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AQUO Project – Modelling of ships as noise source for use in an underwater noise footprint assessment tool

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ABSTRACT

Recent researches outline the need to mitigate underwater noise footprint due to shipping, in order to prevent negative impact on marine life. Within this context, the final goal of the European AQUO project (www.aquo.eu), which started in October 2012 for 3 years, is to provide to policy makers practical guidelines, in order to mitigate underwater noise impacts of shipping noise on marine life. Those guidelines will be based on solutions regarding ship design, including propeller and cavitation noise as well as solutions related to shipping control and regulation. In a first part, this paper will give an overview of the project. In a second part, we'll focus on the introduction of the ship as a noise source in a noise map prediction model. Underwater radiated noise of different categories of ships is represented in a parametric form along frequency, speed and ship size. For that purpose, using available experimental data, a new method is introduced to derive parametric models, based on the decomposition of total radiated noise into three components (machinery noise, propeller noise, and cavitation noise). Each component is defined by a specific "pattern" accounting for the variation of noise with frequency and ship speed. In the last part of the paper, these models are used to determine noise footprint indicators on a test case, and the influence of taking into account or not the horizontal directivity of the noise sources is studied.

Keywords: Ships and marine vehicles Sound, Underwater noise, Environmental impact assessment
I-INCE Classification of Subjects Number(s): 13.5, 54.3, 68

1. INTRODUCTION

Significant efforts have been done so far by industry to reduce the levels of noise and vibration emissions on board ships. It has initially been addressed so as to prevent structural fatigue damage. For the last three decades, the comfort of passengers as well as the health of the crews have been increasingly considered by all the stakeholders: owners, yards and classification societies.

However there's not so much doubt that the increase of underwater noise related to anthropogenic activity at sea induces risk on marine life. The adverse effects of the use of powerful sound sources such as low frequency active sonar, air guns used by oil industry, and pile driving for installation of offshore platforms have been often reported. The problem of underwater noise generated by commercial shipping is presently becoming more acute because of the steady increase of ship traffic and vessel size. Despite the fact that noise levels generated by shipping are lower than for active sonar, the radiated noise occurs continuously and it can impact large maritime areas. The harassment effect on marine life can cause large disturbance on the biologic functions of some marine species, and in the long term, lead to habitat loss and negative consequences on biodiversity.

In that context, the final goal of AQUO project (Achieve QUieter Oceans by shipping noise footprint reduction – www.aquo.eu) is to provide policy makers with practical guidelines, acceptable by shipyards and ship owners. The list of solutions will be split into solutions regarding ship design (including propeller and cavitation noise), and solutions related to shipping control and regulation. This European Collaborative Project, which started in October 2012 for 3 years duration is supported by the 7th Research Framework Program and coordinated with the topic "Oceans of Tomorrow". Thanks to a pluridisciplinary team of specialists and experts from different companies and institutions belonging to 8 different European countries, AQUO project results are expected to have significant impacts and contribute to meet the requirements of the Marine Strategy Framework Directive adopted by the European Union in 2008 [1].

In a first part, this paper will present an overview of AQUO Project. One of the key elements is a “Noise Footprint Assessment Tool” allowing computing noise maps in a given maritime area, using as inputs the physical description of the environment and the distribution and characteristics of the noise sources (i.e. the ships) in the area. Using AIS (Automatic Identification System) data, which is mandatory on most commercial vessels, it is possible to get real-time information on the distribution of ships in the area. However, as detailed ship radiated noise information is generally not available, there is a need to represent ship underwater noise source using generic models in a parametric form as a function of ship type, size, and speed.

For that purpose, in the second part of this paper, a new method is introduced to build these parametric models, based on the decomposition of total radiated noise into three components (machinery noise, propeller noise, and cavitation noise). Each component is defined by a specific “pattern” accounting for the variation of noise with frequency and ship speed.

In the last part of the paper, these models are used to determine noise footprint indicators on a test case, and the influence of taking into account or not the horizontal directivity of the noise sources is studied.

2. AQUO PROJECT OVERVIEW

AQUO is a European research project which addresses to SST.2012.1.1-1. "Assessment and mitigation of noise impacts of the maritime transport on the marine environment" of the call FP7-SST-2012-RTD-1 of the TRANSPORT theme in the Sustainable Surface Transport.

The final outcome of the AQUO project is to deliver practical guidelines. These guidelines are aimed at helping policy makers to meet the requirements of the Marine Strategy Framework directive (MSFD). The outcomes will include:

- an improved knowledge and enhanced prediction of the shipping noise footprint thanks to a Noise Footprint Assessment tool.
- design recommendations for reduction of underwater radiated noise (URN) of ships under practical and economically feasible considerations.
- technical and operational measures for the mitigation of shipping noise impacts on the marine environment, with respects to living species.

AQUO is split into 5 technical work packages (WP), interconnected one to the other as shown in Figure 1.

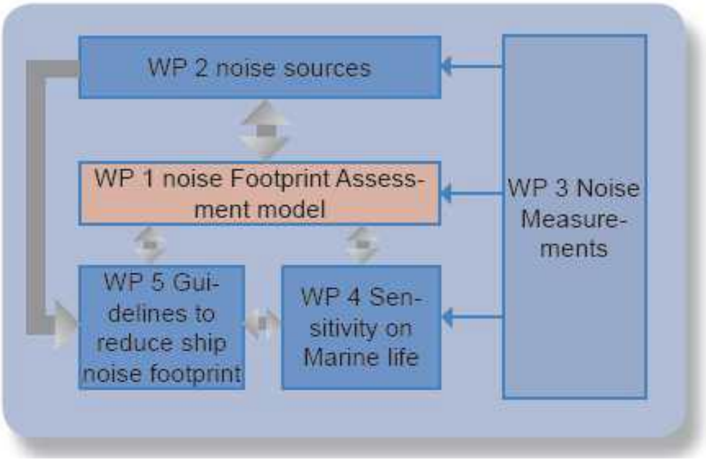

Figure 1 -AQUO project technical workpackages

2.1 Noise footprint assessment model (WP1)

The availability of a validated model for the underwater noise footprint of maritime traffic in a given area is of major importance for AQUO Project for the assessment of the impact on marine life of noise generated by shipping.

Noise footprint indicators are implemented in a predictive model. This model can be used both for prediction and real-time assessment. Indeed, as a predictive tool, dedicated solutions (either technical or operational) are assessed and optimized. Moreover, as a real time tool, it is targeted to draw a map showing the noise footprint in a maritime area combining underwater noise data from ships and ship traffic information through AIS data. In AQUO project, the modeling tool is adapted from Quonops® [**Erreur ! Source du renvoi introuvable.**], an operational global anthropogenic noise prediction system, designed similarly to weather forecasting systems developed by Quiet-Oceans, one of AQUO's partners.

There should not be confusion between:

- The radiated noise level of a ship, which is a physical, measurable quantity, used to characterize a ship as a source of underwater noise,
- The underwater noise map due to shipping, which is a physical quantity used to determine underwater noise due to shipping level in a maritime area. It can be spatially and/or temporally averaged.
- The underwater noise impact on marine life, which is the main issue in the present study. The assessment of the noise footprint must obviously take into account the receiver(s), through the sensitivity of different marine species to underwater noise.

This results in three levels, schematically represented on Fig. 2.

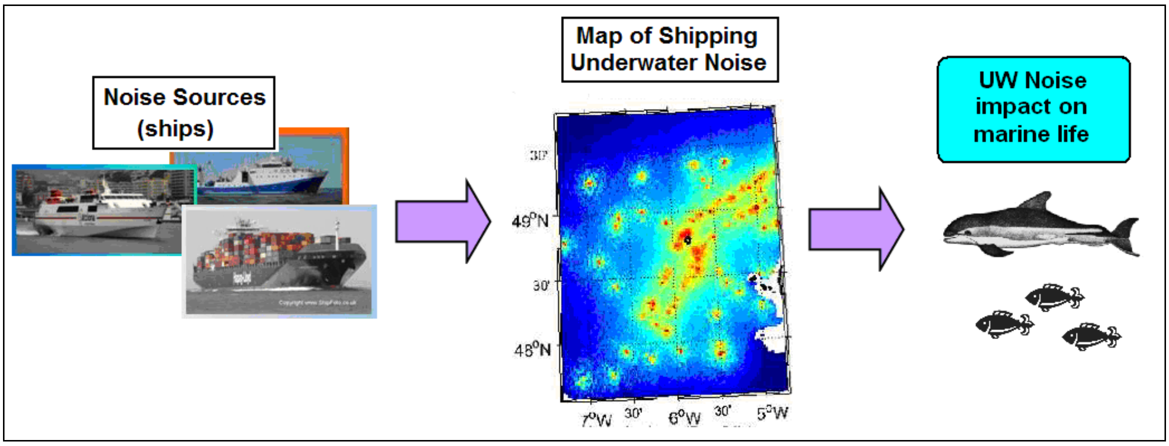

Figure 2: Three levels of characterization of underwater noise footprint due to shipping

Regarding the different definitions, applicable to shipping noise as a whole, AQUO project has adopted the following:

- Signature or underwater radiated noise source level: power spectral density of a sound source back-propagated to an arbitrary distance of 1 meter, possibly as a function of azimuth, bearing. It is a physical, measurable quantity, which can be used to characterize a ship as a source of underwater noise.
- Noise map: Spatial distribution of underwater sound in a maritime area of interest, obtained by superimposing one or more noise sources in the area of interest. It can be either (but not limited to):
  - determined in a given frequency band (for example a 1/3 octave band), or in the form of a spectral level at a given frequency,
  - integrated in a wider band domain, with weighting coefficients if needed (for example M-weighing coefficients for different functional mammal groups),
  - deterministic or statistical in the time domain.
- Noise footprint: The representation of the noise level arising from maritime activities that affects a portion of the sea. It includes the description of the noise sources and the propagation of the sound in the ocean environment that can be represented as a noise map, without frequency weighing. It can be used to assess the effect or impact of anthropogenic sound on marine life, using suitable indicators.
- Indicator: Combination of metrics that allows the partial or exhaustive evaluation of a descriptor, for example the biological effect of underwater noise on marine life.

2.2 Noise sources (WP2)

Work package N°2 includes different tasks regarding the representation of a ship as an underwatetr noise source and related predictive methods:

- Representation of ship underwater radiated noise (source level) in a parametric form, which will be presented in more detail in section 3 of the present paper,
- Prediction of radiated noise using numerical modeling, focusing on propeller noise,
- Prediction of radiated noise using scale models testes in water tank or water tunnel facilities, focusing also on propeller noise,
- Modeling of vibro-acoustic interaction between propeller and ship hull,
- Synthesis of results, taking into account other noise sources (mainly machinery noise).

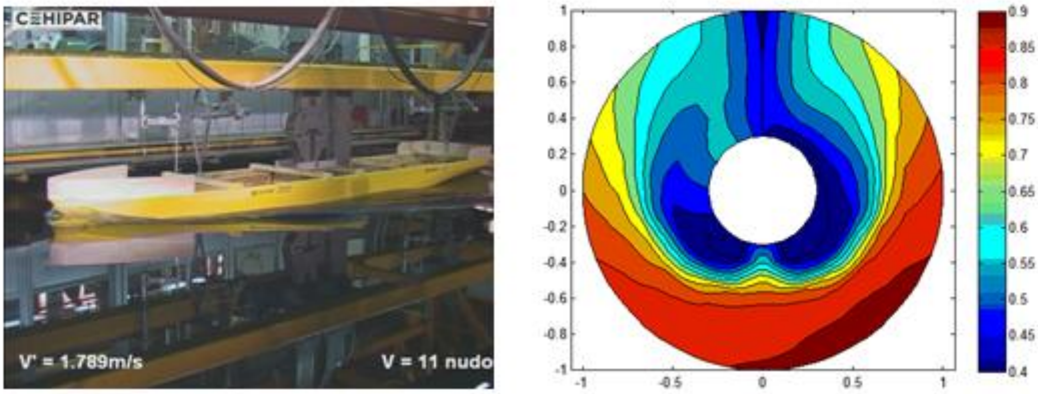

Figure 3: Fluid dynamics studies in the scope of propeller noise prediction

2.3 Experiments (WP3)

To validate the predictive tools and to support the analysis performed in the whole AQUO Project, the purpose of Work package 3 is to collect experimental data at sea. A proposal for improved procedure for radiated noise of ships has been studied.

Also, not less than 6 ships, including 2 commercial vessels, one fishing vessel, and 3 research vessels have been tested for noise, vibration and underwater radiated noise (figure 4).

Other tasks in WP3 are related to detection of cavitation noise and to the collection of underwater noise data.

Figure 4: Vessels tested in AQUO Project

2.4 Sensitivity on marine life (WP4)

Dedicated bio-acoustic studies are conducted on different marine species (fish, marine mammals, invertebrates), representative of European maritime areas, aiming at deriving criteria regarding shipping underwater noise acceptable limits. Currently, there is a lack of scientific knowledge of the impact of underwater sound on marine life, and AQUO Project results are expected to contribute significantly on this topic, thanks to a dedicated Work Package.

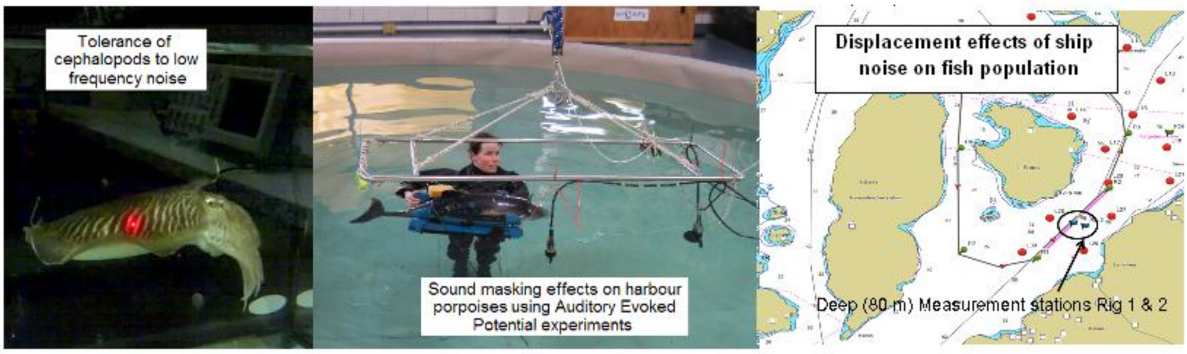

Figure 5: Bio-acoustic studies in AQUO Project

2.5 Practical guidelines (WP5)

In this synthesis Work Package, different mitigation measures for the underwater noise impact of shipping on marine life will be proposed, focusing on the most efficient regarding three criteria reduction of radiated noise, fuel efficiency, and impact on marine life. These can be either technical (reduction of the noise sources themselves, which are the ships), either related to traffic control. The different tools and experimental results obtained in the other WP will be used to assess their effectiveness.

3. NEW PARAMETRIC MODEL FOR THE REPRESENTATION OF SHIPS AS UNDERWATER NOISE SOURCES

3.1 Needs

In AQUO Project, noise maps for different test cases and scenarios are determined using a “Noise footprint assessment model”, connectable to AIS data, as presented in section 2.1. Obviously, the accuracy of the result will depend on the reliability of input data, in particular the noise sources. Ideally, it would be necessary to have at one’s disposal a big database containing ship source information for all the ships sailing in the area. Unfortunately, such information in open literature is very sparse, so it is not possible to set-up presently such a database. For that reason, it is necessary to use instead “generic URN (Underwater Radiated Noise) patterns”.

An “URN pattern” is a representation of the ship source level as a function of frequency, and if possible associated to directivity. Here, we consider only third-octave band averaged radiated noise back-propagated at a reference distance (1 meter). These URN patterns are expressed in dB re 1 $\mu Pa^2/Hz$ (1 meter).

The needs for AQUO project are:

- sufficient frequency coverage, at least [10 Hz – 10 kHz]
- dependence of URN on ship category, consistent with AIS numbering,
- dependence of URN on ship size in a given ship category,
- dependence of URN of ship speed in a given ship category.

Different models already exist in literature: Urick [3], Ross [4], Wales and Heitmeyer [5], ANATRA [6], RANDI in initial and updated versions [7], [8].

Table 1: Features of different ship URN parametric models

Model	Urick	Ross	Wales	ANATRA	RANDI	RANDI 3.1
Speed dependence	X	X			Related to ship category	
Size dependence	X	X			Related to ship category	
Ship categories				Noise	X	X
Categories list				Silent, Standard, Noisy	Supertanker, Large tanker, Tanker, Merchant, Fishing	
Minimum freq. (Hz)	100	100	10	10	10	10
Maximum freq. (Hz)	10000	10000	1000	10000	1000	10000

As a matter of facts, the objective of some of these models was to be used as an input of underwater noise predictive models (ANATRA, RANDI) for sonar detection range predictions. It should also be noted that some authors didn't find a clear dependence of noise with vessel speed or length, probably because most commercial vessels operate at a preferred speed depending on design and type.

3.2 Presentation of the method

The analysis of table 1 shows that the currently available models don't fulfill our needs. In AQUO Project, a new method to represent ship URN in a parametric form is introduced. For a given ship category, the method requires the availability of URN measurement of different vessels at different speeds.

3.2.1 Building a model for a particular vessel

The basic idea is assume that the total underwater noise radiated by the ship is decomposed into:

- noise radiated by internal machinery and equipment, transmitted to water through the hull;
- noise radiated by the propeller, without cavitation;
- noise radiated by propeller cavitation.

$$SL_{TOT}(f,V) = 10\log\left(10^{\frac{SL_{mach}(f,V)}{10}} + 10^{\frac{SL_{prop}(f,V)}{10}} + 10^{\frac{SL_{cav}(f,V)}{10}}\right) \quad (1)$$

Farfield URN due to flow along the hull is neglected in comparison to the other noise sources.

Each noise component is described by characteristic patterns for dependence with frequency and speed, represented on figure 6, affected to unknown coefficients for ship type and size. The corresponding formulae are as follows:

- Machinery noise

$SL_{mach}(f, V) = K_1 + K_4 \log V$, for $f < f_{mach}$ (2a)

$SL_{mach}(f, V) = K_2 + K_3 \log f + K_4 \log V$, for $f > f_{mach}$ (2b)

- Propeller noise

$SL_{prop}(f, V) = K_5 + K_6 \log f + K_9 \log V$, for $f < f_{prop}$ (2a)

$SL_{prop}(f, V) = K_7 + K_8 \log f + K_9 \log V$, for $f > f_{prop}$ (2b)

- Cavitation noise (for $V > V_{cav}$)

$SL_{cav}(f, V) = K_{10} + K_{11} \log f + K_{12} \log V$, for $f < f_{mach}$ (3a)

$SL_{cav}(f, V) = K_{13} + K_{14} \log f + K_{12} \log V$, for $f > f_{mach}$ (3b)

The dependencies of the noise components (i.e. the coefficients associated to frequency and speed) are not arbitrary but are supposed to be within some interval characteristic of the physical phenomenon under consideration, and knowledge of data from existing vessels. For example:

- For machinery noise, the spectrum is generally nearly flat at low frequencies, and slope with frequency is typically -25 dB per decade at higher frequencies. Dependence of levels with speed is not expected to increase more that 30 times the logarithm, as the vibration levels of the propulsion motors will not increase more than the mechanical power increase (theoretically the third power of speed).

- For cavitation noise, the spectrum presents a maximum between 50 and 200 Hz, and typical noise spectrum slope is about 20 dB per decade at low frequencies and -20dB per decade at high frequencies. The dependency with speed is typically between 50 and 60 dB times the logarithm of speed (however the latter might not be applicable to variable pitch propellers).

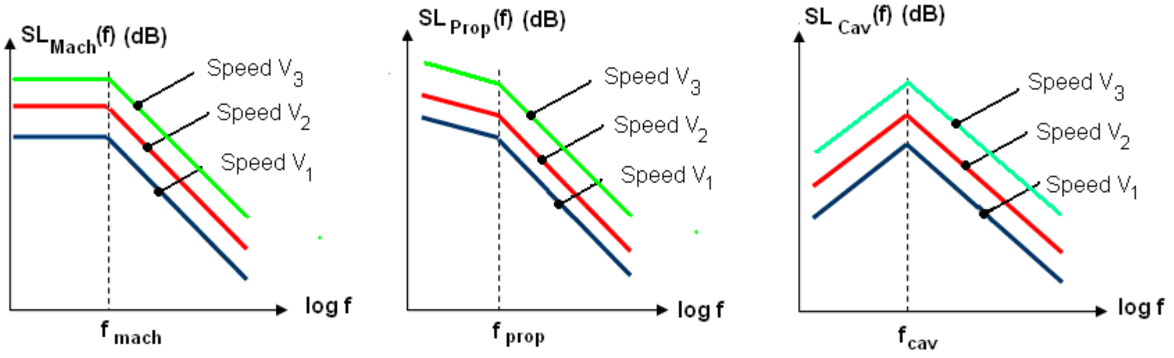

Figure 6: Typical patterns for ship radiated noise components

The next step for a given vessel is to determine the unknown coefficients K_1 to K_{14}. For that, we assume we have at our disposal a set of URN spectral levels measurements for the same vessel at different speeds. A best fit procedure is done in order to minimize the deviation between the model and the measurements, using eq. (4):

$$\sum_{m=1}^{M}\sum_{q=1}^{Q}\left|SL_{\exp}(f_q,V_m)-10\log\left(10^{\frac{SL_{mach}(f_q,V_m)}{10}}+10^{\frac{SL_{prop}(f_q,V_m)}{10}}+10^{\frac{SL_{cav}(f_q,V_m)}{10}}\right)\right|^2 \qquad (4)$$

Here, subscript m is for the speed, and subscript q for 1/3 octave band center frequency.

Once this step is completed, we have a URN simplified model accounting for dependency of URN with frequency and speed of a particular vessel. The result is shown schematically on figure 7.

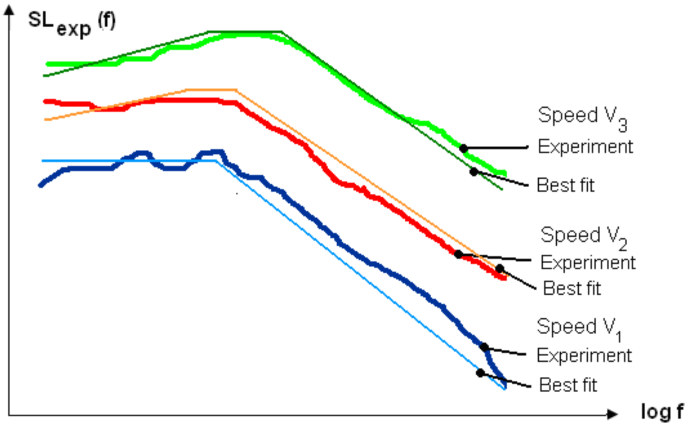

Figure 7: Result of best fit between parametric URN model and experimental data for a particular vessel

3.2.2 Building a model for a category of ships

Different categories of ships have been defined for AQUO Project, in relationship with IMO codes: Cargo, Tanker, Passenger, High speed vessels, Fishing vessels, Leisure crafts, Special vessels (e.g. dredging and tugs), and Other types (including research vessels).

When data are available, then a model derived using method described previously for different particular vessels in a same category is available, it is possible to average or to make some statistics on the models from each individual vessel in the category. For that purpose, the models are scaled to vessel size with respect to a reference length for the category, L_{ref}. Expression (5) gives the assumed scaling law (which is close to laws used in previous work, as in Urick's).

$$SL_{TOT}(f,V,L) = 10\log\left(10^{\frac{SL_{mach}(f,V,L_{ref})}{10}} + 10^{\frac{SL_{prop}(f,V,L_{ref})}{10}} + 10^{\frac{SL_{cav}(f,V,L_{ref})}{10}}\right) + 25\log\left(\frac{L}{L_{ref}}\right) \quad (5)$$

In practice, in addition to the lack of relevant data available, it is not always possible to find consistent models because of the variety of ship design inside the same category. A first possibility is to define sub-categories (e.g. "Large cruise vessels" in the "Passenger ship" category). Another possibility, not used here because not compatible with AIS information, is to define categories based on design (e.g. whether the main engine is resiliently mounted or not, the type of propeller…).

3.2.3 Low frequency correction

Another point to consider is the so-called Lloyd's mirror effect [9] which is related to the reflection of sound waves on sea surface, a pressure release boundary introducing a dipole-like vertical directivity at low frequencies. As a matter of facts, formulae (1) and (5), and most of experimental URN data from literature, represent not a "true" source level, but an "affected" source level. If the affected source level is used, it is likely to underestimate the underwater sound propagated in the far field. Hence, a correction (6) is applied at low frequencies, based on Ainlie's [9]. Here, d is the assumed source length which can be related to ship draught, and θ is the observation angle used in ship URN procedures, which is generally about 20° to 30°.

$$SL_{corr}(f,V,L) = SL(f,V,L) + Max\left[0;10\log\left(\frac{1}{2}+\frac{1}{\left(\left(\left(2\pi f/c\right)d\right)\left(2\sin\theta\right)\right)^2}\right)\right] \quad (6)$$

4. PRESENTATION OF SOME RESULTS

4.1 Bulk cargo "MV Overseas"

Input data are taken from reference [10], and the procedure described in section 3.2.1 has been applied. Figure 8 gives the result of the building of the URN model.

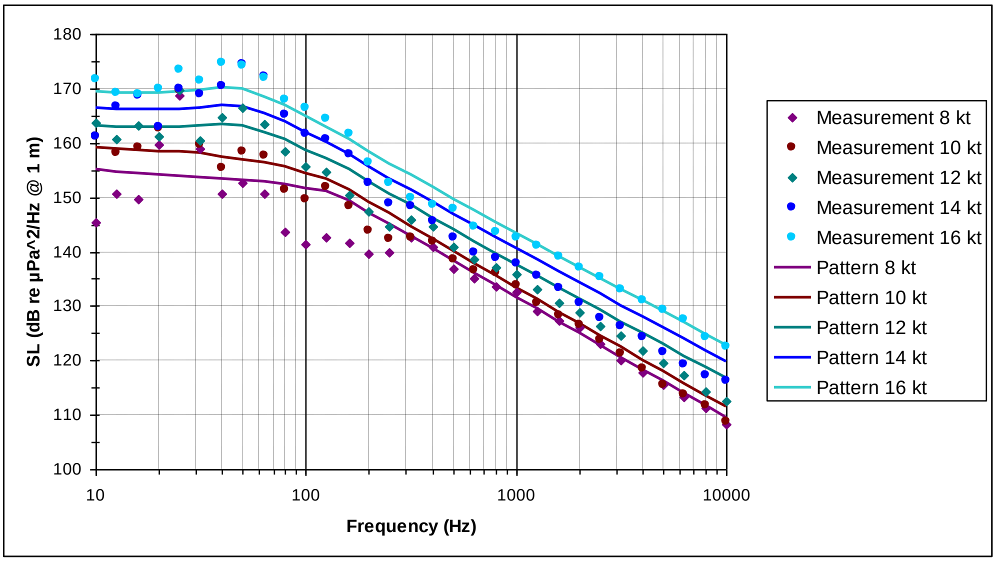

Figure 8: Parametric URN model for cargo "MV Overseas"

Figure 9 gives the estimate of repartition of total URN on the three noise components for two speeds: 8 kts and 16 kts. At 16 kts, cavitation is found to be dominant, at the lower speed, it is machinery noise. Note that the model cannot deal the noise peak at 25 Hz frequency at 8 kts.

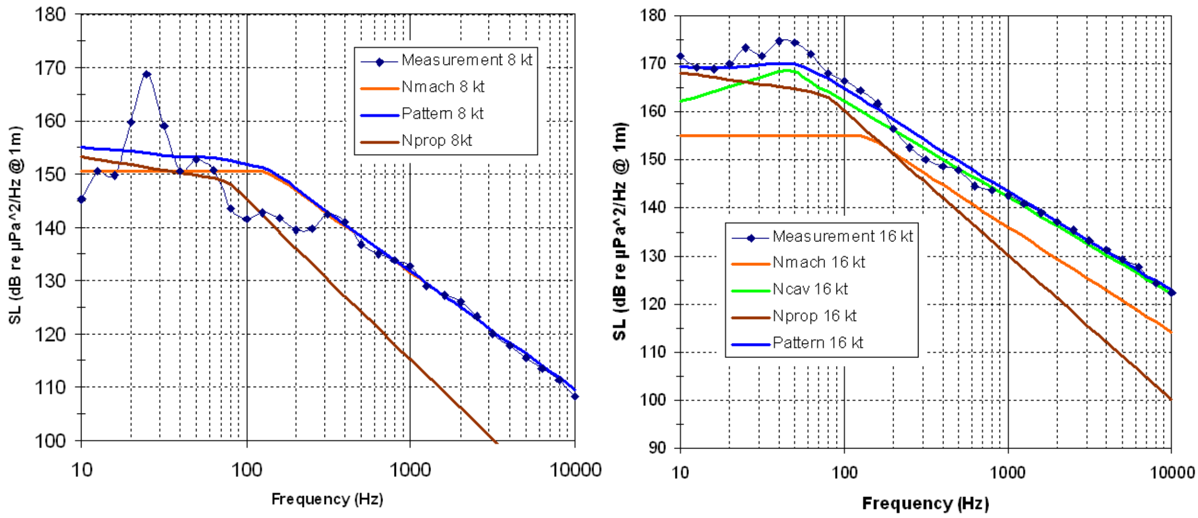

Figure 9: Decomposition of URN in components for cargo “MV Overseas” at two speeds

4.2 Model for “Cruise vessel” sub-category

The full methodology presented in section 5 has been applied to a set of data regarding large cruise vessels, taken mainly from reference [11]. The result is presented on figure 10, after scaling to a reference speed (18 kts) and a reference ship length (250 m).

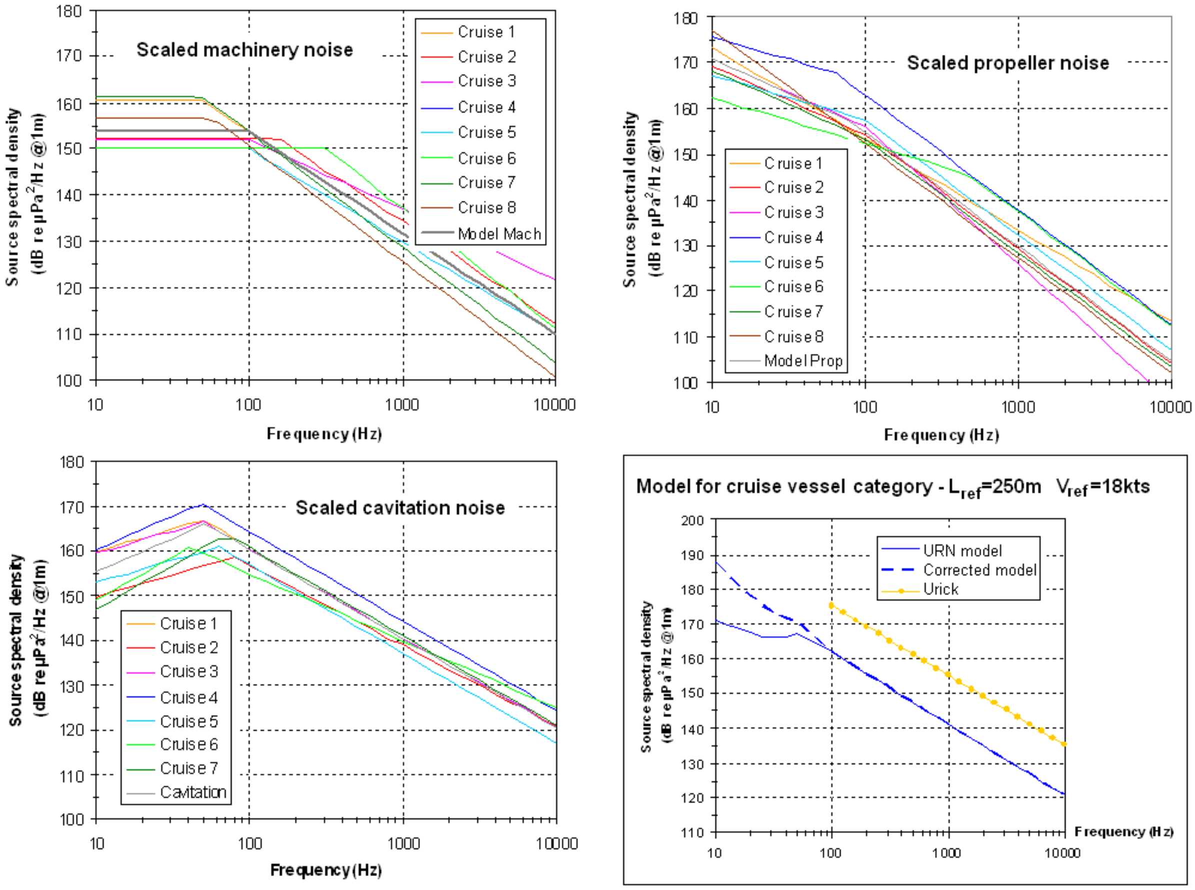

Figure 9: Parametric acoustic source level for cruise vessel category scaled at reference length (250m) and speed (18 kts). Comparison of the noise components of 8 different vessels (top and bottom left). Final model with and without low frequency correction compared to Urick’s model (bottom right)

We can see that, despite some dispersion due to different designs from one vessel to another, the aspect and magnitude of URN levels are similar, allowing to build a consistent model for this category of ships. Also, the final model is found to give a significantly lower radiated noise than Urick’s one, which was to be expected because the latter is mainly based on old vessels designed in the middle of 20th century.

5. CONCLUSIONS

This study was realized in the scope of AQUO Project, a European collaborative research project aiming to propose solutions for the mitigation of underwater sound due to commercial shipping, which may have adverse effects on marine life. An improved model to represent a ship as an underwater sound source is introduced in a parametric form along frequency, speed and ship size for different categories of ships. This model is intended to be used as an input for a shipping noise footprint assessment model for AQUO Project studies.

The basic idea is to decompose the URN into three components (machinery, propeller and cavitation), each one associated to a characteristic pattern, and to determine the unknown coefficients in the model by a best fit procedure between the model and experimental URN data at different speeds for the same vessel. Then, provided available data for different vessels in the same category, it is possible to build a generic model for the category. This methodology has been applied successfully to different cases, some of which have been presented here.

However, there are some limitations, which require more studies in the future. The main problem is the lack of available relevant data, as URN information is needed at different speeds for the same vessel. Another limitation is the heterogeneity of design of vessels in a same category. Additionally, it could be relevant to introduce a horizontal directivity, as discussed in reference [12].

ACKNOWLEDGEMENTS

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