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# The Analysis of Vibro-Acoustic Coupled Characteristics of Ball Mill Cylinder Under Impact Excitation

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**Abstract**

In this paper, a fully coupled vibro-acoustic finite element model (FEM) is developed to characterize the structural and acoustic coupling of a flexible thin shell by a cylinder-like cavity. The combined integral-modal approach is used to handle the acoustic pressure inside the cavity. Based on the modal proposed, the impact excitation effect on the vibro-acoustic behavior of the coupled system is investigated using the modal radiation efficiency at particular frequencies. Simulations are conduced to examine the effect on acoustic natural frequencies, acoustic pressure and structural responses using ANSYS and SYSNOISE software.

**Keywords:** Structural modal, Acoustic modal, Vibro-acoustic coupling, Ball Mill

## 1. Introduction

The noise radiation by a vibrating structure is of particular interest for many industrial applications. Typical examples include cabin noise inside vehicles and aircraft, which are usually modeled by a cavity enclosed by a flexible vibrating structure. In the past, a large amount of efforts has been devoted to investigating the vibro-acoustic behavior of such systems, such as analysis of structural–acoustic modal interaction[1] and sound radiation prediction [2-3]. In general, structural vibration radiates sound into the enclosure through its coupling with acoustic modes. Therefore, an accurate characterization of the sound–structural interaction is essential for the prediction of acoustic field. Some techniques and methods such as the Green theorem, acousto-elastic theory and acoustic modal theory have been developed so far to address the increasing interest on sound–structure interactions of varied geometrical cavity. Base on those theories, the vibro-acoustic characteristics of Ball Mill cylinder are searched using a fully coupled vibro-acoustic finite element model and combined integral-modal approach [4-5].

Ball Mills are larger-scale crush equipment, which are used to crush material in chemical process, steam electric power generation, metallurgy, cement production, etc. In the working state, the noise of Ball Mill affected the health of people, decreased the production efficiency. With the development of acoustic theories and techniques, more attentions are paid to the vibratory noise control of Ball Mill. Understanding the mechanism of vibratory noise of Ball Mill is essential for controlling it. From the past researches [6-8] of Ball Mill noise, Ball Mill noise mainly includes cylinder structural vibratory noise, motor electromagnetic noise and gear mesh noise, in which the cylinder structural vibratory noise is the most important contributor of structural vibration radiation sound.

This paper is a new research about Ball Mill vibratory noise and attempts to provide some useful information of the relationship between structural vibration modal properties and acoustic radiation mode of cylinder and searches main acoustic radiation modes affected significantly by structural vibration using under impact excitation from cycle rolling steel balls inside the cylindrical cavity. A fully coupled vibro-acoustic finite element model and the combined integral-modal approach are used to research the vibro-acoustic characteristics of Ball Mill cylinder. Simulations are introduced to examine the effect on acoustic natural frequencies, acoustic pressure and structural responses by impact excitation.

**2. vibro-acoustic FEM modeling**

The structure under investigation is a cylinder-like enclosure with homogeneous and isotropic vibrating thin shell, as shown in Fig.1. In the linear-elastic system, the homogeneous Structure can be discrete by differential mass particles. Following this, the motion differential equation of cylinder under impact force $\{f_s\}$ is defined as

$$[M_s]\{\ddot{u}\}+[C_s]\{\dot{u}\}+[K_s]\{u\}=[A]^T\{p\}+\{f_s\} \tag{1}$$

where $[M_s]$, $[C_s]$, $[K_s]$ and $[A]$ are the structural mass matrix, the damping matrix, the stiffness matrix and the vibro-acoustic coupling coefficients matrix, respectively. $\{p\}$, $\{\ddot{u}\}$, $\{\dot{u}\}$ and $\{u\}$ are the acoustic pressure vectors inside the cavity, the acceleration vector, the velocity and the displacement at discrete nodes. $T$ denotes transpose.

For the litter damping acoustic field, the acoustic pressure P inside the enclosure satisfies the ideal fluid hypothesis, the discrete FEM equation can be written as

$$[M_a]\{\ddot{p}\}+[C_a]\{\dot{p}\}+[K_a]\{p\}=-\rho_a[A]\{\ddot{u}\} \tag{2}$$

Where $[M_a]$, $[C_a]$, $[K_a]$ and $\rho_a$ are the acoustic cavity mass matrix, the damping matrix, the stiffness matrix and acoustic fluid density, respectively.

Combined Eqs.(1) and Eqs.(2), structural-acoustic FEM equation is

$$[M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\}=\{f\} \tag{3}$$

Where

$$[M]=\begin{bmatrix}[M_a] & \rho_a[A]\\ 0 & [M_s]\end{bmatrix}\quad [C]=\begin{bmatrix}[C_a] & 0\\ 0 & [C_s]\end{bmatrix}\quad [K]=\begin{bmatrix}[K_a] & 0\\ -[A]^T & [K_s]\end{bmatrix}\quad x=\begin{Bmatrix}p\\ u\end{Bmatrix}\quad f=\begin{Bmatrix}0\\ f_s\end{Bmatrix}$$

Assumed $\ddot{u}=-\omega^2 u$, $\ddot{p}=-\omega^2 p$, Eigenequation of vibro-acoustic system can be described as

$$\left(\lambda^2[M]+\lambda[C]+[K]\right)\{\psi\}=0 \tag{4}$$

Where $\omega$, $\lambda$ and $\{\psi\}$ denote natural frequency of the coupling system, eigenvalues and eigenvectors of the Eigenequation(4).

**3. Results and discussions**

*3.1 structural modal analysis*

Under free state, the right of Eqs.(1) is equal to zero. The eigenvalues and eigenvectors computed from Eqs.(4) denote the natural frequencies and modal shapes of structure. Numerical analysis are conducted using the configuration shown in Fig.1 with a dimension of $\phi D\times L=3.8m\times 6.5m$ ,the thickness of the cylindrical thin shell is set as $h=0.08m$ ,the flexible rigidity and the density are 2e11 and 7800kg/m$^3$,respectively. Cylinder structural natural properties including modal frequencies and modal shapes can be solved using Block Lanczos arithmetic by ANSYS software with the 0.02 thickness Solid92 mesh cell. The results are shown in Table.1 and Fig.2(1-4). Table.1 presents the natural frequencies of cylinder. Under the 200Hz frequencies are main structural vibration frequencies. 30Hz and 81Hz are shaft and circle direction vibration, which are not the vital influential frequencies for cylinder shell sound radiation. We therefore neglect them during the following discussion. Fig.2(2) shows the maximal magnitude of structural vibration occurs on the mid of Cylinder shell with the 0.01m distorting displacement.

*3.2 acoustic modal analysis*

Acoustic modal and radiation efficiency of the acoustic cavity are like the structural nature frequencies and shapes. Acoustic modal is described a group independence orthogonal vectors and each vector represents a kind of sound radiation mode. The degree of sound radiation is shown by radiation efficiency. In research, we found that acoustic radiation efficiency only relates with geometrical figure and structural vibration characteristics and is independent of material properties and boundary conditions. Numerical analyses are conducted with the eigenequation(4), eigenvalues and eigenvectors represent acoustic radiation modal and radiation efficiency, respectively. The results from the simulation of SYSNOISE FEM are presented in Table.1 and Fig.3(1-4) and the frequency range from 20 to 200Hz.

*3.3 vibro-acoustic coupling analysis*

Following the above analysis, we research the vibro-acoustic characteristics of cylinder under the impact excitation from the cycle rolling steel balls inside the cylinder cavity. In working state, steel balls impact the cylindrical thin shell seasonally. The magnitude of impact force is up to 10GPa. The time of interaction is very short and is only several milliseconds. Under this state, we combine the structural vibration and acoustic radiation using combined integral-modal approach by system FEM. The calculated results are shown in Table.1 and Fig.4(a-d) at particular frequencies.

For the effect on the acoustic cavity from the structural surface impact force, the acoustic radiation mode has been changed at constant frequency. The Figures clearly indicate this.

**4. Conclusions**

This paper presents a vibro-acoustic modeling of Ball Mill Cylinder and analyzes the characteristics of cylinder's structure vibration –acoustic radiation coupling. Different from previous studies, emphasis is put on analyzing the effect on the vibro-acoustic behavior and the coupling mechanism of the system under impact excitation, leading to the following conclusions.

(1) Under impact excitation, Ball Mill Cylinder vibration frequencies concentrate on low frequency field and the range from 20 to 200Hz. The maximal magnitude of structural vibration is appeared on the mid of Cylinder shell.

(2) The acoustic radiation modal has close relationship with the structural vibration, The head four structural vibratory frequencies significantly affect the acoustic radiation of Cylinder shell and acoustic radiation efficiency can be amplified at resonated frequencies.

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Table 1. Natural frequencies (Hz) of the fluid cavity, the structure and the coupled system

| Mode number | Structural frequency | Mode number | Acoustic frequency | Mode number | Coupled frequency |
|---|---|---|---|---|---|
| 1 | 20.6 | - | - | 1 | 20.1 |
| - | - | 1 | 37.6 | 2 | 35.2 |
| - | - | 2 | 47.8 | 3 | 42.3 |
| 2 | 61.7 | 3 | 62.9 | 4 | 62.0 |
| 3 | 72.1 | 4 | 71.1 | 5 | 72.0 |
| - | - | 5 | 81.3 | - | - |
| - | - | 6 | 90.6 | 6 | 94.3 |
| 4 | 101.5 | 7 | 100.8 | 7 | 101.2 |
| 5 | 115.5 | 8 | 112.4 | 8 | 116.0 |
| 6 | 123.1 | 9 | 122.1 | 9 | 124.3 |
| - | - | 10 | 135.5 | 10 | 136.4 |
| 7 | 142.3 | 11 | 142.2 | 11 | 141.2 |
| 8 | 162.2 | - | - | 12 | 168.0 |
| 9 | 175.9 | 12 | 171.8 | 13 | 170.3 |
| 10 | 180.1 | 13 | 182.6 | 14 | 183.4 |

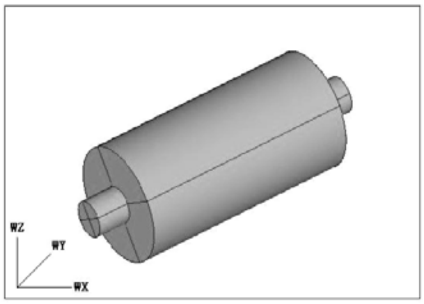


Figure 1. The structural sketch of Ball mill cylinder

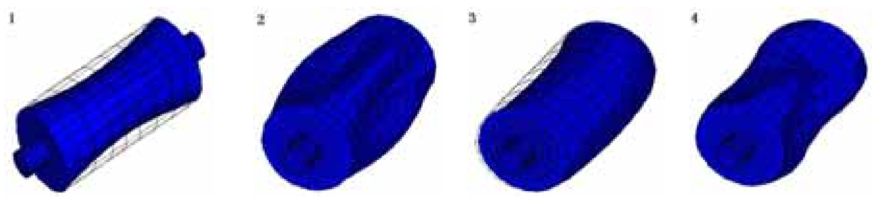


Figure 2. structural natural vibration modal shape of cylinder:
(1) $f$ = 61.7Hz, (2) $f$ = 72.1Hz (3) $f$ = 101.5Hz and (4) $f$ = 123.1Hz.

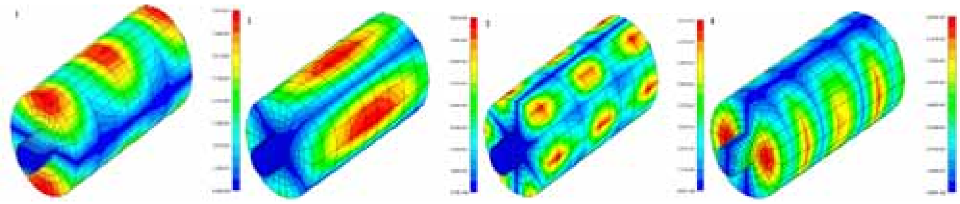

Figure 3. acoustic radiation modal shape of cylindrical cavity :
(1) $f$ = 62.9Hz, (2) $f$ = 71.1Hz (3) $f$ = 100.8Hz and (4) $f$ = 122.1Hz.

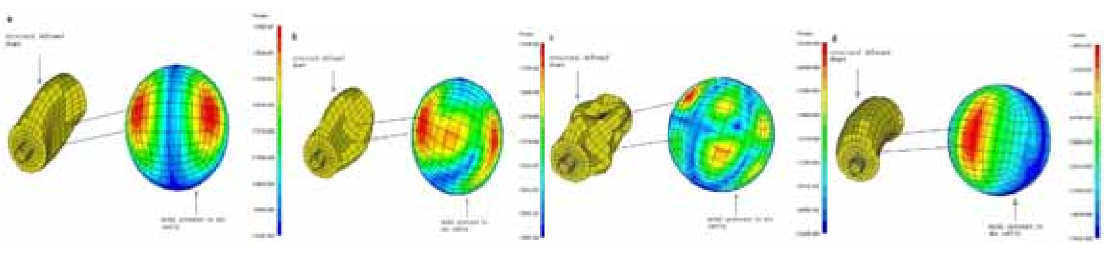

Figure 4. Deformed modal shape of coupled system:
(a) $f$ = 62.0Hz, (b) $f$ = 72.0Hz, (c) $f$ = 124.3 Hz and (d) $f$ = 101.2Hz.