New European Underwater Noise Measurement Standard Developed in the AQUO Project

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Abstract—The acoustic impact of ships has gained growing attention during the last few years. The European Union within the MSFD and associated TG Noise has assigned the anthropogenic noise from shipping as one of the contributors to a downgrading of the environmental status. The assessment and the corresponding mitigation measures would have to be proposed by 2016 and put in force by 2020. Therefore, it is vitally important for the ship industry and regulatory bodies to have available measurement procedures enabling the correct estimation of underwater noise radiated by vessels.

Some international standard bodies such as ANSI and ISO have already developed and are still developing procedures for civil applications to quantify the underwater noise emission of ships. However, there are aspects of these procedures that are not yet consolidated from a technical point of view like the uncertainty associated to the procedure, and topics that are not yet addressed, like measurements in shallow waters. In this regard, the AQUO project, in the scope of the FP7 European Research Framework, set as one of its targets the development of a new European standard for underwater noise measurements adapted to both, shallow and deep waters with a special emphasis on the assessment of the uncertainties.

This paper is a follow-up to the one previously written by TSI identifying the sources of uncertainties of the current measurement procedures. It will firstly present the measurement procedure resulting from the research done in the AQUO project. Thanks to the collaboration agreement signed by BV and TSI, this procedure has been largely adopted by Bureau Veritas in its new rule note (NR 614) titled Underwater Radiated Noise. Finally, the paper will also present the outcomes of the theoretical and experimental studies of its associated sources of deviation trying to provide realistic values for the uncertainty and repeatability of the measurement procedure. Due to its impact on marine life, the abatement of the Underwater Radiated Noise by ships has become the most out-standing novelty and difficult challenge that the Shipbuilding industry has ever faced. Therefore, the industry is trying to provide new solutions in order to comply with the new directives and requirements having been recently developed and promoted by the EU, Marine Institutions and the scientific community.

Keywords—Underwater radiated noise, measurement methods

I. INTRODUCTION

One of the aims of the AQUO project is to develop a proposal of a new European URN standard measurement method by detecting the gaps and improving current protocols.

The European Union within the MSFD and associated TG Noise has assigned anthropogenic noise as one of the main contributors of oceans noise and requires mitigation measures to put in force before 2020. Therefore, accurate measurement methods to measure URN from ships are necessary to assess the underwater noise pollution of each ship and to identify sources and noise paths that may help to apply cost-effective solutions.

Important bodies and organizations like ANSI/ASA or ISO have already addressed or are addressing this topic producing measurement methods (1, 2, 3, 4). However, some gaps still exist and, even more important, there is a lack in the literature consulted by the authors of supported studies about their accuracy.

This paper tries to give some insight of the needs and gaps identified in the existing methods following up a previous paper dealing with this topic (5) and proposes a new measurement method, result of the work carried out in the AQUO project and used as reference in the measurement procedure in the URN notation of Bureau Veritas (6).

II. IDENTIFIED NEEDS AND POTENTIAL IMPROVEMENTS OF EXISTING STANDARDS

A. General Needs

An applicable measurement procedure shall be aimed at the civilian shipbuilding industry, which imposes a series of economical constrains that have to be considered. On the other hand, it has also to be sufficiently accurate so the technicians and stakeholders can rely on the results obtained so they can make good decisions. In particular, this implies the following requirements:
Unlike most of the existing standards, the measurement procedure shall contemplate measurements in shallow waters in any part of the world to avoid long trips of the ships built by certain shipyards, for example for those placed in the European waters (see Fig 1).

This procedure has to be applicable in any part of the world, which means that it has to permit the use of portable devices in a reasonable amount of time.

The measurement method has to be not only sufficiently accurate but it has to provide enough support for its associated uncertainty and repeatability.

The reader will imagine that in order to fulfil these requirements some technical solutions are required.

B. Analysis of the existing standards

The paper ([5]) provides a deeper analysis on the existing gaps of the current measurement methods. This paragraph does not intend to reproduce that analysis here but to summarize its main conclusions. In this regard, the most important gaps identified can be grouped as follows:

- Lack of standardisation or even definition of the magnitude to be measured. In this regard, most measurement methods consider the ship as a point source. However this is a strong assumption that has to be proved and even sometimes it is not well defined if the magnitude measured is the vessel alone without the effect of the sea surface reflection (monopole source) or if the levels obtained are “affected” by the sea surface (dipole source). This distinction is especially important in the low frequency.

- Simplified approach for the computation of the actual transmission loss. Most of the measurement methods consider simplistic ways of sound transmissions like the spherical propagation ([1]) or something between a cylindrical and spherical propagation suited for very specific test places ([4]).

No definition of the uncertainty and repeatability associated to the procedure or if it exists, it does not seem to be very realistic according to experiences of full scale measurements.

The measurement procedure described in the following paragraph tries to make some progress to fill these gaps.

III. DESCRIPTION OF THE UNDERWATER NOISE MEASUREMENT PROCEDURE

A. Aim of the procedure

During the development of the procedure special emphasis has been put in the uncertainty and repeatability of the measurement, so any assumption made and technical solution proposed have been assessed in this terms, theoretically, numerically and whenever possible experimentally. In this regard, the paragraph IV will show one the measurements carried out to validate the uncertainty and repeatability of the measurement.

B. What is measured

This procedure will make the same assumption as most of the existing measurement methods: the vessel is considered a noise point source. In order to achieve this, a minimum distance between the hydrophones and the ship is required. The definition of this distance has been verified experimentally by means of the directivity diagrams of the ship taken at different distances. The hypothesis behind this study is that the ship can be considered a point source from the point at which its directivity does not vary more than the uncertainty of the measurement. Fig 2 shows that for low frequencies this holds from 200m. More information can be found in ([7]).

On the other hand, unlike other procedures, it will try to remove the Lloyd’s Mirror effect from the levels so the results obtained can correspond to an ideal situation where the vessel is not affected by its surroundings. This is known as the monopole source levels. Lloyd’s Mirror effect is important in the low frequency region with calm seas (below 200Hz most likely, see Fig 2).
Fig 3). If it is not taken into account, the source levels of the vessel may be very underestimated. Moreover, this effect also depends on the source depth, thereby the vessel draught somehow, so it will affect differently to different ships. The Fig 3 shows a spectrogram where the Lloyd Mirror effect can be well identified.

![Spectrogram where Lloyd's mirror effect can be appreciated](image)

**Fig. 3.** Spectrogram where Lloyd’s mirror effect can be appreciated

Finally, the final signature of the ship will not be provided for each side of the ship which means that there will be no distinction of the underwater noise between portside and starboard. This change is supported by experimental data obtained in different types of ships within the framework of AQUO and previous projects (SILENV). Fig 4 and Fig 5 show only a sample of the data used to support this assumption.

![One-third octave band source levels at both sides of a research vessel](image)

**Fig. 4.** One-third octave band source levels at both sides of a research vessel

![One-third octave band noise source levels at both sides of a ferry vessel](image)

**Fig. 5.** One-third octave band noise source levels at both sides of a ferry vessel

**C. Where is it measured**

As said previously, the measurement procedure should attend the reality of certain yards in the sense that some of them are placed in coastal areas where achieving sufficiently deep waters, as some existing methods requires, is difficult. Therefore the procedure should define a method to carry out not only deep water measurements but also shallow water measurements in any part of the world. In this regard, two different “types” of measurements with a few different requirements are considered: shallow water measurements (between 60m and 200m) and deep water measurements (from 200m upwards).

**D. Measurement set-up**

As it is said previously, the unawareness of the transmission loss is one of the main sources of uncertainties with regard to the computation of the noise source levels of the ship. This is due to the fact that it will depend on many factors, especially the sound celerity profile, the sea state and the sea bed if, as in this case, measurements in shallow waters are to be carried out. Even though the effect of these parameters on the sound transmission could be computed thanks to some existing numerical models, most often the knowledge of these parameters is not sufficient or even it is non-existent and they will have to be estimated.

A way around this problem is to measure in different positions. Deploying several hydrophones can provide averages that increases the repeatability of the measurement. In this regard, the hydrophones will be located far enough among each other so the measurement points can be as much representative of the sound of the water column as possible. In addition to this, they will be placed far enough from the sea surface and the sea bottom to reduce their effect on the sound level received by the hydrophones.

The Fig 6 shows the constraints of the 3-hydrophone line with regard to the separation among each other and the minimum distance to the sea bed and sea surface in both cases, shallow water and deep water measurements.

![Hydrophone line configuration](image)

**Fig. 6.** Hydrophone line configuration

Another sensitive topic is the measurement of the distance between the ship and the hydrophones. Traditionally, the measurement between the hydrophone and the ship has been
carried out by measuring the horizontal distance between a reference location on the sea (commonly a buoy) and the ship and knowing the depth where the hydrophone was placed at. However, as soon as a tilt angle appears in the line an error is made in the computation of the distance. In order to avoid this, more complicated methods have to be used to measure directly this distance.

In order to know the importance of this source of error in the final levels, and therefore the necessity of incorporating in the procedure a more sophisticated distance measurement method, a Montecarlo simulation was performed in ([7]). This simulation consisted on computing numerically the transmission loss at the location of the hydrophone for hundreds of test cases where different tilt angles (between 0 and 20º), distances between the hydrophone and the ship and test site conditions were considered. The variance of the results of each one-third octave bands for the shallow and deep water configuration (see Fig 6) is shown in the Fig 7. It can be seen that the average error associated to this phenomenon, even though not negligible, it can be assumed if we consider other sources of uncertainties much more important like the transmission loss.

![Fig. 7. Standard deviation of the TL after considering different tilt angles](image)

**E. Measurements to be carried out**

The procedure developed requires to measure the sound emitted by the vessel in different runs at different distances. As said before, transmission loss is one of the most important sources of uncertainty and it is difficult to compute it correctly due to the unawareness in most of the cases of necessary environmental parameters. This is why performing runs at different distances is required so the results can be averaged and the accuracy and repeatability of the measurement increased.

Performing runs at different distances is an important novelty. Statistically speaking, what is being done is to vary as much as possible the conditions of the measurement, in this case the distance between the source and the receiver, so the error of the model used to compute the transmission loss can be averaged and thereby the variance of the estimates reduced.

Besides, and in case of desiring a more accurate transmission loss, complementary measurements should be performed. In particular, celerity profile measurements so, along with information of sea state and properties of the seabed, numerical computation of the transmission loss can be carried out.

Finally, as every other existing standard, background noise measurements have to be carried out. As a remarkable novelty, background noise measurements before and after the trial have to be performed to estimate the variability of the background noise so that we can have an idea if the correction defined, in case the SNR is between 3dB and 10dB, could be applied.

**F. Post-processing**

The post-processing of the signals recorded has to be correctly defined so the results between two different vessels can be comparable. The post-processing for the measurement of each run is as follows:

- Computation of the one-third octave band sound pressure level received for each hydrophone during each data window. The data window length (DWL) is the ship length of the vessel or 100m, whichever is greater.
- Background noise correction if applicable.
- Distance correction. There are two possibilities here: Using simplified laws which are the average of the results of hundreds of simulations with different environmental parameters performed in ([7]) or numerical models to compute it more accurately (see below).
- Sound power average on hydrophones.
- Linear average of all data windows (see Error! Reference source not found.).

![Fig. 8. Post-processing of each run](image)

Two noticeable differences with regard to the existing measurement methods exist:

- The possibility of computing the transmission loss using numerical model. In this regard it is important to obtain what is called “average transmission loss”, which is an average transmission loss for each one-third octave band. The uncertainty associated to the unwariness of the environmental parameters will be compensated by the exploitation of the runs at different distances, the number of hydrophones and the post-processing defined.
• The linear average of all data windows. According to the philosophy of using as much data as possible, the post-processing requires to subdivide each run in different data windows taken at different angles. Certain overlap will exist between two consecutive data windows, so we are using some kind of a resampling technique to estimate the average noise source level of the vessel. This estimation will have less variance. This approach may have a flaw: the directivity of the ship. However, it is important to note that we are interested in evaluating the overall noise impact of the ship.

As a proof of what have been achieved with this new type of post-processing the Fig 9 shows the results obtained in a series of runs taken at different distances and the Fig 10 the differences between the variance of the estimates using existing methods and the variance of the proposed one. As one can see, the repeatability achieved is high (the results for this vessel were background noise affected below 40Hz).

Fig. 9. Noise source levels obtained from different runs taken at different distances to show the repeatability

Fig. 10. Comparison between the post-processing of ANSI/ASA 12.64 procedure and the proposed procedure in terms of repeatability

IV. FULL SCALE MEASUREMENTS FOR THE VALIDATION OF THE UNCERTAINTY AND REPEATABILITY OF THE NEW PROCEDURE

A. General description of the trials

Special emphasis of its uncertainty and repeatability was put during the development of this measurement method. In ([7]) a whole theoretical-experimental study of the accuracy of the method was developed (it cannot be included due to the extension of this paper). Finally, a final experimental validation was carried out to assess the uncertainty and repeatability of the procedure. This validation consisted on carrying out several full scale measurements of underwater radiated noise of a fishing vessel according to the measurement procedure proposed above: twice in the first day, to assess the repeatability, and once more the following day under as different conditions as possible (sea state, heading, variable bathymetry, etc.), to assess the uncertainty of the measurement. The Fig 11 shows the different locations and the schematic directions of the runs performed in these three measurements. As can be seen in this figure, the runs performed during the first day were perpendicular to the ones performed during the second day. The first day corresponded with constant bathymetry and the second one with variable bathymetry.

Fig. 11. Trajectory and location of the different runs carried out

Fig. 12. Measurement device

B. Results

The Fig 14 shows the two final URN signatures obtained, after applying the whole post-processing, during the first day of the trial. Due to the rough sea state (sea state 4) during the first day the frequency range below 100Hz had to be discarded as it was background noise affected. This is why a red shaded zone is present in this frequency range. The Fig 14 clearly shows the high repeatability of the measurement procedure.

The Fig 15 shows the signature taken during the second day and one of the signatures taken during the first day so we can
assess the uncertainty of the measurement. This figure shows worse accordance between these two signatures than what is shown in the Fig 14. This was expected due to the changes in the condition of the measurement (celerity profile, effect of bathymetry, sea state, etc.). Moreover, the average difference between these two signatures is about 2dB, which shows that the uncertainty of the measurement procedure looks reasonable and does not contradict the uncertainty obtained theoretically (see [7]).

Fig. 13. Measurement team

Fig. 14. Signatures obtained during the first day to assess the repeatability.

Fig. 15. Signatures obtained during day 1 and da 2 to assess uncertainty

V. CONCLUSIONS AND RECOMMENDATIONS

This paper has described a new method to measure underwater radiated noise of ships that tries to fill the existing gaps of the current methods. As a result of this study we can extract the following conclusions:

- This new method puts special emphasis on the repeatability and accuracy of the measurement. Following this philosophy, this study gives supported figures of its uncertainty and repeatability.
- This measurement procedure has been developed for shallow (from 60m) and deep waters applicable all over the world.
- Transmission loss remains as one of the most important sources of uncertainties. The new measurement requirements and post-processing are defined so this uncertainty can be reduced. In any case, in order to obtain more accurate transmission loss estimates, data of some environmental parameters, like the properties of the sea bottom and of the water column should be measure with more accuracy and made available.
- The different measurements for the validation of the procedure reveal that the repeatability achieved by the new post-processing defined is higher than what is obtained applying other existing methods.
- Therefore, and in the view of the results, this measurement procedure can be applied by technicians to assess the underwater noise signature of the vessels. Both, the uncertainty and repeatability of the measurement are provided and supported by experimental data obtained in the framework of AQUO project.

REFERENCES

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