrix, $\boldsymbol{K}_{\mathrm{G}}$ is the stress stiffness (or geometric stiffness) contribution, written symbolically as

$$\boldsymbol{K}_{\mathrm{e}}=\int\boldsymbol{B}^{\mathrm{T}}\boldsymbol{D}\boldsymbol{B}\mathrm{d}v,$$

$$\boldsymbol{K}_{\mathrm{G}}=\int\boldsymbol{G}^{\mathrm{T}}\boldsymbol{\tau}\boldsymbol{G}\mathrm{d}v,$$

where $\boldsymbol{G}$ is the matrix of shape function derivatives, and $\boldsymbol{\tau}$ is the matrix of the current Cauchy (true) stresses.

3 Experimental verification of natural analysis

In this paper, the five natural frequencies of an annular ring submerged in water extending to infinity will be determined. A natural frequency analysis is carried out assuming the outer diameter of the ring to be 0.260 35 m, 1 460 m/s for the speed of sound, and 0.254 m for the inner diameter.

The infinite acoustic elements that absorb the pressure waves are used, simulating the outgoing effects of a domain that extends to infinity beyond fluid elements. They can provide a second-order absorbing boundary condition so that an outgoing pressure wave reaching the boundary of the model is absorbed with minimal reflections back into the fluid domain.

According to the Ref.[1], the distance from the center of the ring to the infinite elements will at least be equal to $(D/2)+0.2\lambda$, where D is the outer diameter of the ring and $\lambda=c/f$ is the dominant wavelength of the pressure waves. For this case, however, $(D/2)+0.2\lambda=0.260\,35+0.2\times(1\,460/36)\approx 8.37$, which is forty times greater than D. Because the dominant wave length of the pressure waves is much greater than D, a distance of 2 times the outer radius of the ring will be used when using the acoustic infinite element. The finite element type in the analysis model of the infinite acoustic elements is shown in Fig.1.

In the Ref.[2], the potential theory is used to deduce the relationship between the added mass and wave numbers of an infinitely long cylindrical shell vibrated in an infinite fluid domain, the unity of added mass method and exact method is demonstrated. The added mass equation is given by

$$m_{\text{add}} = \iint_{\Gamma} \sigma_{\text{add}} \mathrm{d}\Gamma , \qquad (6)$$

where $\sigma_{\text{add}}=\rho R\dfrac{K_n(m)}{mK_{n+1}(m)-nK_n(m)}$, kg/m^2; n is circumferential wave numbers of cylindrical shell; m is longitudinal wave numbers of cylindrical shell; K is the modified Bessel function of the second kind; ρ is the density of water; and Γ is fluid-structure coupling boundary.

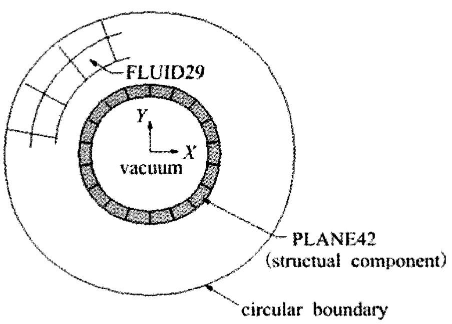


Fig.1 Model of the infinite acoustic elements

In order to further validate the finite element method (FEM), the study has been carried out on an infinitely long cylindrical shell vibrated in an infinite fluid domain, the density of fluid is $\rho_w=1\,030$ kg/m^3 and the one of shells is $\rho_{\text{shell}}=7\,929$ kg/m^3. Table 1 compares the results of natural frequencies for the infinite shell, $f_n^{(1)}$ is obtained by FEM of acoustics and $f_n^{(2)}$ is acquired by Bessel Function Approach. It is observed that there is a good check for the validity of the present analysis on the effect of hydrostatic pressure.

Table 1 Comparison of $f_n^{(1)}$ and $f_n^{(2)}$

Mode number	$f_n^{(1)}$/Hz	$f_n^{(2)}$/Hz	Error/%
n=2	33.60	34.51	2.71
n=3	105.86	107.98	2.00
n=4	220.70	224.65	1.78
n=5	381.52	388.65	1.87

4 Case study

4.1 Fluid effect on vibration characteristics

The same model of cylindrical shell shown in chapter 3 is used. Table 2 lists the results of the natural frequencies for the infinite cylindrical shell in three different conditions:

1) In vacuum;

2) Immerged in water considering hydrodynamic pressure, i.e. direct analysis by FEM of acoustics, without considering water depth;

3) Immerged in water, considering hydrodynamic and hydrostatic pressure caused by water depth h=200 m.

And Fig.2 and Fig.3 present normal circumferential mode patterns for the infinite cylindrical shells with the sound pressure contour under condition 2) when n=2, 3.

Table 2 Comparison of three different conditions/Hz

Conditions	Natural frequency				
	n=1	n=2	n=3	n=4	n=5
1)	—	60.81	172.97	334.40	546.59
2)	163.02	34.51	107.98	224.65	388.65
3)	63.31	59.49	64.02	241.11	456.34

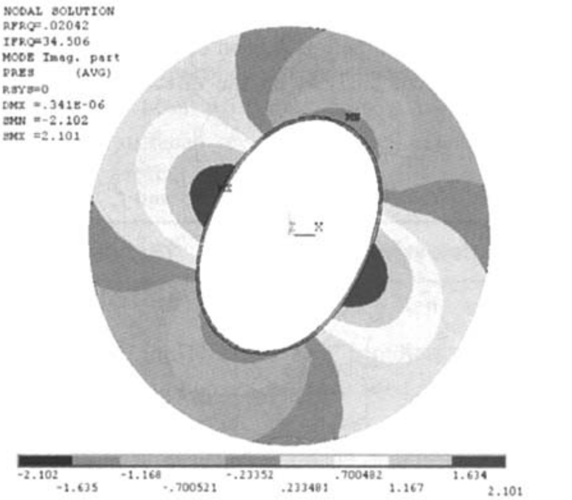


Fig.2 Circumferential mode pattern with the sound pressure contour under condition 2) when n=2

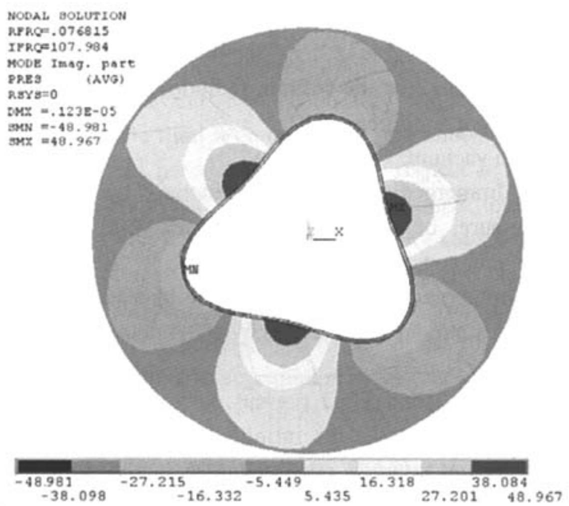


Fig.3 Circumferential mode pattern with the sound pressure contour under condition 2) when n=3

A conclusion can be drawn from the results that hydrodynamic pressure and hydrostatic pressure play an important role in determining natural frequencies of underwater cylindrical shell. Frequencies will decrease if considering hydrodynamic pressures, and considering water depth can lead to increase of the nature frequencies value of underwater structure.

4.2 Effect of still water pressure on sound radiation

In the first example, using the same infinitely long cylindrical shell as mention in 4.1, a harmonic acoustic analysis has been performed with the frequency sweep between 30 Hz and 60 Hz. The cases include:

1) Sound radiation analysis not considering water depth;

2) Sound radiation analysis considering water depth h=200 m.

Fig.4 shows the variation of sound pressure level in case 1) and case 2). From Fig.4, a conclusion can be drawn that the hydrostatic pressure plays an important role in determining a large submerged body's motion, and the characteristics of sound radiation change with water depth.

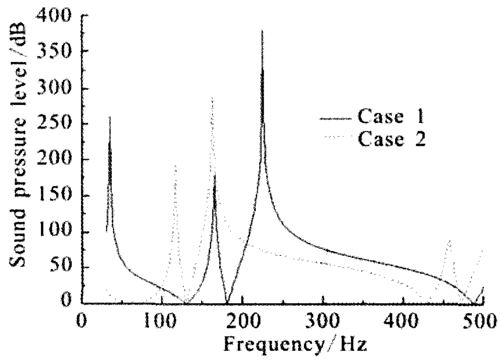


Fig.4 Variation of sound pressure level with different harmonic frequencies at node 60, which location is (0.336 74, 0.139 48)

The second example is a more complicated underwater structure, which is axisymmetric about X-axis, and its section is shown in Fig.5.

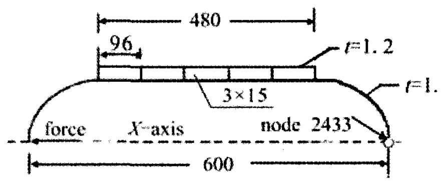


Fig.5 Section of the axisymmetric underwater structure (unit: mm)

A harmonic acoustic analysis using a frequency sweep between 500 Hz and 1 500 Hz has been performed with considering water depth h=50 m. Fig.6 presents the sound pressure level of the second example's structure, which can be used as a reference for other complicated structure. The sound pressure level is defined as

$$L_p = 20\lg(P/P_0),$$

where $P_0 = 1\times10^{-6}$ Pa is the reference pressure.

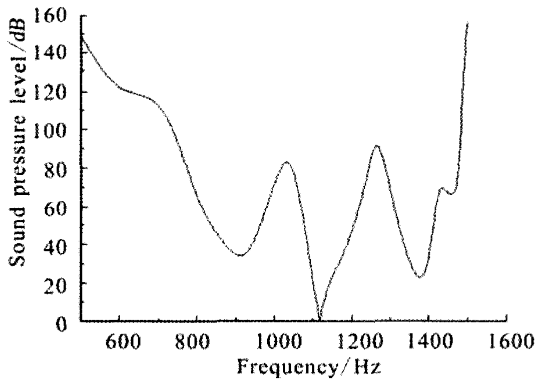


Fig.6 Sound pressure level with different harmonic frequencies at node 2 433

5 Conclusions

Using the finite element method of acoustics, the natural frequencies and sound pressure of underwater structure are analyzed in this paper. By comparison between the acoustic method and the added mass method, there is a good check for the validity of the present analysis on the effect of hydrostatic pressure. The vibration characteristic of underwater structures is influenced not only by hydrodynamic pressure but also by hydrostatic pressure usually corresponding to different depth. It is a feasible method that hydrostatic pressure has been taken into account in terms of initial stress stiffness. The results show that hydrostatic pressure plays an important role in determining a large submerged body motion, and the characteristics of sound radiation change with water depth. The analysis methods can be used as a reference for studying other complicated submarine structures.

References

[1] XU M B. Three methods for analyzing forced vibration of a fluid-filled cylindrical shell[J]. Applied Acoustics, 2003, 64(7): 731-752.

[2] LIU Z Z, HUANG Y Y, et al. Relationship between added mass and wave numbers of an infinitely long cylindrical shell submerged in water[J]. Shipbuilding of China, 1998(2): 52-56(in Chinese).

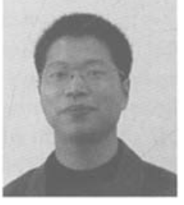
[3] LAULAGNET B, GUYADER J L. Modal analysis of a shell's radiation in light and heavy fluid[J]. Journal of Sound and Vibration, 1989, 131(3): 397-415.

[4] CRAGGS A. A finite element model for acoustically lined small rooms[J]. Journal of Sound and Vibration, 1986, 108(2): 327-337.

[5] XIE G M. The effects of hydrostatic pressure on acoustic radiation of ring-stiffened cylindrical shells[J]. Journal of Wuhan University of Technology, 1995, 17(1): 77-79(in Chinese).

[6] SUN L P, AI S M, et al. Vibro-acoustic statistical energy analysis of a classic submarine structure[J]. Journal of Harbin Engineering University, 2006, 27(Suppl. 2): 507-512(in Chinese).

[7] CHEN Y P. Study on the acoustic design of stiffened cylindrical shell[D]. Wuhan: Huazhong University of Science & Technology, 1999(in Chinese).



AI Shang-mao was born in 1978. He is a Ph.D. student of Harbin Engineering University. His current research interests include fluid-structure coupled analysis, vortex induced vibration, etc.

SUN Li-ping was born in 1962. She is a professor of Harbin Engineering University. Her current research interests include deepwater engineering, etc.

Fluid-structure coupled analysis of underwater cylindrical shells

作者： AI Shang-mao， SUN Li-ping
作者单位： College of Shipbuilding Engineering, Harbin Engineering University, Harbin 150001, China

刊名： 船舶与海洋工程学报
英文刊名： JOURNAL OF MARINE SCIENCE AND APPLICATION
年，卷(期)： 2008，7(2)
引用次数： 0次

参考文献(7条)

1. XU M B Three methods for analyzing forced vibration of a fluid-filled cylindrical shell 2003(07)

2. LIU Z Z.HUANG Y Y Relationship between added mass and wave numbers of an infinitely long cylindrical shell submerged in water 1998(02)

3. LAULAGNET B.GUYADER J L Modal analysis of a shell's radiation in light and heavy fluid 1989(03)

4. CRAGGS A A finite element model for acoustically lined small rooms 1986(02)

5. XIE G M The effects of hydrostatic pressure on acoustic radiation of ring-stiffened cylindrical shells[期刊论文]-Journal of Wuhan University of Technology 1995(01)

6. SUN L P.AI S M Vibro-acoustic statistical energy analysis of a classic submarine structure 2006(z2)

7. CHEN Y P Study on the acoustic design of stiffened cylindrical shell

相似文献(0条)

本文链接：http://d.g.wanfangdata.com.cn/Periodical_hebgcdxxb-e200802002.aspx
下载时间：2010年6月22日