FINITE ELEMENT ANALYSIS APPROACH TO DETERMINE UNDERWATER SOUND CONTRIBUTION OF MACHINERY FOR A ROAD FERRY

Renaud Gaudel Research engineer Sound and vibration, DAMEN RD&I, Gorinchem (NL)
Tjakko Keizer Research engineer Sound and vibration, DAMEN RD&I, Gorinchem (NL)

1 INTRODUCTION

The main propulsion machinery (diesel engine, thruster, electric motor…) is an important contributor to the Underwater Radiated Noise (URN) of a vessel together with the propeller. Being able to predict the contribution of machinery is therefore essential during the design stage to be able to reduce the overall URN of the vessel and fulfil the requirements or diminish the impact of the vessel operations on marine life. Finite Element Analysis (FEA) can be used to calculate the structure mobility of main machinery foundations and the transfer functions between these foundations and underwater acoustic locations.

In this paper, a scale model validation is first performed to understand and establish the best approach for the FEA in terms of modelling, excitation/response, boundary conditions and solving methods. Then the method is extended to a full scale case, a 87 m hybrid propulsion double ended road ferry, for which the main excitations from the electric motor, the thruster and the diesel generator are considered. Finally, a methodology is developed based on the derived transfer functions and onboard vibration levels to simulate the contribution of each of the sources to the total URN for the comparison between two configurations: full electric (power generated by batteries only) and diesel electric (power generated by a diesel generator).

2 UNDERWATER ACOUSTICS WITH FINITE ELEMENT METHOD

The simulation of vibro-acoustic problems using FEA is a common approach in many industries and applications, ranging from the determination of sound pressure levels in room acoustics to the estimation of sound transmission loss or the prediction of acoustic properties related to absorption and radiation of different materials into acoustic domains. The use of FEA is typically restricted to the low frequencies and/or to relatively small objects in order to limit the degrees of freedom to maintain a reasonable solving time. But with the evolution of computational power and advanced numerical techniques, it becomes more and more feasible to use FEA for larger problems such as ship URN. For the higher frequencies, other methods can be used such as Statistical Energy Analysis[1].

One advantage of the FEA method is the well defined two ways coupling between the structural shell elements of the vessel hull and the (acoustic) fluid elements of the surrounding water, coupling the displacement response of the shell elements to the pressure response of the acoustic elements. This means that the added water mass is taken into account in the prediction of the radiated acoustic pressure. Another advantage of FEA is that the Kirchoff-Helmholtz integral equation makes it possible to calculate the pressure response at a receiver position outside the meshed fluid domain (far-field extrapolation) and therefore reduce the size of the fluid domain for far-field responses.

The FEA discretization of the fluid domain should be able to capture the spatial harmonic characteristics of the acoustic waves. This is achieved by defining an optimal number of nodes per acoustic wavelength, usually six to ten, based on the targeted frequency domain of the analysis[2]. The number of nodes in the model has a direct influence on the degrees of freedom to be solved and a balance should be found between a sufficient number of elements per wavelength and a reasonable solving time. The low frequency range requires a large fluid domain to capture the acoustic wavelengths radiated by the hull inside and beyond the fluid domain and the high frequency range requires very small element size which both increase the solving time.

3 MODEL SCALE

To assess the performance of FEA for structure borne radiated sound, a ship-like scale model was constructed and tested for different excitations (force hammer) and responses (accelerometers) locations on the structure and multiple receiver locations (hydrophones) in an anechoic water basin[3]. An FEA model was created to achieve the best validation. The scale model and the FEA model are shown in Figure *1*.

Figure 1 Scale model experimental setup (left) and numerical model (right)

The goal of this validation model was to achieve the highest possible accuracy for structure mobility and underwater transfer functions based on the possibilities of the FEA software (ANSYS APDL) in terms of fluid domain, mesh size, boundary conditions and solving methods. Different boundary conditions were used around the fluid domain to avoid the acoustic wave reflections such as Perfectly Match Layer (absorption elements) suitable at high frequencies or an infinite surface flag (impedance surface) for the lower frequencies. An accuracy of around 4.5 dB for the acoustic underwater transfer functions up to 10 kHz was achieved in this scale model.

For this approach, it was found that an important parameter is related to the frequency range of the analysis: the lowest frequency defines the minimum size of the fluid domain and the highest frequency defines the number of elements. Because of the small size of the scale model (1.8×0.9×0.3 m), the lowest frequency of interest is relatively high (>200 Hz), therefore the size of the fluid domain was reduced and the number of nodes/elements for both the structure and fluid domains was limited even for frequencies up to 10 kHz. This means that the solving time was reasonable for the full frequency range of the analysis. When scaling up to a full size model for a vessel, it is necessary to find the right balance, as explained in section 2, to minimize the size of the model and the number of elements to obtain a reasonable solving time. Therefore a sensitivity study was conducted with the scale model in which the effects of the different FEA options have been evaluated such as the frequency resolution, the mesh size, the boundary conditions and the size of the fluid domain. The results have been used to determine the approach for the full scale model presented in the next chapter.

4 FULL SCALE

4.1 Validation data

The full scale validation is performed on a 87 m double ended ferry for which the URN and the onboard vibration levels on the main machinery foundations were measured[4]. Two conditions are used for this paper, with the vessel running at the same speed of 10 kt, using battery generated power for one condition and diesel generated power for the other. At this speed, the contribution of machinery can be identified in the measurements as presented in Figure *2*.

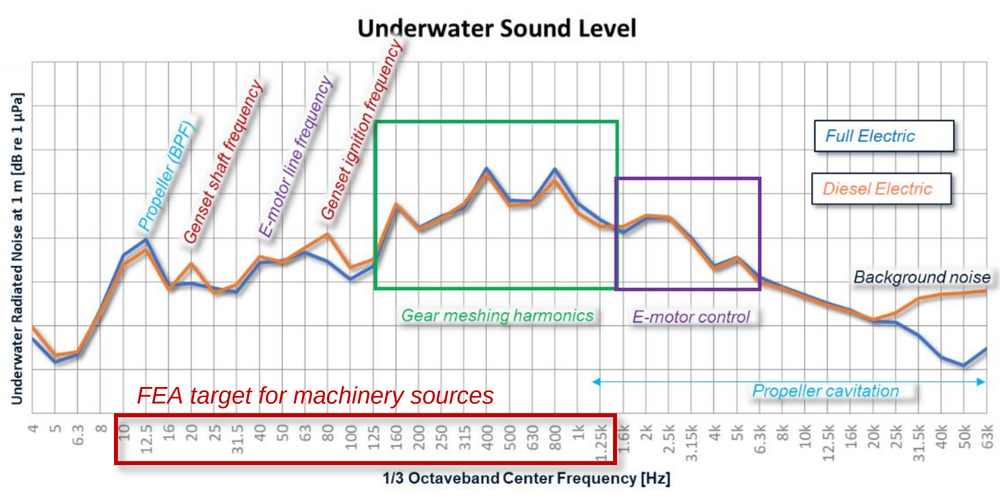


Figure 2 URN spectra for two propulsion conditions at 10.0 kt

As can be seen in the graphs, the URN is very tonal up to 1 kHz corresponding to the propeller blade passing, the electric motor, the thruster gear meshing and – when used – the diesel generator. At higher frequencies, the spectrum has a broadband character caused by the propeller cavitation. The lower frequency part of the spectrum can be used for the machinery contribution validation.

A measurement uncertainty of 3 to 4 dB for the URN was measured between similar vessels[4], which means that the two conditions shown in Figure *2* can be considered identical with the exception of the peak at 80 Hz from the diesel generator and the increased background noise above 20 kHz (dolphin clicks).

Due to the large size of the ship, only the aft half of the ship is modeled and due to fore/aft symmetry of this vessel type, as can be seen in Figure *3*, the same model can be used to derive the transfer functions from the sources situated in the foreship.

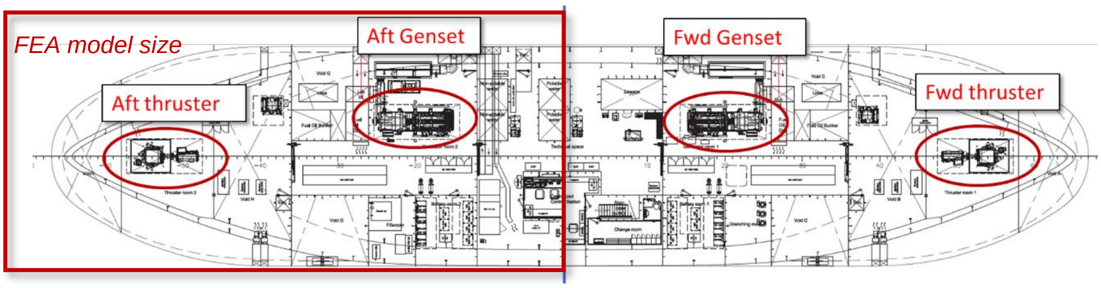


Figure 3 Main machinery sources onboard

4.2 FEA model

The vessel has been modelled according to the as-built drawings with a level of detail adapted to this analysis (including plating, primary/secondary structural members, girders, openings and main machinery foundations). A constant structural damping coefficient of 0.015 is used which is typical for ship steel structure.

To cover the targeted frequency range of [12.5-1250] Hz and optimize the solving time, two models are created: a Low Frequency (LF) model for frequencies from 75 to 500 Hz and a High Frequency (HF) model for frequencies from 500 to 1250 Hz. In Figure *4* more details are given about the two models.

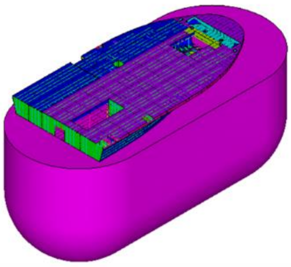
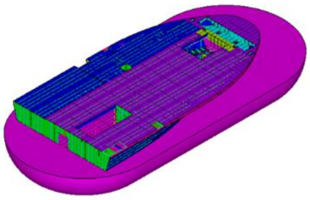
<table>
<tr><td rowspan="6">LF Model</td><td rowspan="6"></td><td>Dimensions</td><td colspan="2">45 × 20 × 20 m</td></tr>
<tr><td rowspan="2">Element size</td><td>Structural</td><td>0.150 m</td></tr>
<tr><td>Acoustic</td><td>1.0 m</td></tr>
<tr><td rowspan="2">Element count</td><td>Structural</td><td>172 687</td></tr>
<tr><td>Acoustic</td><td>718 156</td></tr>
<tr><td>Frequency steps</td><td colspan="2">91</td></tr>
<tr><td rowspan="6">HF Model</td><td rowspan="6"></td><td>Dimensions</td><td colspan="2">45 × 20 × 5 m</td></tr>
<tr><td rowspan="2">Element size</td><td>Structural</td><td>0.08 m</td></tr>
<tr><td>Acoustic</td><td>0.5 m</td></tr>
<tr><td rowspan="2">Element count</td><td>Structural</td><td>497 500</td></tr>
<tr><td>Acoustic</td><td>1 722 817</td></tr>
<tr><td>Frequency steps</td><td colspan="2">28</td></tr>
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Figure 4 The two FEA models and their characteristics

4.2.1 Boundary conditions

For this analysis, three boundary conditions are applied to the models (see Figure *5*):

- *Surface pressure release*: this results in p=0 for the nodes at the surface of the fluid domain.
- *Fluid structure interface*: coupling boundary condition between the structure and acoustic fluid where the displacement and pressure degrees of freedom are solved simultaneously.
- *Infinite surface*: infinite radiation boundary condition around the fluid domain (except the surface) that assumes the ratio of the pressure and outward normal velocity (impedance) is equal to $Z_0 = c_0\rho_0$ (water fluid).

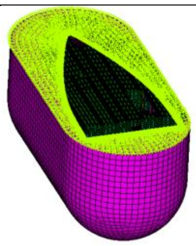
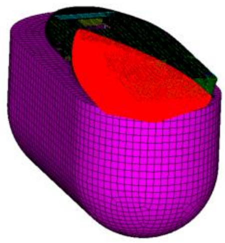
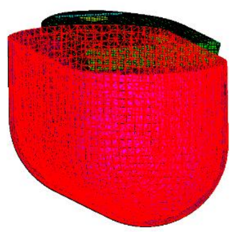
P=0 at surface	**Fluid Structure Interface**	**Infinite Surface**
		

Figure 5 Boundary conditions for the low frequency model (similar for HF model)

4.2.2 Frequency resolution

In general, the underwater acoustic response at the lower frequencies is driven by the global modes of the vessel which are well separated in frequency. Therefore a lower frequency resolution (defined as the number of frequency solving steps per 1/3 octave band) can be used to simulate the response. When the frequency increases, the number of local modes is increasing up to a point that the number of natural frequencies per 1/3 octave band is very large. This means that the frequency resolution of the FEA should also increase to better capture this dynamic behavior. Based on the results of the model scale validation, an optimal frequency resolution was chosen to find the right balance between accuracy and solving time.

The LF model analysis starts at 12.5 Hz in order to calculate the structure mobility. This is lower than the lowest frequency defined by the fluid domain size (75 Hz) but it was shown that the size of the fluid domain has little influence on the accuracy of the structure mobility.

For this validation, a total of 91 frequency steps are used for the LF model and 28 frequency steps for the HF model (including a frequency overlap with the LF model) which results in a total solving time of approximately 30 hours per model.

4.2.3 Force input main machinery

To reproduce the contribution of each machinery source to the URN, a vertical nodal force of 1 N is successively applied at the main sources foundations, on a node positioned at a stiff location. The total solving time being proportional to the number of unit load that are applied, it is important to keep this number low and for this validation, five locations are selected and shown in Figure *6*:

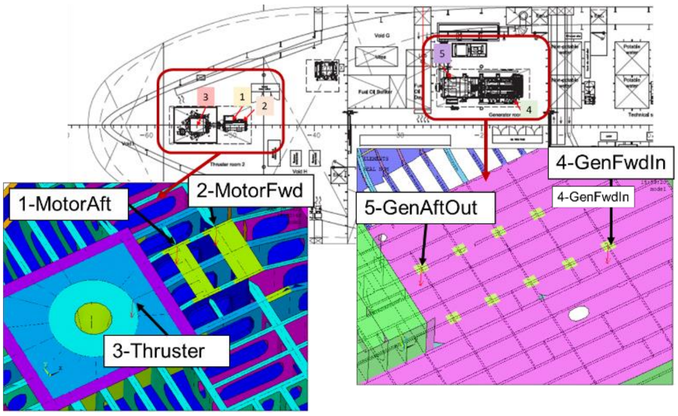


Figure 6 Locations of the machinery input forces

These input loads are calculated in successive harmonic analyses to identify the individual transfer functions between each machinery source and the underwater acoustic responses. This is done for both the LF and HF models.

4.3 Post processing

For the post processing, the nodal complex displacements on the structure are used for the structure mobility (input and cross) and the far-field extrapolation is used for calculating the complex pressure at three locations beyond the meshed fluid domain corresponding to the three hydrophones locations used in the URN measurement. An equivalent source surface boundary that encloses the radiating structure is used around the fluid domain to calculate the far-field pressure beyond the meshed fluid domain in the post processing.

In Figure *7* an impression of the three response locations in the FEA model are shown:

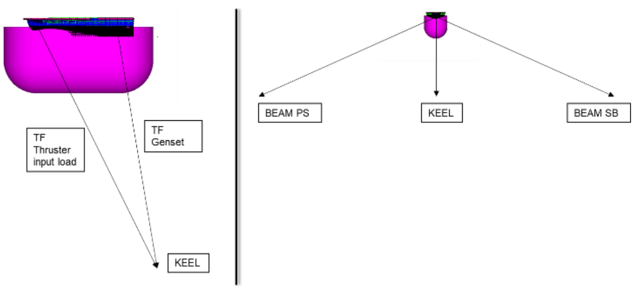


Figure 7 Acoustic response locations for the LF model (similar for HF model)

The transfer functions derived from the FEA are defined as below:

Structure mobility $Y(f) = 20log\left(\left|\frac{v(f)}{F(f)}\right|\right)\ [dB\ ref\ 1\ m/s/N]$

Underwater transfer function $S(f) = 20log\left(\left|\frac{p(f)}{F(f)}\right|\right)\ [dB\ ref\ 1\ Pa/N]$

In which $F(f)$ is force (N), $v(f)$ the complex velocity (m/s) and $p(f)$ the complex pressure (Pa).

The FEA approach is based on unitary force, which means that the pressure at the hydrophones cannot directly be compared with the underwater sound measured during sea trial. The force levels from each source are scaled using measured structure-borne vibration levels at the sources foundations combined with the calculated structural/pressure transfer functions. The steps of the methodology are described below.

First the mobility transfer functions from the FEA are assembled in the following matrix:

$$|v(f)|^2 = |Y(f)|^2\ |F(f)|^2 \text{ with } |Y_{ij}|^2 = \left|\frac{v_i}{F_j}\right|^2$$

Using the measured structure-borne vibration levels at each of the main sources foundation, the input forces can be calculated to match the trial response using the nonnegative least squares method.

Then the pressure transfer functions from the FEA are assemble in the following matrix:

$$|p(f)|^2 = |S(f)|^2 |F(f)|^2 \text{ with } |S_{ij}|^2 = \left|\frac{p_i}{F_j}\right|^2$$

The contribution from each source can then be combined to calculate the total pressure at each hydrophone position used for the validation. The assumption behind this method is that the sources considered are incoherent which might not be the case onboard since the electric motor is rigidly mounted to the hull very close to the thruster, the thruster might have influenced the vibration levels measured at the motor. For the higher frequencies however, this is a reasonable assumption.

5 RESULTS

In Figure *8*, the structural displacement and the pressure in the meshed fluid are shown for a frequency of 500 Hz. In these plots, a unit force load was used at each source location.

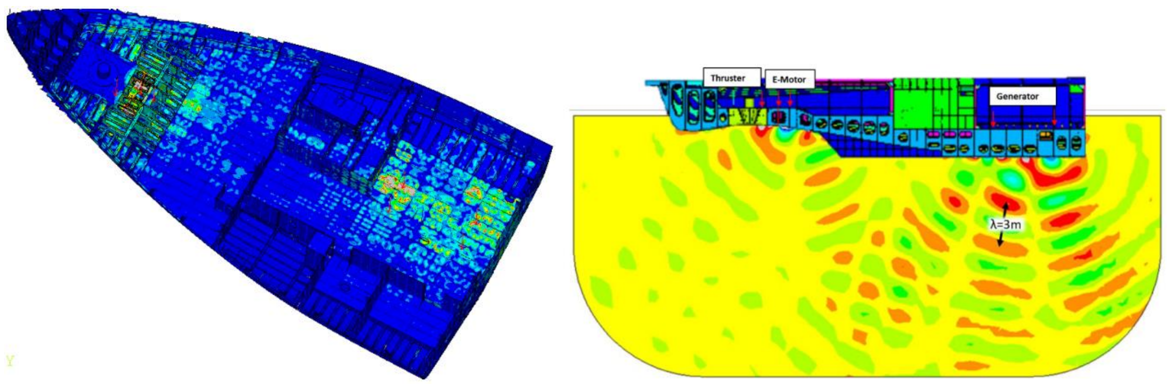


Figure 8 Structural and acoustic pressure responses at 500 Hz (unitary force input)

In the structure, the displacements are highest close to the main machinery sources and multiple local plating responses can be observed. In the fluid domain, the acoustic waves from the different source locations can be observed radiating with a wavelength of 3 m, corresponding to the 500 Hz frequency. The interferences between the different waves can also be seen between the thruster and diesel generator.

The underwater transfer functions from the FEA are shown in Figure *9* for the keel hydrophone (frequencies <80Hz are shown with dotted line to indicate the higher uncertainty in this frequency range due to the limited fluid domain size):

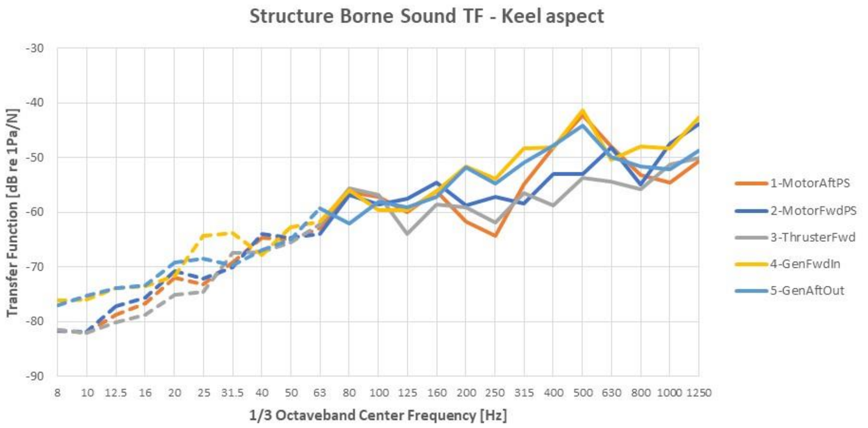
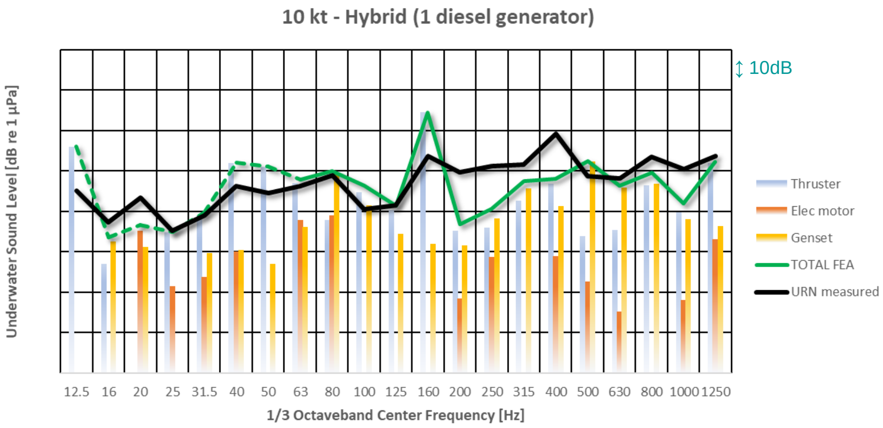


Figure 9 Ship underwater transfer functions from FEA

Based on the methodology described in paragraph 4.3, the total underwater sound levels can be calculated and compared to the URN measurements in the frequency range of interest for the two conditions of interests. The total levels from the FEA (green) and the contribution of each source to the total FEA level are compared to the measurements (black) in Figure *10*.



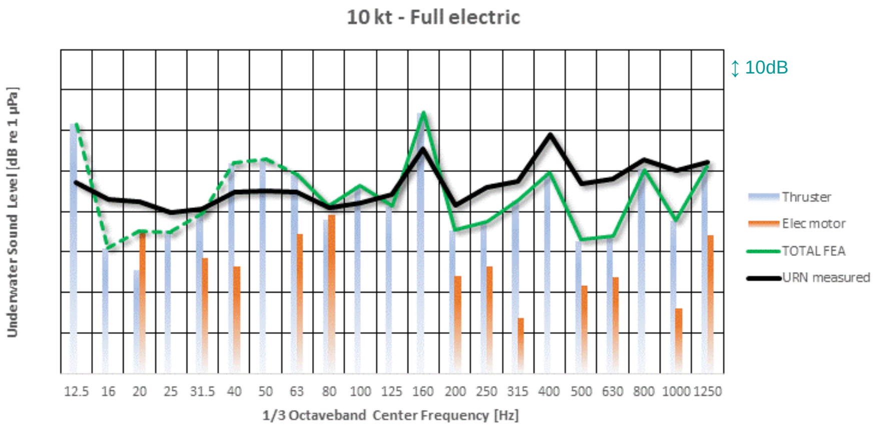


Figure 10 URN FEA vs Measurements for two conditions (keel aspect)

In both conditions, the contribution of the thruster (blue) that effectively includes the gearing of the Z-drive system and the excitations from the propellers, is dominant for most of the spectrum. The FEA is matching the measurements for most of the lower frequency range (<200 Hz) while slightly under-estimating them at higher frequencies. The electric motor (in red) is the least dominant source, except for the 20 Hz band (motor shaft frequency). In the hybrid condition, the diesel generator (yellow) is the dominant source only in certain bands, such as 80 Hz where the firing frequency of the combustion engine is dominant. This is very similar to the measurements. At higher frequencies [400-800] Hz, the contribution of the diesel generator is over-estimated by the FEA since only 2 excitation locations only have been used for the ten mounts.

In the frequency range below 75 Hz (green dotted line), the FEA is giving a good validation despite the insufficient size of the fluid domain for this frequency range.

In general the simulated spectrum representing the contribution of the main machinery excitations to the URN is showing similar characteristics as the measured spectrum and an overall accuracy of around 6 dB is achieved for these two conditions.

6 CONCLUSION

In this paper the Finite Element Analysis has been applied to simulate the underwater contribution from the main machinery to underwater acoustic response. First a validation was conducted on a scale model to establish the main characteristics of the FEA model in terms of level of detail, fluid domain size, element size, frequency resolution and boundary conditions resulting in an accuracy of 4.5 dB.

Then a sensitivity analysis was conducted to pave the way towards a more practical use of the method for a full scale vessel. This method was then applied to a 87 m ferry in the determination of the structure borne contribution of the thrusters, electric motors and diesel generator to the underwater radiated noise. The calculated structure mobility and the measured vibration levels of the main machinery were used to obtain the excitation forces which have been combined to the underwater transfer functions from FEA to obtain a total URN of the vessel.

An accuracy of around 6 dB was found which is only slightly more than the scale model and aligns with expectations due to the higher uncertainties related to the size of the full scale model and the measurements. The FEA approach presented in this paper allowed to obtain the URN for two different conditions of the ferry (hybrid VS full electric) which shows levels that are comparable to the measurements in the studied frequency range.

In both the simulation and the measurements, very little difference is observed between the two conditions for the ferry which is in line with observations of other ferries[5].

In the future, finite element modelling can be used in the development of effective mitigation strategies to reduce the impact of vessel on marine life.

7 REFERENCES

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