ESTIMATION OF THE ACOUSTIC NOISE RADIATED BY VESSELS FROM THE MEASUREMENT OF THE VIBRATION OF THE HULL

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Abstract: *Nowadays, the interest on the acoustic noise emission level of vessels is increasing worldwide. In fact, the European Union (EU) promoted the Marine Strategy Framework Directive (MSFD) to monitor the Good Environmental Status (GES) of the EU seas. The measurement of the underwater acoustic noise is expensive and usually is not feasible. For this reason, a method to estimate the underwater acoustic noise generated by a vessel from the measurement of the vibrations of the hull is proposed. This method estimates the noise radiated from an adequate relation between the vibration of the hull and this radiated noise. In this paper, real measurements of the vibrations of a hull and the acoustic radiated noise are presented. Using signal processing methods, the relationship between the vibrations of the hull and radiated noise was computed. Finally, the goodness of the computed relation between the vibrations of the hull and radiated noise was performed by comparing real acoustic measurements and estimations. The measurements were performed using the Smart Digital Hydrophones (SDH) and Noise and Vibration Control System (CRV), both equipment, manufactured by SAES.*

Keywords: *Underwater Acoustic Noise, Hull vibrations, Environmental protection, Digital Signal Processing.*

1. INTRODUCTION

The structure-borne noise is a predominant noise source of Underwater Radiated Noise (URN) generated by a ship at low speeds [1]. The control of the 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.

For these reasons, it is mandatory to control the URN generated by the ships. The measurement of the underwater acoustic noise generated by a ship is too expensive and complex and therefore, different techniques for the prediction of the URN are studied. Other way to estimate the URN is based on the implementation of the Transfer Function. This function relates the ship structure-borne noise and the URN. Estimations of the URN can be done by applying the Transfer Function to structure-borne noise measurements performed with accelerometers. Further, the measurements of the vibrations of the hull in real time are feasible and this method can be used in real operational scenarios.

In this work, real measurements of the vibrations of the hull and URN were used to compute the Transfer Function and then estimate the URN from the hull vibration measured data.

The measurements of the vibrations of the hull were performed using the CRV system manufactured by SAES. This system is operative and installed in real naval ships. The URN measurements were performed using the SDH system, also manufactured by SAES. This system has been used for long-term underwater noise measurement campaigns with successful results.

2. DATA COLECTION

The measurements were collected during one day at Villajoyosa port, close to the city of Alicante (Spain). The ship under measurement was ‘Ali-Sur 5º’ of 12 meters length. This ship is used for divers training and operations. The material of the hull of the ship is Glass-Fiber Reinforced Plastic (GFRP). During the measurements, the ship was moored. Fig. 1 shows the ship under measurement.

Fig. 1: Ship under measurement with GFRP hull.

In order to measure simultaneously the vibrations of the hull and the URN, the Vibration Control System (CRV) and Smart Digital Hydrophone (SDH) system manufactured by SAES were installed onboard the ship.

The CRV system is an equipment based on accelerometers installed onboard the ship so as to measure in real time the vibrations of the hull. The two main objectives of the CRV system are to control the URN generated by the ship and to monitor the health of the structural elements and onboard systems such as motors, gears, pumps, etc. The CRV system is composed by the following units:

- <u>Accelerometers</u>. The number of the accelerometers integrated in the CRV system basically depend of the size of the ship, but usually more than forty (40) fixed accelerometers are installed. Usually two (2) additional portable accelerometers are used. For the current measurements, five (5) accelerometers of the CRV system were fixed to a frame of the ship.
- <u>Acquisition Units (AUs)</u>. The Acquisition Units are located in different compartments of the ship and are responsible for powering the sensors connected to the AUs, acquiring the signal and transmitting these digitized signals over to the Distribution Units. For the measurements, one (1) AU of the CRV system was installed in the command room.
- <u>Distribution Units (DUs)</u>. The Distribution Units are interfaces between Acquisition Units and the Operator Control Unit. DUs are responsible for powering the AUs and for data distribution over to the Operator Control Unit. During the measurement campaign one (1) DU of the CRV system was installed in the command room.
- <u>Operator Control Unit (OCU)</u>. The Operator Control Unit supports the Broadband and Narrowband Signal Processing and Human Machine Interface (HMI). The OCU is responsible on providing AC power to the DUs. During the measurement campaign, the OCU was substituted by a laptop.

The Smart Digital Hydrophone (SDH) is a portable underwater acoustic measurement system composed by the following units:

- <u>Hydrophones</u>. The SDH integrates up to four (4) digital hydrophones with programmable sampling frequency. Each hydrophone integrates the acoustic transducer and the electronic for acquisition and communication. To measure the

URN, three (3) hydrophones were deployed at stern, middle and bow positions of the ship.

- Hydrophones Connection Unit (HCU). The Hydrophones Connection Unit allows the communication between the hydrophones and the Control and Analysis Unit (CAU), and provides the power supply to the hydrophones. For the measurements, one CU was installed in the command room.
- Control and Analysis Unit (CAU). The CAU records the data from the hydrophones and allows controlling them. Also, the CAU integrates the signal processing and analysis capability. The software for recording the digitalized signals from the hydrophones was installed in the same laptop used as OCU of the CRV system in order to start and stop the measurements of the vibration of the hull and URN simultaneously.

Fig. 2 shows a general diagram of the installed units and deployed sensors for the measurements of vibrations of the hull and URN.

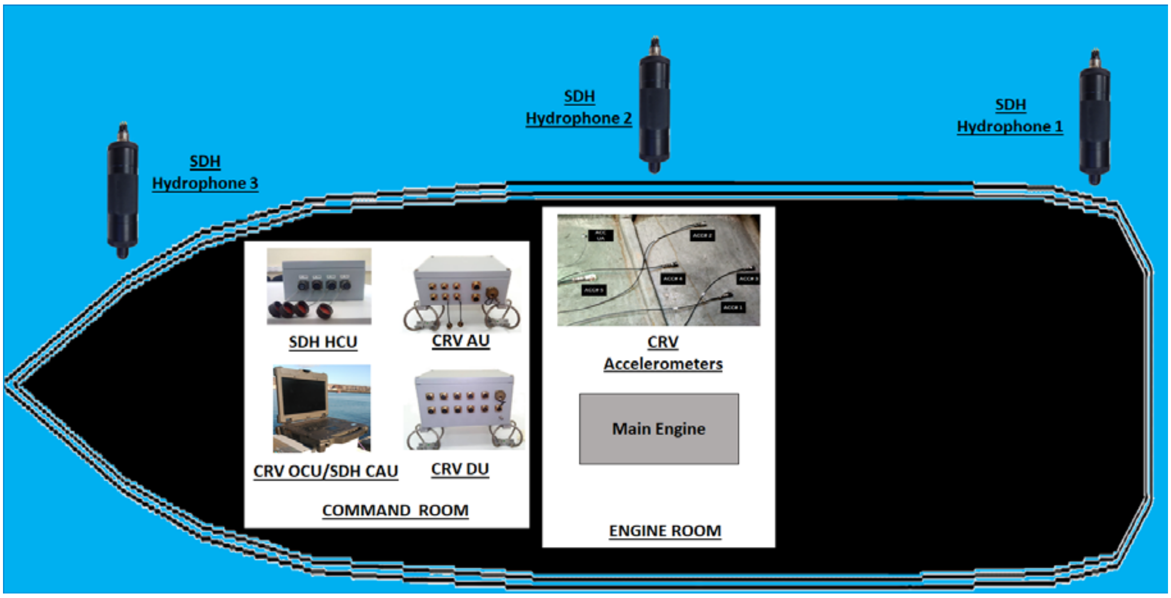

Fig. 2: General diagram of the installed units and deployed sensors for the measurement of the vibrations of the hull and URN.

The main engine was used as source of excitement of the hull by generating vibrations on it. Several measurements with the main engine stopped and started were performed. Typical time series of the vibration of the hull and underwater radiated noise measurements with the main engine started are shown in the Fig. 3. The start of the engine is perfectly identifiable in the time series as a transient peak emerging from the background noise.

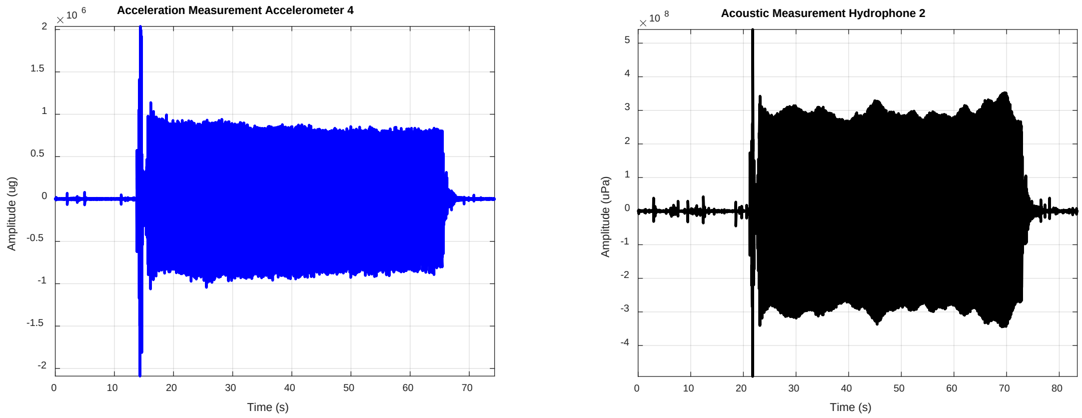

Fig. 3: Typical time series of the measurement of the vibration of the hull (left) and underwater radiated noise (right) with the main engine started.

3. TRANSFER FUNCTION CALCULATION AND URN ESTIMATION

The main goal of this research was to calculate the Transfer Function of the hull under measurement and to use it to estimate the URN. The Transfer Function calculation was performed processing the measurements of vibration of the hull and URN in broadband. Once the Transfer Function was computed, it was used to predict the URN applying it to the measurement data of the vibration of the hull.

In order to evaluate the accuracy of the measurements and therefore the validity of the estimations based on them, the first step of the study was to perform a repeatability analysis on the measurements. The repeatability analysis was based on the processing of the mean value of each third octave band of all the measurements for each sensor, and on the computation of the maximum deviation of all third octave bands for each measurement and sensor. Fig. 4 Shows the mean value of each One Third Octave (OTO) band of the vibration and URN measurements. Table. 1 shows the maximum deviation between the mean value of the OTO values and processed OTO for all sensors in dB referenced to 1 µPa/√Hz for URN measurements and 1 µg/√Hz for vibration measurements.

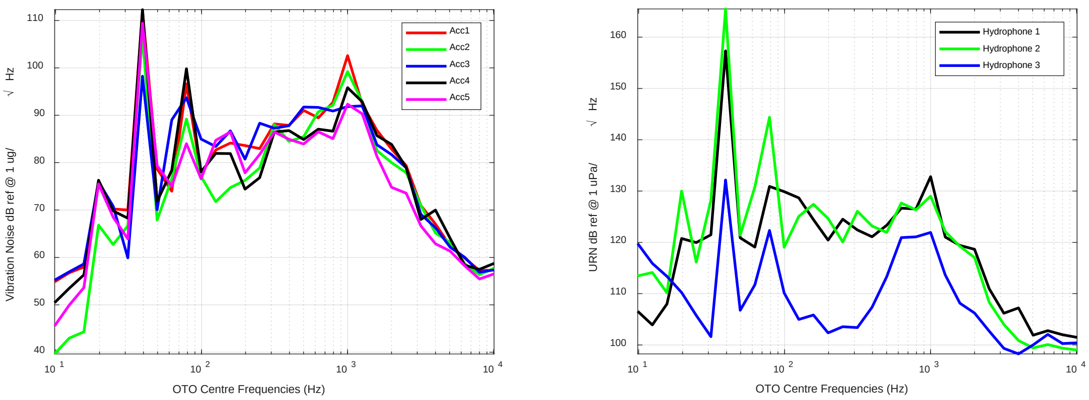

Fig. 4. Mean value of each OTO band for the vibration (left) and URN (right) measurements.

Maximum deviation of OTO from the mean value								
	dB referenced to 1 µg /√Hz					dB referenced to 1 µPa /√Hz		
M. ID	**Acc1**	**Acc2**	**Acc3**	**Acc4**	**Acc5**	**Hydro1**	**Hydro2**	**Hydro3**
4	1.9	1.22	1.86	1.48	1.88	2.27	1.44	3.82
6	0.63	0.54	0.86	0.83	1.49	1.96	1.53	2.7
8	0.89	0.43	0.59	0.74	1.07	1.72	1	2.74
10	1.37	0.82	1.33	1.09	2.06	1.32	1.63	2.24
12	1.11	0.78	0.97	0.99	1.35	0.91	1.04	6.11

Table 1: Maximum deviation between the mean value of each OTO and real values for all sensors and measurements (M. ID).

The maximum deviation of the vibration measurements (0.43 – 2.06 dB referenced to 1 µg/√Hz) were lower than the maximum deviations of the URN measurements (0.91 – 6.11 dB referenced to 1 µPa/√Hz). These results were expected since the underwater background noise was higher than the vibration noise. By other hand, the lowest maximum deviations of the hydrophones data appeared for the measurements of the hydrophone 2 because it was deployed closer to the main engine than the others. The maximum deviations obtained were acceptable and hence the measurements were perfectly valid for the calculation of the Transfer Function.

The calculation of the Transfer Function was based on the assumption that the hull vibration radiates underwater acoustic noise as a unique source; therefore, the broadband vibration of the hull was computed integrating the OTO bands of the five accelerometers for all the measurements. The same process was performed for the measurement data of the underwater radiated noise for each hydrophone. The Transfer Function for each hydrophone position was calculated as the difference between the integrated values of the OTO bands of URN and the integrated values of the OTO bands of the acceleration. Fig. 4 shows the broadband integration of the vibration and URN, and the estimated Transfer Function for each hydrophone position.

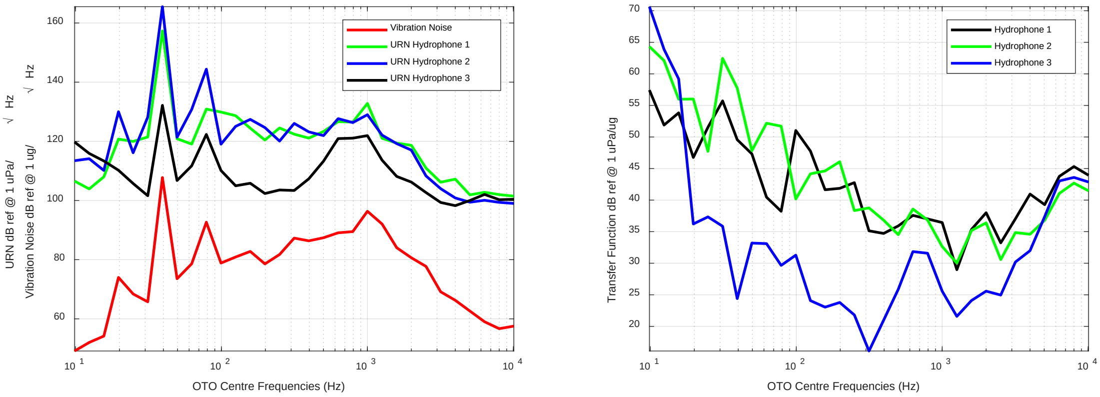

Fig. 4: Broadband integration of the vibration noise and URN (left) and estimated Transfer Function for each hydrophone position (right).

To evaluate the accuracy of each calculated Transfer Function, these functions were used to predict the radiated noise by applying them to the vibration measurement data. The estimations were compared with the real measurements performed with the SDH system.

As an example, Fig. 5 shows the estimated and measured URN for each hydrophone and the differences between them for the eighth measurement (M. ID 8).

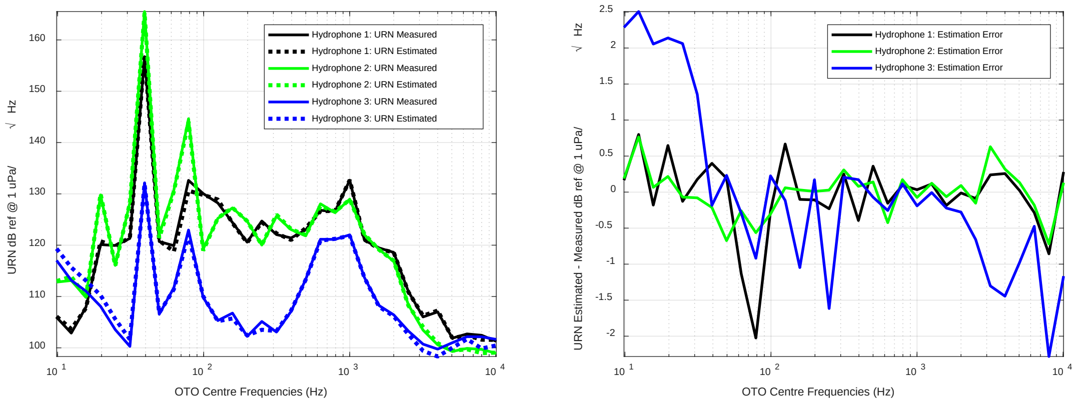

Fig. 5: Measured and estimated URN using the Transfer Function for each hydrophone (left) and differences between them (right).

The highest errors in the estimations of the URN were obtained for very low and high frequencies. This is related with the bandwidth of excitation of the source. Usually, the engines do not excite the hull at very low and high frequencies, so that these bands are dominated by the background noise. The underwater and vibrating noise are uncorrelated and the deviations between the estimated and measured URN are higher in the bands dominated by this noise that in the bands dominated by the source.

Table. 2 shows the maximum and mean error values between the estimated and measured URN by each hydrophone for all the measurements.

Error values in the Estimated URN (dB ref @ 1 µPa/√Hz)						
	Hydrophone 1		**Hydrophone 2**		**Hydrophone 3**	
M. ID	**Maximum**	**Mean**	**Maximum**	**Mean**	**Maximum**	**Mean**
4	2.2	0.59	1.08	0.33	3.75	1.29
6	2	0.54	1.21	0.36	2.8	0.64
8	2.02	0.35	0.77	0.24	2.51	0.87
10	1.86	0.43	1.23	0.27	3.13	0.72
12	1.24	0.41	1.24	0.39	6.11	1.23

Table 2: Maximum and mean error values between the estimated and measured URN by each hydrophone for all the measurements.

As it was expected, the maximum error in the estimated URN is lower in the position of the hydrophone 2 because it was closer to the vibrating source. The higher error appears in the position of the hydrophone 3 located at the bow. This is because during the measurements, the ship was moored with the bow oriented to the open waters and therefore, the uncorrelated noise in this hydrophone is higher than for the rest of hydrophones. By other hand, this hydrophone was located farer of the vibrating source. Relative to the mean values of the error, these are close to 1 dB or less. This denotes the accuracy of the measurements and the validity of this method to estimate the URN from the measurements of the vibration of the hull by means of the Transfer Function.

4. 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 this. The goal of this research was to calculate the Transfer Function of the ship under measurement and to use it to estimate the underwater radiated noise from the vibration measurements. The analysis was done in broadband, processing the OTOs of the measurements.

The repeatability analysis verified that the measurements had the quality to be processed and used to estimate the Transfer Function.

The predicted URN obtained by applying the Transfer Function to the real measurements of the vibrations of the hull using accelerometers has a maximum error of 1.24 dB referenced to 1 µPa/√Hz in the position closer to the frame, being 2.2 dB and 6.11 dB referenced to 1 µPa/√Hz in the stern and the bow, respectively. The mean value of the error is close to 1 dB referenced to 1 µPa/√Hz or less.

The low error values in the prediction of the URN verifies that the control of the radiated noise of a ship can be done by “converting” the real-time measurement data of the vibration of the hull to underwater acoustic noise by means of the Transfer Function.

Finally, the CRV and SDH systems have been proven fully capable and accurate to control the vibration of the hull and to measure the URN with high quality.

5. ACKNOWLEDGEMENTS

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