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TRANSFER FUNCTION OF THE STRUCTURE-BORNE NOISE TO UNDERWATER RADIATED NOISE FOR SHIPS WITH HULL OF DIFFERENT MATERIAL

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ABSTRACT

The Transfer Function (TF) relates the structure-borne noise level of the hull with the Underwater Radiated Noise (URN). Therefore, the acoustic noise generated by the vibrations of the hull of a ship could be estimated from real measurements of the structure-borne noise levels of the hull by applying the TF in real time. This function depends on the material of the hull of the ship. In this paper, real measurements of the structure-borne noise level of the hull and URN of two ships constructed of steel and Glass fiber Reinforced Plastics (GRP) are used to estimate the TF of the hull.

RESUMEN

La Función de Transferencia (FT) relaciona el nivel de ruido estructural del casco con el nivel de ruido acústico submarino. Por lo tanto, el ruido acústico generado por las vibraciones del casco de un buque se puede estimar a partir de medidas reales del nivel ruido estructural del casco aplicando la FT en tiempo real. Esta función depende del tipo de material del casco del buque. En este trabajo, se utilizan medidas reales del nivel de ruido estructural del casco y ruido acústico radiado para estimar la FT del casco de dos buques construidos con acero y fibra de vidrio reforzada.

1. INTRODUCTION

The control of the Underwater Radiated Noise (URN) is a critical issue for two main reasons: the stealth of the naval vessels and the reduction of the environmental acoustic pollution of the seas.

When the naval ships operate at low speeds, usually in shallow waters, they can be detected by different acoustic systems such as naval mines. Therefore, the URN generated by a naval ship supposes a risk for itself, and must be controlled in order to reduce it.

By other hand, from the point of view of the acoustic pollution, currently, nations are developing regulations to control the acoustic emissions in the marine area to reduce their impact in the marine life. In Europe, stands out the Marine Strategy Framework Directive (MSFD), focused to the marine environment preservation, based on the achievement of the Good Environmental Status (GES) of EU marine waters by 2020.

There are three kinds of underwater sound; propeller induced, machinery induced and flow sound [1]. The structure-borne noise is a predominant noise source of Underwater Radiated Noise (URN) generated by a ship at low speeds [2].

The Transfer Function (TF) relates the ship structure-borne noise and the URN and is defined as follows [2]:

$$TF = L_p - L_a \quad [W] \tag{1}$$

Where, TF is the Transfer Function of structure-borne noise, L_p is the URN level (dB referenced to 1 μPa, 1m, 1 Hz) and L_a is the 1/3 octave band acceleration level (dB reference to 10^{-5} m/s^2. The radiated pressure at 1 meter apart from the source under the assumptions of spherical spreading and omnidirectional directivity is defined as:

$$L_p = L_W - 10log(\Delta f) + 54 \quad dB\, ref\ 1\,\mu Pa\ @\ 1\,m, 1\,Hz \tag{2}$$

L_w is the acoustic power level (dB referenced to 10^{-12} W) and Δf is the bandwidth. Finally, the acoustic power radiated sound into water by vibrating plates is given by:

$$W = \rho_0 c_0 \sum_{i=1}^{N} \sigma_{rad,i}\, A_i \langle v^2 \rangle_i\ [W] \tag{3}$$

In equation (3), ρ_0 and c_0 are the properties of the seawater, this is, the density and sound speed respectively, $\sigma_{rad,i}$ is the radiation efficiency of the plate i, A_i is the area of the plate i, and $\langle v^2 \rangle_i$ is the space-time averaged velocity squared of plate i. N is the number of individual plates vibrating incoherently. It is demonstrated that the Transfer Function depends on the radiation efficiency.

In [3] the Maidanik's and Uchida's equations are used to compute theoretically the sound radiation efficiency. In [4] Maidanik defined the radiation efficiency for ribbed a plate in a reverberant field as follows:

$$\sigma_{rad} = \frac{4A_{rad}}{c^2} f^2\ ;\ f_{11} = \frac{c^2}{2A_{rad} f_c}\left(\frac{P^2}{8A_{rad}} - 1\right) \qquad (f < f_{11}) \tag{4}$$

$$\sigma_{rad} = \frac{\lambda_c^2}{A_{rad}} g_1(\alpha) + \frac{P\lambda_c}{A_{rad}} g_2(\alpha);\ \lambda_c = \frac{c}{f_c}\ ;\ \alpha = \sqrt{\frac{f}{f_c}} \qquad (f_{11} < f < f_c) \tag{5}$$

$$f_c = \frac{1}{2\pi} c^2 (\rho_s h)^{\frac{1}{2}} \left[\frac{Eh^3}{12\,(1-\nu^2)}\right]^{-\frac{1}{2}} \quad (5a)$$

$$\sigma_{rad} = \sqrt{\frac{a}{\lambda_c}} + \sqrt{\frac{b}{\lambda_c}} \qquad (f = f_c) \quad (6)$$

$$\sigma_{rad} = \left(1 - \frac{f_c}{f}\right)^{-\frac{1}{2}} \qquad (f > f_c) \quad (7)$$

$$g_1(\alpha) = \frac{4}{\pi^4} \frac{1-2\alpha^2}{\sqrt{\alpha^2(1-\alpha^2)}} \qquad \left(f < \frac{f_c}{2}\right) \quad (8)$$

$$g_1(\alpha) = 0 \qquad \left(f > \frac{f_c}{2}\right) \quad (9)$$

$$g_2(\alpha) = \frac{1}{4\pi^2} \frac{(1-\alpha^2) ln\left(\frac{1+\alpha}{1-\alpha}\right) + 2\alpha}{(1-\alpha^2)^{\frac{3}{2}}} \quad (10)$$

a, *b* and *h* are the width, height and thickness of the plate respectively, *P* = 2x(a+*b*) is the circumference of the plate, A_{rad} is the area of the plate, ρ_s is the density of the plate, *E* is Young's modulus of the plate and ν is the Poison ratio of the plate.

In [5] Uchida defined the radiation efficiency as follows:

$$10log(\sigma_{rad}) = 10log\left(\frac{m\sqrt{B}}{A_{rad}}\right) - 78 \qquad (f \leq f_1) \quad (11)$$

$$f_1 = 0.25\, f_0\,;\; f_0 = 700\left(\frac{m\sqrt{B}}{A_{rad}}\right)^{0.2} \quad (11a)$$

$$10log(\sigma_{rad}) = \left(\frac{50}{3}\right) log\left(\frac{4f}{f_0}\right) + 10log\left(\frac{m\sqrt{B}}{A_{rad}}\right) - 78 \qquad (f_1 < f \leq f_2) \quad (12)$$

$$f_2 = 2f_0 \quad (12a)$$

$$10log(\sigma_{rad}) = 50log\left(\frac{f}{1600}\right) - 10 \qquad (f_2 < f \leq f_3) \quad (13)$$

$$f_3 = 16000\, Hz \quad (13a)$$

$$10log(\sigma_{rad}) = -10 \qquad (f_3 < f) \quad (14)$$

m is the mass per unit area (ρ_s x *h*) and *B* is the bending stiffness defined as:

$$B = \frac{Eh^3}{12\,(1-\nu^2)} \quad (15)$$

According to the Maidanik's and Uchida's radiation efficiency equations, the sound radiation efficiency depends on the material of the hull.

In order to show numerically the dependency of the sound radiation efficiency with the material of the hull, as example, Figure 1 shows the sound radiation efficiency computed using the Maidanink's and Uchida's equations for the same panel but with different type of material, Glass fiber Reinforced Plastic (GRP) and steel.

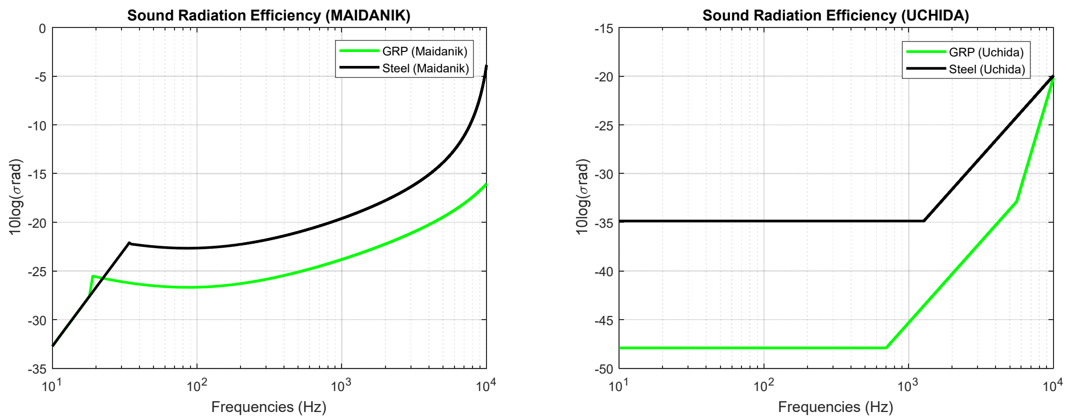

Figure. 1: Sound radiation efficiency computed using the Maidanik's and Uchida's equations for a panel of Width: 2m, Height: 1.5 m and Thickness: 2 mm using steel and GRP materials.

The sound radiation efficiency of the panel of steel is higher than the panel of GRP using both models. The difference between models is that in Maidanik's model the sound radiation efficiency is higher for a panel of steel practically in the complete bandwidth with similar differences for all frequencies while in Uchida's model the differences of the sound radiation depending of the material of the hull are higher at low-mid frequencies.

In this work, measurements of the vibration and URN of two ships with hull of Glass fiber Reinforced Plastic (GRP) and steel are used to estimate the TF and discuss the differences between them.

2. DATA COLECTION

The ships under measurement were two fishing vessels, 'Verdú Verdú' and 'Manuela Lloret'. The dimensions of the first one are of 23 meters length and 6 meters beam with hull of Glass-fiber Reinforced Plastic (GRP) material. The dimensions of the second one are 24 meters length and 6 meters beam with hull of steel material. Figure 2. shows pictures of both ships.

Figure. 2: Ships under measurement: 'Verdú Verdú' with hull of GRP (left) and 'Manuela Lloret' with hull of steel (right).

The measurements of the vibrations of the hull and the URN were performed simultaneously. For the ship of hull of GRP material, sixteen (16) points of acceleration measurement were selected, twelve (12) under waterline and four (4) above waterline. For the ship of hull of steel material, thirty-six (36) points of measurement under waterline were selected. Figure 3 shows the measurement points on the 'Verdú Verdú' ship with hull of GRP. Figure 4 shows the measurement points on the 'Manuela Lloret' fishing with hull of steel.

Figure. 3: Measurement points on the 'Verdú Verdú' with hull of GRP. Twelve (12) points under water line and four (4) points above water line.

Figure. 4: Measurement points on the 'Manuela Lloret' with hull of steel. Thirty-six (36) points under water line.

3. PROCESSING OF THE MEASUREMENTS

The measurements of vibrations of the hull (Structure -Borne Noise) and URN radiated by it are processed in broadband and narrowband.

The broadband processing is based on the calculation of the One Third Octave (OTO) values from 10 Hz to 10 kHz according to [6].

The narrowband processing is based on the calculation of the spectrogram with a resolution of 1 Hz in the band from 1 Hz to 10 kHz.

Figure 5 and Figure 6 show the integrated values of the broadband and narrowband outputs of the Acceleration level for each position of the accelerometers and corresponding URN for the measurements of the ship with hull of steel and GRP respectively using the main engine such as source of vibrations of the hull.

The hydrophone was maintained in a fixed position during the data collection and therefore the URN measurements generated by the vibrations of the main engine are similar independently of the position of the accelerometer.

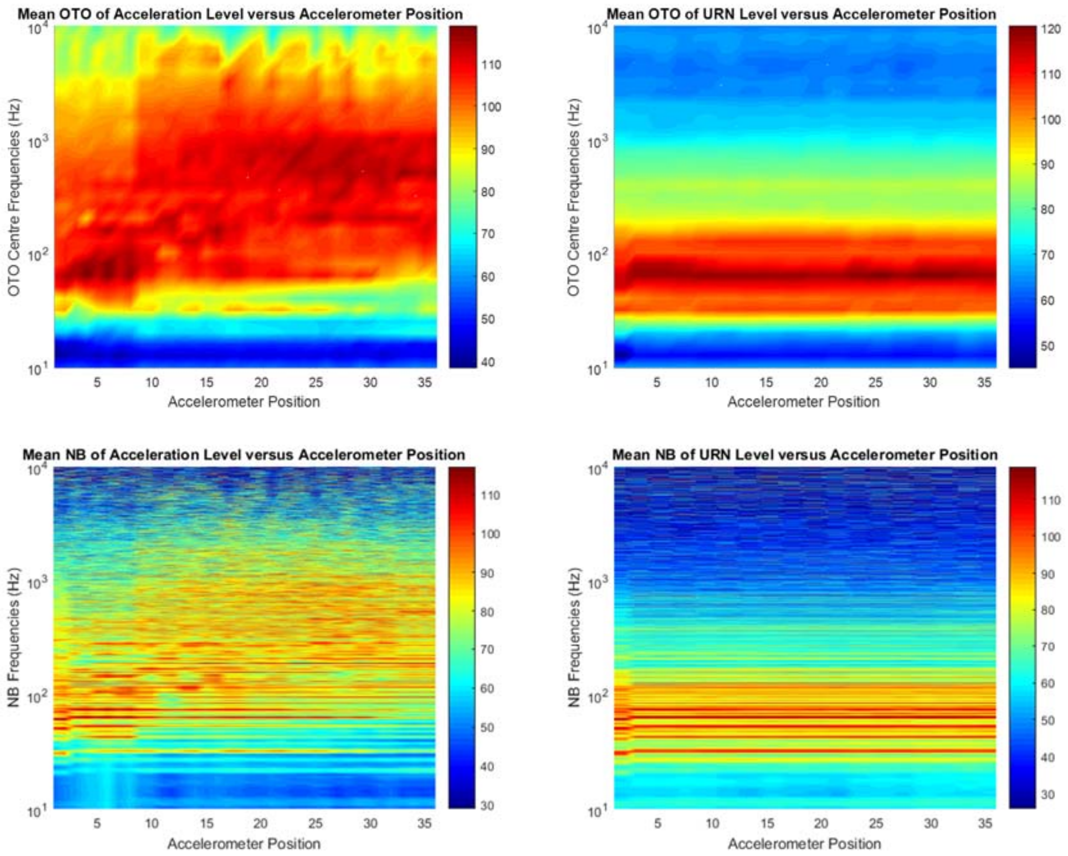

Figure. 5: Broadband (upper) and Narrowband (lower) outputs of the Acceleration level (left) and URN (right) for each accelerometer of the measurements of the ship with hull of steel.

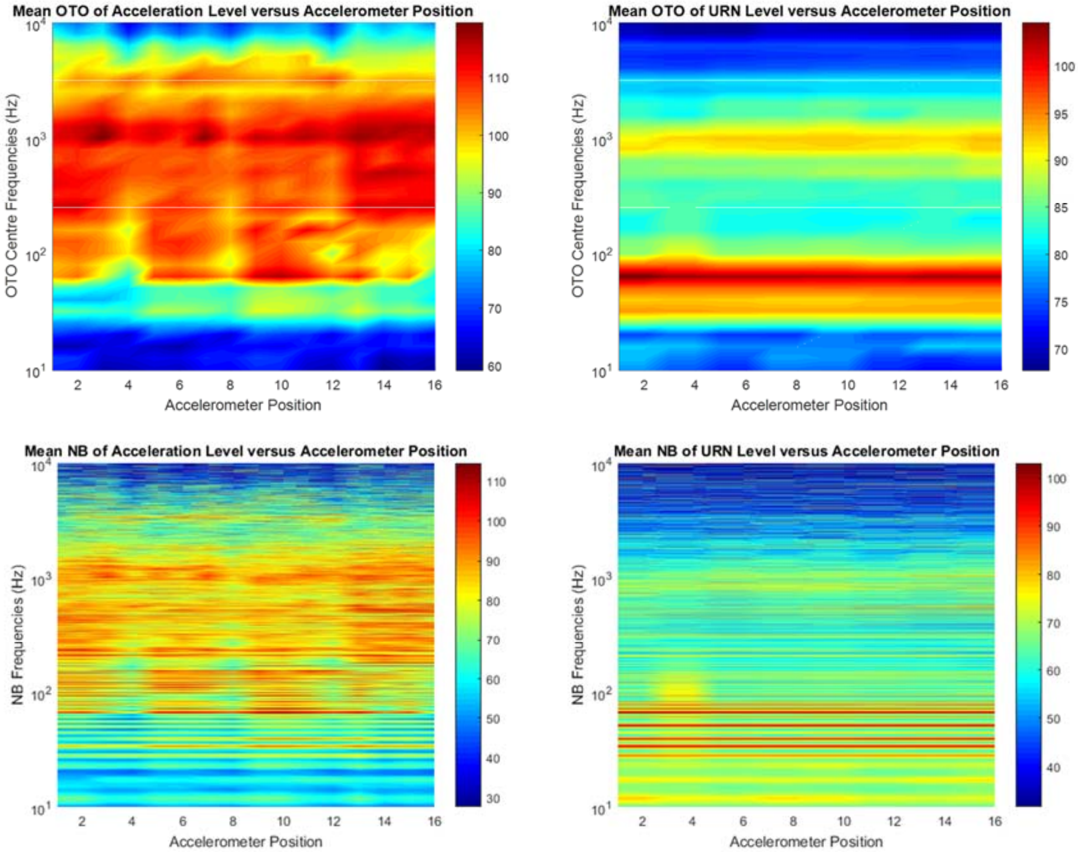

Figure. 6: Broadband (upper) and Narrowband (lower) outputs of the Acceleration level (left) and URN (right) for each accelerometer of the measurements of the ship with hull of GRP.

4. TRANSFER FUNCTION CALCULATION

The main goal of this research was to calculate the TF of the hull under measurement of ships with different hull's materials. Figure 7 y Figure 8 show the Transfer Function using the equation (1) obtained from the real measurements.

In order to compare the TF of hull of steel and hull of GRP, the mean values of the transfer functions at the positions of the accelerometers closer to the hydrophone position for both ships and type of processing are done.

Figure 9 shows the broadband and narrowband mean TF computes for each type of hull. The TF of the hull of steel is higher in the band from 10 to 500 Hz. Both functions are similar in the from 500 Hz to 3 kHz. Finally, the TF of the hull of GRP is higher in the band from 5 kHz to 10 kHz. This conclusion is different than the obtained in the theoretical analysis. This is due to the noise has been not remove from the measurements and the sizes of the panels have been not considered in the analysis.

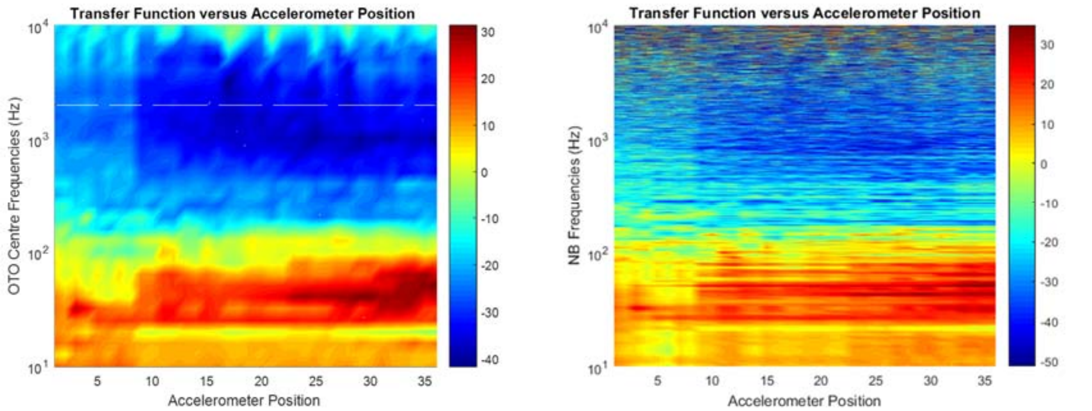

Figure. 7: Broadband (upper) and Narrowband (lower) Transfer Function for each accelerometer position of the measurements of the ship with hull of steel.

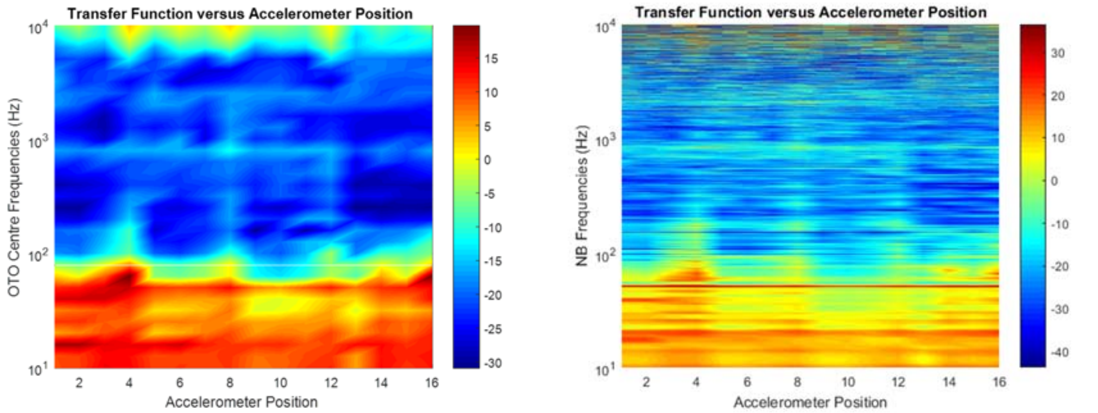

Figure. 8: Broadband (upper) and Narrowband (lower) Transfer Function for each accelerometer position of the measurements of the ship with hull of GRP.

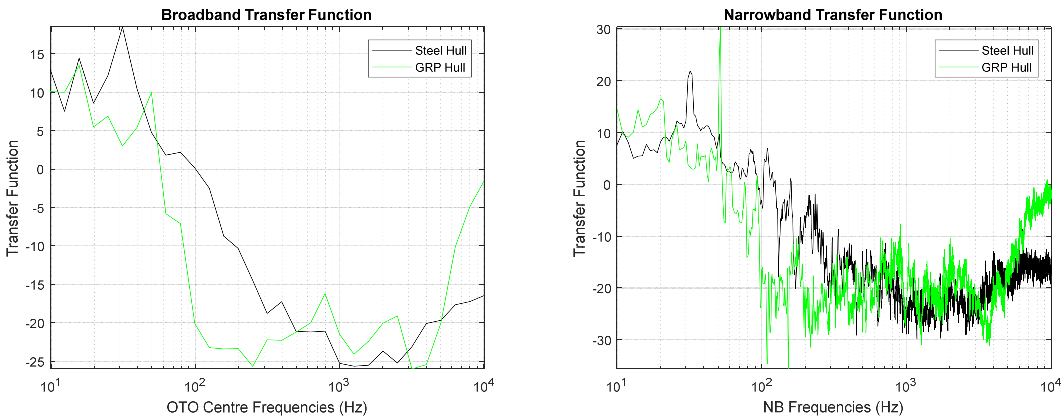

Figure. 9: Broadband (left) and Narrowband (right) mean Transfer Function of the measurements of the ship with hull of steel and GRP.

5. CONCLUSIONS

The Transfer Function relates the structure-borne noise and the URN generated by a ship, that is to say, it relates the vibration of the hull and the acoustic noise radiation due to it. Theoretically, it is demonstrated than the TF depends clearly of the material of the hull using different models to estimate the sound radiation efficiency. The goal of this research was to calculate the Transfer Function of ship with hull of steel and GRP in order to evaluate the dependency of the type of material of the hull in the TF using real measurements of the vibration of the hull and URN. Experimentally, it is verified that others parameters such as size of the vibrating panels, position of the sensors (accelerometers and hydrophones) and the ambient noise must be taken into account to estimate the TF and the dependency of it with the material of the hull.

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