Analysis of mechanical excitation transfer function between the source equipment and the sonar platform on board the ship

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Abstract. The work of this paper is aiming at a reasonable description or hypothesis of mechanical platform excitation of sonar array cavity on board the ship, which is necessary for comprehension of mechanism of the mechanical self-noise in sonar cavity. Through analytical deduction of the mechanical excitation transfer function between the source equipment and the sonar platform in a SPR (Source-Path-Receiver) system and corresponding numerical simulation, the excitation transmission characteristics is investigated. It is proved that weaker coupling between the solid sound propagation path and the sonar platform is essential for attenuation of sonar platform excitation. And in the condition of weak coupling, the excitation transmitted to the sonar platform is mainly dependent on the intrinsic vibration mode of the solid sound path.

1. Introduction

The mechanical self-noise in sonar array cavity, which is caused by the mechanical excitation transmitted through connection structures between the vibratory source equipment and the sonar cavity’s wall, might significantly weaken the detection performance of sonar at lower frequencies [1~3]. There are several methods for calculation of the fluid-structural vibration of the water filled enclosures such as sonar array cavity, e.g. Dowell’s modal coupling method [4, 5], FEM/BEM [6], etc. However, the characteristics of the exterior mechanical excitation of sonar array cavity has little been investigated before, which would be essential to the prediction, evaluation, and control of interior hydro acoustic noise. In this paper, through a hypothesis SPR (Source-Path-Receiver) model composed of vibratory source equipment, intermediate transmission structures, and sonar array cavity, the mechanical excitation transfer function between the source equipment and the sonar platform is deduced, and the influence of path and receiver mobility on excitation transmission is analyzed theoretically.
2. Theoretical SPR model for analysis of platform excitation of sonar array cavity

Figure 1 is a SPR model to describe the relationship between the excitations of vibratory source equipment and sonar platform on board the ship, where $Z_z$, $\phi$, $Y_H$ and $Y_C$ denote the inner impedance of source equipment, the four-pole parameter matrix of isolation devices for source equipment, the mobility matrix of intermediate hull structures, the four-pole parameter matrix of sonar platform interface devices and the mobility matrix of sonar cavity, respectively; and $F_S$, $F_I$, $F_H$, $F_E$ and $P_C$ are excitations forces, $V_S$, $V_I$, $V_H$, $V_E$ and $V_C$ are velocity responses at the acting points of corresponding excitations.

![Figure 1. The theoretical SPR model.](image)

According to the theory of transfer function, the excitation forces and velocity responses could be related as following.

$$
\begin{align*}
[ F_S ] &= Z_z [ V_S ] = [ Z_{SS} & Z_{SI} ] [ V_S ] \\
[ F_I ] &= \phi [ F_H ] = [ \phi_{11} & \phi_{22} ] [ F_H ] \\
[ V_H ] &= Y_H [ F_H ] = [ Y_{HH} & Y_{HE} ] [ F_H ] \\
[ F_E ] &= \gamma [ P_C ] = [ \gamma_{11} & \gamma_{22} ] [ P_C ] \\
V_C &= Y_C \cdot P_C
\end{align*}
$$

(1) (2) (3) (4) (5)

After some algebraic manipulation, a transfer function (matrix) $T$ could be obtained to describe the transmission relationship between the source excitation $F_S$ and sonar platform excitation $P_C$, i.e.

$$
P_C = T \cdot F_S = \left\{ \left[ ( \gamma_{11} + \gamma_{22} Y_C ) + ( H_{21} Y_S H_{12} - H_{22} ) ( \gamma_{11} + \gamma_{22} Y_C ) \right]^{-1} H_{21} Y_S Z_{IS} Z_{SS}^{-1} \right\} F_S
$$

(6)

Where $Y_S = \left( H_{11} - Z_{11} + Z_{IS} Z_{SS}^{-1} Z_{SI} \right)^{-1}$.

3. Analysis on excitation transmission characteristics

The difficulty in practical application of equation (6) lies in that the hull structures’ mobility matrix $Y_h$ would not be calculated or tested easily. On the other hand, no matter how complicated the $Y_h$ is, it would conform to a general description of admittance function. The difficulty in determining $Y_h$ is mainly in the “quantitative” sense. And that would not prevent us from carrying out some theoretical qualitative analysis on the transmission characteristics between the source excitation $F_S$ and the sonar platform excitation $P_C$. 
Figure 2 is a theoretical establishment for simulation of transmission of source excitation to sonar platform. The solid sound propagation path is simplified to a series of multistage elastic coupling structure composed of mass-spring-damping. The sonar array cavity is modeled by a rectangular water filled enclosure with one simply supported panel (for simulation of sonar platform). The boundary of the system is assumed to be rigid.

According to equations (1)~(3), via solving the following equation

\[
\begin{bmatrix}
    m_{H1} & 0 & 0 & 0 \\
    0 & J_{H1} & 0 & 0 \\
    0 & 0 & m_{H2} & 0 \\
    0 & 0 & 0 & J_{H2}
\end{bmatrix}
\begin{bmatrix}
    z_1 \\
    \theta_1 \\
    z_2 \\
    \theta_2
\end{bmatrix}
+ \begin{bmatrix}
    k_{w1} \\
    k_{w2}
\end{bmatrix}_{4 \times 4}
\begin{bmatrix}
    z_1 \\
    z_2
\end{bmatrix}
= \begin{bmatrix}
    F_1 \\
    T_1 \\
    F_{E1} + F_{E2} \\
    -\lambda_{L1}F_{E1} + \lambda_{R1}F_{E2}
\end{bmatrix}_{4 \times 1}
\]

(7)

Where

\[
k_{H1} = k_{H2} = k_{H} (1+j \eta_{H1}) \text{, } k_{H} = k_{H2} = k_{H} (1+j \eta_{H2}) \text{, } k_{H1} = k_{H1L} + k_{H1R} + k_{H} + k_{H2},
\]

\[
k_{H21} = (0.5k_{H1L} - 0.5k_{H1R} + \lambda_{L1}k_{H1} - \lambda_{R1}k_{H2})I_{L}, k_{H22} = (0.25k_{H1L} + 0.25k_{H1R} + \lambda_{L1}^2k_{H1} + \lambda_{R1}^2k_{H2})I_{L}^2,
\]

\[
k_{H23} = -k_{H1} - k_{H2}, k_{H24} = (-\lambda_{L1}^2k_{H1} + \lambda_{R1}^2k_{H2})I_{L}, k_{H25} = k_{H2L} + k_{H2R} + k_{H1} + k_{H2},
\]

\[
k_{H41} = (-\lambda_{L2}k_{H1} + \lambda_{R2}k_{H2})I_{L}, k_{H42} = -(-\lambda_{L1}^2k_{H1} + \lambda_{R1}^2k_{H2})I_{L},
\]

\[
k_{H43} = (0.5k_{H2L} - 0.5k_{H2R} + \lambda_{L2}k_{H1} - \lambda_{R2}k_{H2})I_{L}, k_{H44} = (0.25k_{H2L} + 0.25k_{H2R} + \lambda_{L2}^2k_{H1} + \lambda_{R2}^2k_{H2})I_{L}^2.
\]

The four-pole parameter matrix of sonar platform interface devices is expressed as

\[
\gamma_{11} = \gamma_{22} = \text{diag}(1,1), \gamma_{12} = 0, \lambda_{21} = j\omega \cdot \text{diag}\left[1/K_s(1+j\eta), 1/K_s(1+j\eta)\right]
\]

(8)

The mobility matrix of \(Y_c\) could be calculated as [1]
\[ Y_c = \left[ Y_{c_{ij}} \right]_{2 \times 2}, Y_{c_{ij}} = j\omega \sqrt{W^T} \left( \sigma_i \right) \left( \Omega_B \sqrt{M_B} \right)^{-1} X_B H \left( \omega \right) TW \left( \sigma_j \right) \] (9)

Where \( H \left( \omega \right) = \left( -\omega^2 M_c + \Omega_c^2 M_c \right)^{-1}, T = -X_A^H \left( \sqrt{M_A} \right)^{-1} L M_B^{-1} + X_B^H \Omega_B \left( \sqrt{M_B} \right)^{-1}, W, \Omega_B, \) and \( M_B \) are column vector of modal functions, diagonal matrices of natural frequencies and modal masses of sonar platform, respectively; \( X_A, X_B, L, \Omega_c, \) and \( M_c \) are modal matrices, fluid-structural coupling matrix, diagonal matrices of fluid-structural coupled frequencies and modal masses of sonar cavity, respectively, whose derivations have been expounded in reference [1].

A numerical analysis is carried out to investigate the influence of variation of receiver (sonar cavity) mobility \( Y_c \) on the excitation transmission characteristics, by comparing the sonar platform excitation \( P_c \) in the situation of the cavity filled or unfilled with water. Figure 3 demonstrates two typical situations: (a) when \( K_e < K_{cp} < K_{rb} \), which named as weak coupling, the sonar cavity mobility \( Y_c \) makes little influence on \( P_c \); (b) when \( K_{cp} < K_{rb} < K_y \), which named as strong coupling, the intrinsic modes of the solid sound propagation path and the sonar cavity are coupled to each other, which together have a significant effect on the spectrum of \( P_c \). Here, \( K_y \) is the stiffness of the sonar platform interface devices as shown in Figure 2, and \( K_{cp} \) and \( K_{rb} \) are the first order modal stiffness at the connection points of the sonar platform interface devices with the solid sound propagation path and the sonar platform, respectively. And moreover, the weak coupling mode could provide a significant reduction of sonar platform excitations.

Another two typical situations are demonstrated in Figure 4: (a) \( K_y < K_{cp} < K_{rb} \), (b) \( K_{cp} < K_{rb} < K_y \). Comparing Figure 4(a) with Figure 3(a), or Figure 4(b) with Figure 3(b), it could be found that if the stiffness of the solid sound propagation path become higher, the influence of receiver (sonar cavity) mobility \( Y_c \) on excitation transmission would become greater.
4. Conclusions
The work of this paper is aiming at a reasonable description or hypothesis of mechanical platform excitation of sonar cavity on board the ship, through theoretical analysis on excitation transmission characteristics in a SPR (Source-Path-Receiver) system. It could be concluded that:

(1) In the weak coupling situation, which means the stiffness of the sonar platform interface devices is much small than that of the sonar platform and the solid sound propagation path, the excitation transmitted to the sonar platform is mainly dependent on the intrinsic vibration mode of the solid sound propagation path.

(2) In the condition of the same sonar platform interface stiffness, greater solid sound path stiffness would cause greater influence of sonar cavity mobility on excitation transmission.

(3) Weaker coupling between the solid sound path and the sonar platform is beneficial to attenuation of sonar platform excitation.

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