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THE EFFECT OF FLOATING DECK STRUCTURES ON UNDERWATER RADIATED NOISE

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A concept for underwater machinery noise mitigation of future civil and military ships is the application of a common deck structure, supporting multiple machines, which is installed on resilient mounts on the ship's foundation structure. TNO is addressing the availability and testing of tools to be able to set realistic targets for the radiated noise signature and to verify future vessel designs against these targets.

The TNO Assessment Model for Radiated Underwater Sound (AMRUS) is a semi-empirical prediction tool to predict separate contributions of different resiliently machinery noise sources to the underwater radiated noise at far field locations. It is a compilation of measured machinery source acceleration levels, mounting transfer and ship transfer functions, which are present in a large database. Until recently, the effect of resiliently mounted ('floating') deck structures on machinery noise transmission was not included in AMRUS. To be able to the support the complex design process of a floating deck, a formulation of the deck mount transfer function has been derived. For that purpose this formulation is split into the separate deck structure input and transfer mobilities, which can serve as acoustic indicators for a specific deck design during the specification, design and building phases. The formulation can be used to assess global design parameters of a deck in an early design phase, but can also serve as a base for finite element model results to determine the mount transfer function for a more detailed deck design.

Keywords: NOISE CONTROL, UNDERWATER RADIATED NOISE ASSESSMENT, FEM

1. Introduction

Ships engaging in military operations desire to restrict their radiated underwater noise in order to avoid detection from threats such as sea mines, enemy submarines and torpedoes. Private ship owners are also moving towards limiting the noise radiated from future ships as concerns about the environmental effects of underwater noise are rising.

Conventional measures to control the underwater radiated noise include the application of silent propellers and the isolation of machinery vibrations by the application of flexible mounts and bellows. An increased reduction of vibration transfer can be achieved using a double mounting system, i.e. the application of an intermediate 'mass' between the machine and the ship structure with flexible mounts on both ends.

An alternative for a single or double mounting system for individual machines, is a common resiliently mounted deck on which multiple machines are installed either rigidly or on flexible mounts. Such a modular floating deck structure has the potential of being advantageous for reduction of costs, convenience of manufacturing and noise control. This paper addresses an analytical approach for the evaluation of the acoustic transfer function in order to guide the design process of floating decks. The analytical approach is complemented with a numerical evaluation of the acoustic transfer function.

2. Assessment Model for Radiated Underwater Sound (AMRUS)

The Assessment Model for Radiated Underwater Sound (AMRUS) is a semi-empirical prediction tool that consists of a large database enabling to predict separate contributions of different machinery noise sources to the underwater radiated noise level of ships, as measured according to measurement standards such as ISO 17208-1.

A prediction of the contribution of structure-borne noise from resiliently mounted machinery to the radiated noise level (L_{RN}) can be made by using Eq. (1) (see also Fig. 1)

$$L_{RN} = L_a + L_M + L_S + 10\lg(3N) \text{ in dB re 1 } \mu\text{Pa}^2 \tag{1}$$

With:

- Source acceleration level $L_a = 20\log_{10}|a/a_0|$ dB , with a_0 = 1 µm/s^2
- Mount transfer function $L_M = 20\log_{10}|M/M_0|$ dB, with $M = |F/a|$ the ratio of the force F at the foundation structure and the acceleration a of the machine foot, and M_0 = 1 kg,
- Machinery noise ship transfer function $L_S = 20\log_{10}|S/S_0|$dB, with S_0 = 1 m^{-1}, and $S = |p(R)R/F|$ the ratio of the underwater radiated noise level $L_{RN} = 20\log_{10}|p(R)R/p_0r_0|$dB of the ship due to the force F, with $p(R)$ the free-field sound pressure at a distance R, p_0 = 1 µPa and r_0 = 1 m,
- Number of mounts N, with a factor 3 to account for the three orthogonal vibration transmission components

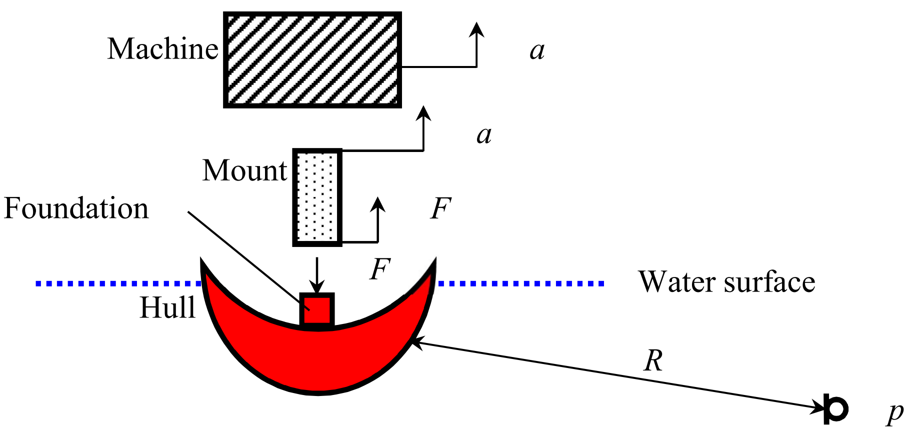

Figure 1: Schematic overview of structure-borne UWN path from a resiliently mounted machine.

The current empirical database accounts for mount transfer functions L_M for single mounting systems only. In this paper it is proposed to extend the AMRUS methodology with mount transfer functions for floating deck structures, which combine the acoustic transfer functions of the upper machinery mounts with these of the intermediate mass or deck and the lower mounts. Such a mount transfer function will depend on the input mobilities of and transfer mobilities between the upper and lower mount locations.

Any requirements set to a mount transfer function, in view of governing underwater radiated noise levels, can be translated to requirements for the mobilities of the intermediate mass or floating deck, which can be measured at the yard during the building stage.

3. Analytical approximation of the floating deck noise transfer function

Figure 2 gives a schematic overview of a resiliently installed machine on a deck structure, which is resiliently mounted on its foundation of the ship structure. An all-in one AMRUS deck mount transfer function can be defined as:

$$L_{M,deck} = L_{F,found} - L_{a,source} \tag{2}$$

With, $L_{F,found}$ the force level on the foundation in dB re 1 μN and $L_{a,source}$ the acceleration level of the machine in dB re 1 μm/s^2.

Whereas for a conventional single mounting system L_M depends on and the acoustic stiffness only, $L_{M,deck}$ is more complex and depends on the following parameters:

- Number and acoustic stiffness of upper mounts
- Number and acoustic stiffness of lower mounts
- Distributed mass and stiffness properties of deck structure
- Location of mount connections relative to centre of gravity of the deck.

Requirements for the AMRUS mount transfer function can be calculated from (budgeted) underwater noise requirements, see the next chapter, and compliance with these requirements can be tested in-situ during the Harbour or Sea Acceptance Tests (HATs and SATs), where the floating deck is installed on the mounts on the actual ship foundation. Ideally, the acoustic performance of the deck structure would be tested during a Factory Acceptance Test (FAT), once the construction of the deck is finished, for example by hammer impact transfer mobility measurements on a soft mounted deck.

3.1 Floating deck input and transfer mobilities

An analytical approach requires understanding of how the deck mobility is related to the overall AMRUS mount transfer function. For this purpose the overall mount transfer function is split into several sub-transfer functions, see also Fig. 2.

Y_{source}:	Input mobility of the machine feet in [m/s/N].
$Y_{k,upper,i}$:	Transfer mobility of the machine mount *i* on the deck [m/s/N].
$Y_{deck,i,j}$:	Transfer mobility between the machine mount position *i* on top of the deck to the deck mount position *j* [m/s/N].
$Y_{k,lower,j}$:	Transfer mobility of the lower deck mount *j* [m/s/N].
Y_{found}:	Input mobility of the foundation positions of the deck mounts on the ship structure [m/s/N].

All mobilities can be converted into mobility levels by:

$$L_Y = 20\lg(Y/Y_0) \text{ dB} \quad \text{, with } Y_0 = 1 \text{ m/s/N} \tag{3}$$

Each interface point has 6 degrees of freedom, with cross terms between the points and degrees of freedom. These can all be taken into account in finite element (FE) calculations. Simplification of the mobility relations results in a lower accuracy of the predictions, but allows for a fast comparison between global design variations. The transfer mobility $Y_{deck,i,j}$ is a good candidate as an acoustic indicator which allows for early design specification of acoustic targets for a floating deck structure.

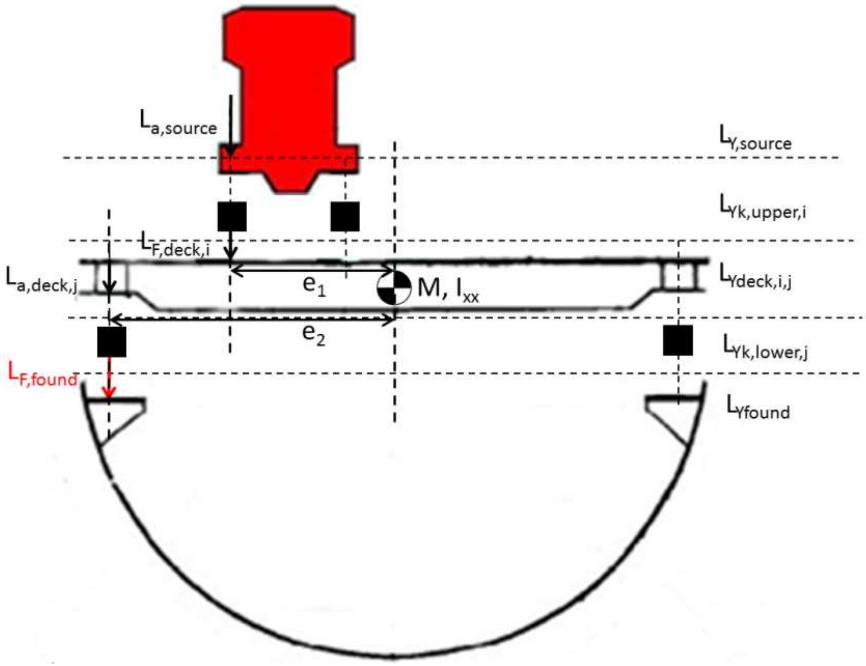

Figure 2: Schematic overview of a resiliently installed machine on a floating deck, which is resiliently mounted on the ship structure. Overview of the overall mount transfer function separated into sub-mobility functions. Mass and inertia properties and the off-centre excitation of the deck are shown (offsets e1 and e2).

3.2 Single mounting system transfer function

For a single resilient mounting system with ideal springs, the mount transfer function L_M can be derived from Hooke's law:

$$L_M = 20\log_{10} |M / M_0| \text{ dB} = 20\log_{10} |k/(2\pi f)^2| \text{ dB} \tag{4}$$

With, M_0 = 1 kg, k the total stiffness in N/m and f the frequency in Hz.

This function is decreasing for increasing frequency at -12 dB/octave. A resilient mount will not behave as an ideal spring in the entire frequency range and will experience stiffening effects due to standing waves over the mount. This typically results in a decreasing slope of the mount transfer function at higher frequencies.

3.3 Rigid body behaviour of double mounting systems

For a single resilient mounting system with ideal springs and a rigid mass-like intermediate structure, the mount transfer function can be determined from mass-spring theory by solving the equations of motion for the intermediate mass [1].

$$M = \frac{F}{a} = \left(i\omega \left(\frac{Z_{m1}}{Z_{k1}.Z_{k2}} + \frac{1}{Z_{k2}} + \frac{1}{Z_{k1}} \right) \right)^{-1} \tag{5}$$

In which, Z_{m1}: impedance of intermediate mass m_1 [Ns/m]:

$$Z_{m1} = m_1 \mathrm{j}\omega \tag{6}$$

Z_{k1}: spring impedance [Ns/m] of lower spring with stiffness k_1 [N/m]

$$Z_{c_1} = \frac{k_1}{\mathrm{j\omega}} \tag{7}$$

Z_{k2}: spring impedance [Ns/m] of upper spring with stiffness k_2 [N/m]

$$Z_{c_2} = \frac{k_2}{\mathrm{j\omega}} \tag{8}$$

If the deck is excited at an offset from its centre of gravity, rotational effects in the rigid body motion should be taken into account by using an equivalent mass in evaluating the impedance of the intermediate mass as in Eq. (6). The equivalent mass is defined as:

$$m_{eq} = \frac{1}{\frac{1}{m}+\frac{ey^2}{I_{xxm}}+\frac{ex^2}{I_{yym}}} \tag{9}$$

With, e_y and e_x the offsets from the centre of gravity in x and y direction [m] and I_{xxm} and I_{yym} the mass moments of inertia relative to the x and y axes [kg m^2]. The mount transfer function has a decreasing slope of -24 dB/octave for frequencies in excess of the second resonance frequency.

3.4 Flexible behaviour of floating deck structures

In reality the deck structure does not behave as a rigid mass, due to flexibility and modal behaviour of the deck structure. At the first flexural or torsional mode, the deck does not exhibit a mass-like behaviour anymore, which will affect the mount transfer function. The occurrence of the first flexural resonance depends on the mass/stiffness properties of the deck design and the overall dimensions.

The model as used in the previous section is extended with a matrix equation capturing the interaction between the upper and lower mounting support points of a deck structure:

$$\begin{Bmatrix} v_1 \\ v_2 \end{Bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix} \cdot \begin{Bmatrix} F_1 \\ F_2 \end{Bmatrix} \tag{10}$$

With: v_1 : velocity of the deck at the upper mount positions [m/s], v_2 : velocity of the deck at the lower mount positions [m/s], Y_{11}: deck input mobility of the upper mount positions [m/Ns], Y_{22}: deck input mobility of the lower mount positions [m/Ns], F_2: force of the lower mounts on the foundation [N], F_1: force of the upper mounts on the deck structure [N]. The AMRUS deck mount transfer function for flexible decks now reads:

$$L_M = 20\lg\left(\omega\left(\left|\frac{Z_{k1}Z_{k2}Y_{21}}{(1+Z_{k1}Y_{11})(1-Z_{k2}Y_{22})+Z_{k1}Z_{k2}Y_{12}Y_{21}}\right|\right)/M_0\right)\ \mathrm{dB} \tag{11}$$

The required input and transfer mobilities and impedances can be taken from calculations based on equivalent isotropic plate theory, in an early design stage when more detailed information is not available, and from FE calculations once more details on the deck design are available. Mobility measurements can be taken once the deck structure has been built.

This approach accounts for the stiffness and mass properties in the mount transfer function via the input and transfer mobilities. As a check: in case both deck input and transfer mobilities are set equal to the mass mobilities Eq. (6), Eq. (11) equals Eq. (5) as expected.

Equations (11) and (6) represent the mount transfer function of the acceleration of the engine feet above the mount to a force on the foundation, under the mount. In order to assess the total radiated noise level, a summation over the number of mounts and the 3 orthogonal directions of the vibrations is required. Equation (11) allows for the conversion of deck input and transfer mobilities to a deck mount transfer function. Inversely, if spectral requirements have been set to the mount transfer function, requirements for the mobilities can be derived. These can be used as acoustic indicators to specify a floating deck design.

4. Numerical approximation of a floating deck transfer function

As an example a floating deck structure is modelled by a FE model using shell elements for the deck structure. This allows to study the effect of the deck modes on the mount transfer function. This deck design should be regarded as an example, and is not intended to be a recommendation for an actual deck design. The dimensions of the deck are 6.7×7.8 m^2. The total weight of the deck is 11.7 tons. The plate elements have the geometrical properties of the flange and wedge of a HEA-320 profile. The FE model of the deck has free boundary conditions. This simulates the free dynamical behaviour of the deck when decoupled of the surroundings by the resilient mounts. The effect of the mount stiffness is taken into account later by application of Eq. (11). The 6 upper and 8 lower springs have the following stiffness properties: k_y, k_z: 2.65e6 N/m and k_x: 0.58e6 N/m.

Figure 3 shows the first order bending and torsion modes of the free floating deck starting at 25 Hz. Above this frequency the deck will not behave as a mass, its dynamic behaviour is affected by the mass/stiffness distribution. For low frequencies (< 100 Hz) near the first bending and torsional modes the deck will have the highest displacements, depending on the damping. Therefore a detailed dynamic FE analysis is important to predict these natural frequencies. It is unavoidable that somewhere in the complex structure a mode is excited. The location of excitation however determines the effectiveness of the excitation. The FE analysis will also give insight into these local modal effects.

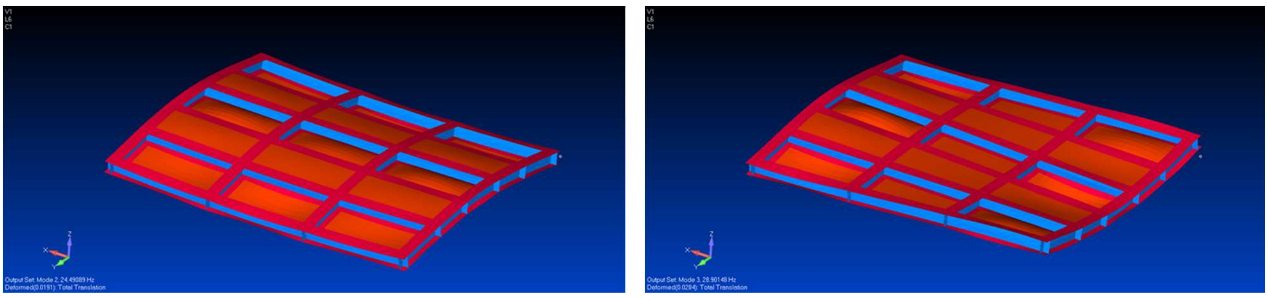

Figure 3: Selected mode shapes (bending 24.5 Hz and torsional 28.9 Hz) at natural frequencies of the floating deck.

Figure 4 shows the calculated input mobilities at four locations, and the transfer mobilities in both narrow-band and one-third octave frequency bands. A constant damping of 10% was assumed. The upper deck mobility seems to converge to the semi-infinite plate value well governed by Eq. (12) [2]. Due to the positioning of the mounts close to the edges of the deck, a semi-infinite plate approximation is more appropriate than infinite plate behaviour. At low frequencies the mass governed behaviour of the free deck is found [2].

$$|Y| = \frac{1}{|Z|} = \frac{1}{3.5\sqrt{EI'm'}} \quad (12)$$

With E the Young's modulus of the deck material (steel) in N/m^2 and I' the second moment of inertia per unit width in m^3 and m" the mass per unit area in kg/m^2 of the equivalent isotropic homogeneous plate.

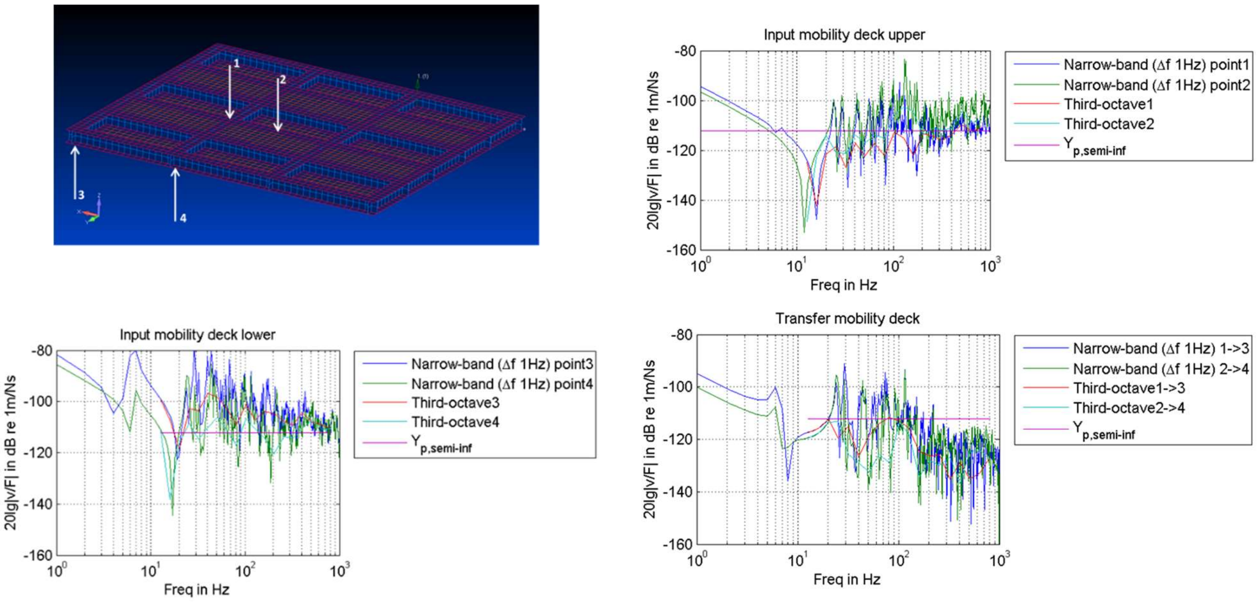

Figure 4: Input- and transfer mobility levels for driving points 1 and 2 and supporting points 3 and 4 of the example deck structure presented as narrow band and one third octave band spectra.

When it is assumed that all transfer and input mobilities of the deck equal the semi-infinite plate values, the mount transfer function can be calculated from Eq. (11) and Eqs. (4) and (5) for single and double mounting systems. This implies that the interaction between different mounting positions is neglected, i.e. the distance between the excitation forces is small compared to the governing wave-length.

The analytical semi-infinite plate deck mount transfer function is compared to a transfer function for which the input and transfer mobilities are obtained from the FE model as discussed above. The results are shown in Fig. 5. As expected, the FE calculations of the mobilities converge to the semi-infinite plate values, as described in the previous section. Therefore in an early design stage, before the detailed design of the deck structure is available, the semi-infinite plate approach can be used to calculate the deck mount transfer function for AMRUS calculations. Modelling the deck as a rigid mass is only applicable at the lowest frequencies (below ~30 Hz).

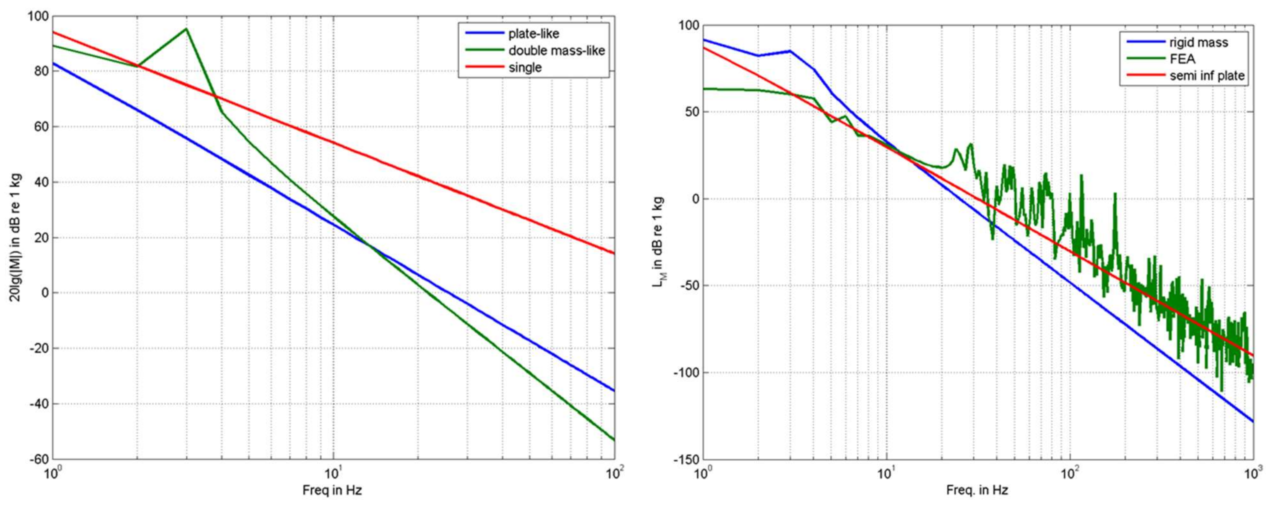

Figure 5: Analytical floating deck transfer function compared to analytical transfer functions for single- and double mounting systems (left) and analytical vs numerical floating deck transfer function (right).

5. Conclusions

An approach has been developed for quantifying the underwater radiated noise of equipment installed on floating decks, following the AMRUS approach. For this purpose a so-called deck mount transfer function is determined by measurements and/or calculations. The deck mount transfer function includes the dynamic properties of the upper and lower mounts and the deck structure. All aspects are captured in an overall mount transfer function.

The deck mount transfer function can be calculated from the individual input- and transfer mobilities of the deck. The deck mobilities can be estimated from a semi-infinite plate approach during the early design stage when little engineering details are determined yet and multiple concepts are to be assessed efficiently. A more detailed transfer function can be obtained using FE calculations of the deck's dynamic behaviour when a more detailed design is available.

Relating the mount transfer function to the deck input- and transfer mobilities allows for the translation of requirements for the deck mount transfer function, based on budgeted underwater noise targets, into requirements for the floating deck mobilities. Deck transfer and input mobilities can be used as acoustic indicators for which floating deck design requirements can be specified.

Given a certain starting point for deck dimensions, in terms of length and width, the semi-infinite plate approach of a floating deck allows for a fast estimation of global deck key design parameters such as deck mass and deck height in an early design stage that fulfil basic requirements for naval architecture, rigid body natural frequencies, as well as acoustic mounting stiffness and transfer functions.

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