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UNDERWATER NOISE LIMITS AND MEASUREMENT OF UNDERWATER RADIATED NOISE FROM MERCHANT VESSELS

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Underwater acoustic noise radiated by civilian vessels is becoming of increasing importance because of its possible impact on marine fauna. For example, the URN lists three fundamental consequences: masking (interfering with communication, navigation, hunting, etc.), behavioral changes and physiological impacts (temporary or, in extremis, permanent injury). While for military purposes well-established procedures and dedicated acoustic ranges are used in measuring the underwater radiated noise of naval vessels, for civilian ships standardization institutes and classification societies have only in recent years published measurement procedures, while, in parallel, some entities are still trying to define noise criteria to assess impacts.
In this paper the authors outline the evolution of the international regulation framework, with reference to the first class notations issued from the Registers and to summarize the outcomes of recent EU funded research projects that investigated this topic and provide suitable guidelines. The European Union has included the impact of anthropogenic underwater noise on marine life into the Marine Strategy Framework Directive (MSFD). Also, existing standards for both measurement and data analysis of underwater noise from merchant ships are presented and compared, and the issues encountered in their application are discussed. Examples of such issues managed by Fincantieri group during measurements at sea on different ships using systems compliant with international standards are reported.
Keywords: Underwater noise, measurements, limits

1. Introduction

Anthropogenic noise in the marine environment has the potential to impact marine life across many trophic levels (e.g. Solan et al., 2016, Rolland et al. 2012). Some noise sources are a consequence of time limited, spatially localised, processes, e.g. pile driving and seismic surveys. The responsibility for mitigating potential impacts that arise from such activities can be assigned to specific operators. This provides a clear route by which governing bodies can, to a limited extent at least, control such activities within their jurisdiction. By contrast noise from shipping is a chronic noise source, i.e. it is a persistent source extending over large geographical areas and arises from a large number of individual vessels. Its pervasive nature complicates both efforts to control it as a source of noise (since effective action requires international agreement) and severely hampers field studies into its impact on marine life. In spite of this reduction of vessel emissions into the marine environment, including energy like the sound radiated underwater, has received growing attention in recent years. Surface vessels radiate underwater noise mainly due to propeller cavitation; on-board machinery and the flow of water around the ship's hull and appendages also contribute to the overall radiated noise (Urick, 1975; De Jong, 2009).

To date, the measurement of radiated noise from ships has been carried out mainly at fixed noise ranges. Only recently, a quite large set of different mobile deployable systems to measure shipping noise have been used in the civilian ambit. Even if these measurements have provided a valuable contribution to the understanding of the phenomena, the lack of a standardized methodology in terms of measurement procedure and data analyses has hindered accurate comparisons between datasets of different origin. Moreover, non-standardized data from far field measurements of underwater radiated noise of ships have resulted uncertainties in the data which forms the basis of numerical models that generate sound maps of specific sea areas.

The publication of standards by international bodies is an important step towards rectifying the above issues. On the other hand, some difficulties in undertaking the measurements according to the highest precision standards in the real world have emerged, and are discussed in this paper.

Section 2 discusses some of the initiatives and activities which are aimed at controlling ship noise. In Section 3 an overview of the relevant standards for measurement of ship noise is presented. Section 4 illustrates some of the most commonly adopted measurements systems. Section 5 reports some example of the actual use of such systems during measurements carried out by Fincantieri and CETENA. In Section 6 issues and limitations from the field application of standardized systems are discussed. Conclusions are resumed in Section 7.

2. International activities on shipping noise

At present, there are no regulatory requirements on the underwater noise from individual vessels. The absence of standards for measuring ship noise is one reason for this, progress in this area is detailed subsequent sections of this paper. Probably the greater hindrance is the problem of obtaining international agreement on the very great practical problems implementation of any such conditions would raise. It is unsurprising then that at present agreements have been either voluntary or not legally binding. The following details two of the most important initiatives in this area.

The European Union, under the auspices of the Marine Strategy Framework Directive (MSDF) has developed metrics for assessing Good Environmental Status (GES) in terms of underwater noise. One element of these metrics is based on measuring noise in 1/3rd octave bands centred on two frequencies (63 Hz and 125 Hz) (Dekeling et al. 2014). The goals these metrics aim to assess is simply whether progress is being made towards GES: they are not a direct mechanism by which specific criteria are imposed.

The second major international initiative which was conducted with the explicit objective of reducing ship was conducted by the International Maritime Organisation (IMO). The IMO have established non-mandatory Guidelines intended to provide general advice about reduction of underwater noise were also released by the IMO (MEPC.1/Circ.833), where these guidelines focus on the design of the primary sources of underwater noise and consider types of computational models, common technologies and measures that may be relevant in reducing underwater noise (IMO MEPC.1/Circ.833)

3. Measurement standard methods for civil ships

Underwater radiated noise measurement methods, for the application to civil ships, have been issued by technical committees of different international bodies, especially during the last half a decade. These methods, each of which implies specific precision levels and exhibits strong points and limitations in terms of actual application, cover all the aspects of ship radiated noise trials in full scale, i.e. the measurement system specification, the location requirements for the tests, the prescribed vessel course, the analysis and the reporting of the data. Moreover, all include a rule to assess the noise levels at a reference distance, even if often according to different criteria, in general clearly specified. So, they can be considered as measurement standards for the underwater radiated noise assessment of commercial vessels, which should allow the of comparison of measurements, even when the relating datasets are obtained according by different groups.

Among Classification Societies, to date Det Norske Veritas and Bureau Veritas have published their additional class notations on underwater radiated noise from ships, that is the DNV Silent Class Notation (Det Norske Veritas, 2010) and the BV URN Rule Note NR 614 (Bureau Veritas, 2014) respectively. Furthermore, RINA plans to issue at the beginning of 2017 its Dolphin Notation.

In the ISO (International Organization for Standardization), the Draft International Standard ISO/TC8 DIS 16554.3 (ISO, 2014) and the ISO/TC43 WD 17208-1 (ISO, 2013) are soon to be released, while an ISO Publicly Available Specification (PAS) is available (ISO, 2012), which is based on the popular ANSI/ASA (American National Standards Institute/Acoustical Society of America) S12.64-2009/Part 1 (ANSI/ASA, 2009).

Of course, the additional class notation documents, in addition to methodologies, also include radiated noise limits against which vessels must be compliant in relation to the proposed methods and the different operational conditions of the ship. Noise limits were also included into the ICES Cooperative Research Report No.209 (ICES, 1995), which addresses (fishing) research vessels. Noise limits, when reported in the standards, are expressed in terms of spectra, in the frequency range specified within each standard.

Procedure and systems described in the most of the standards above are summarized in section 4.

4. Measurement systems and procedures

The ANSI/ASA method, on which subsequent documents are largely based, is outlined here. Three measurement Grades with related requirements and geometry conditions are specified. Grades A and B both require the use of a three hydrophone sparse array with variable geometry, depending on the length of the ship to be measured. Grade A (Precision Method) prescribes noise analysis in the widest bandwidth (10 to 50,000 Hz), while Grade B (Engineering Method), requires the same hydrophone array geometry as Grade A, but limits noise analyses to the frequency band 20 to 25,000 Hz. For Grades A and B, the hydrophones have to be positioned vertically in the water column at depths (d_1, d_2, d_3) which result from nominal $\theta_1=15^o$, $\theta_2=30^o$, $\theta_3=45^o$ angles from the sea surface, at a distance equal to the so-called Closest Point of Approach (CPA, see figure 1 - left). The nominal distance at the CPA (d_{CPA}) must be one ship length or 100 m, whichever is greater. Simultaneous sampling of data from all hydrophones is required. The distance measurement of the horizontal separation between acoustic centre of the vessel under test (‘target vessel’) and the position on the sea surface above the hydrophones is required continuously throughout the data acquisition for Grade A, and only at the CPA for Grade B (and C). Ship underwater noise is measured when the vessel passes closest to the hydrophones, which are assumed to remain stationary. The distance between ship and hydrophones changes throughout the measurement period, and this may be accompanied by changes in the sound propagation conditions, affecting the propagation loss.

For Grade C (Survey Method) the analysis frequency range is 50 to 10,000 Hz, and just one hydrophone is positioned at a depth resulting from the $\theta=20^o$ angle from the sea surface at the CPA, with a tolerance of ±5°. The nominal distance at the CPA shall be one ship length or 75 m, whichever is greater.

In the ANSI/ASA measurement procedure, the target vessel transits a straight line course at constant speed with the array at the side, both in port aspect and starboard aspect between the COMEX (starting point) and the FINEX (ending point) to achieve the Closest Point of Approach (CPA), for an assigned number of runs. In figure 1 (right) the sketch of the test course according to ANSI/ASA is reported. The DWL (Data Window Length) is the distance on the track defined by a $\pm30^o$ angle before and after the CPA, and represents the distance between the start data (acquisition) location and the end data location. The distance between the CPA point and the COMEX and the FINEX points respectively must be twice the DWL.

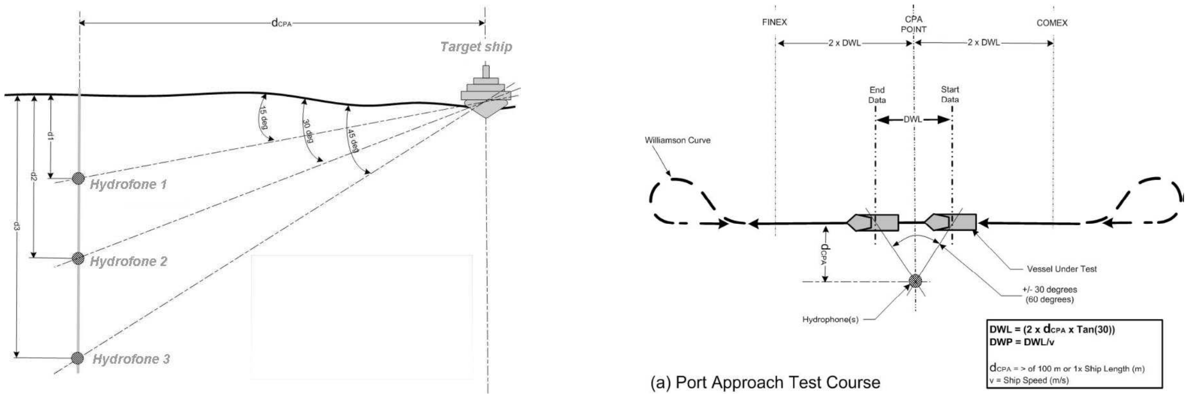

Figure 1. Left: hydrophone geometry – Right: course configuration, Gr. A-B (both according to ANSI/ASA).

As described in Section 3, ISO PAS is largely based on the ANSI/ASA method. ISO/TC43 WD 17208-1, it removes the Grades approach, but still presents a three hydrophone methodology close to that of the ANSI/ASA. The BV URN Rule Note can be assimilated into the previous standards in terms of requirements and procedure.

ISO/TC8 DIS 16554.3 and DNV Silent lay down the use of a single hydrophone, similar to the ANSI/ASA Grade C.

As far as water depth at the test location is concerned, ANSI/ASA and all the ISO standards discussed here imply deep water applications. The BV URN Rule Note includes prescriptions both for deep and shallow waters, whereas the DNV Silent is applicable to depth below the keel from d=30 m up, or $d \geq 0.64\ v^2$ for vessel operating at high speed, where v is the maximum ship speed in m/s required for the test and d is the depth in meters.

Regarding the deployment of the hydrophone(s) at sea, standard methods can be grouped into two main categories: bottom mounted/anchored systems and floating lines deployed from a support vessel or suspended to a floating buoy. In general, the former configuration is adopted in shallow water trials, but such a possibility is also included as one of the options in the ANSI/ASA.

5. Use of measurement systems

The interest for environmental implications of underwater noise grew at the beginning of the century, and rapidly the need of effective measurement systems suitable for civilian application emerged.

According to this trend, a first system was jointly developed, implemented and first applied by Fincantieri and CETENA (Pescetto et al., 2006). An effort was made to align layout and procedures of a cost effective system with the emerging measurement standards. In particular, the system was composed of two separate units: an in-water unit (a cylindrical ‘buoy’ of 1,900 mm height 220 mm diameter) and a receiving station on the target ship. A single omni-directional hydrophone was suspended to the underwater cable which could be arranged for measurements at depths of 30 / 50 / 80 or 100 m. The surface buoy was provided with an audio board that digitalized the acoustic data recorded from the hydrophone with a sampling frequency of 44,100 Hz and 16 bit quantization. The adopted course configuration was similar to that shown in figure 1.

In figure 2 (left) the emerging part of the buoy-based system is visible during its first application on a 290 m length and 110,000 tonne cruise ship. After that first trial, several other ships have been tested through the same system. In figure 2 (right) some measured third octave band radiated noise levels are reported for three different ships at 10 knots.

During the first period of application of the single hydrophone system, it became clear that a more sophisticated method would be necessary to fulfil the emerging standards. So, a second measurement system, fulfilling the ANSI/ASA approach and the other similar methods, has been developed (Figoli et al., 2013; Gaggero et al., 2014), based on a vertical array of three digital hydrophones. The layout of the system is visible in figure 3 (left). The array has variable total length and variable spacing between hydrophones, to conduct measurements on ships of different size, according to standard requirements. Each hydrophone includes a depth sensor and an electronic calibrator. Depth data are included in the digital acoustic data flow for providing real-time monitoring of hydrophone's depth. The hydrophones are hosted by a single underwater cable of 335 m of length. The data are addressed to a multi-channel data receiver able to obtain a continuous flow of digital data at very high rate simultaneously from all the hydrophones. The receiver allows the user to set the array parameters, in particular the sampling frequency (96 or 192 kHz). In September 2013, the system was firstly deployed (Dambra et al., 2015) to measure the underwater radiated noise of a research vessel (the Princess Royal) managed by the University of Newcastle, as part of the EU 'SONIC' (Suppression of Underwater Noise Induced by Cavitation) project (http://www.sonic-project.eu/). After the SONIC trials, the system has successfully been applied in subsequent measurements on Fincantieri vessels. A typical narrow band spectrum of underwater noise from the three hydrophones of the system is shown in figure 3 (right).

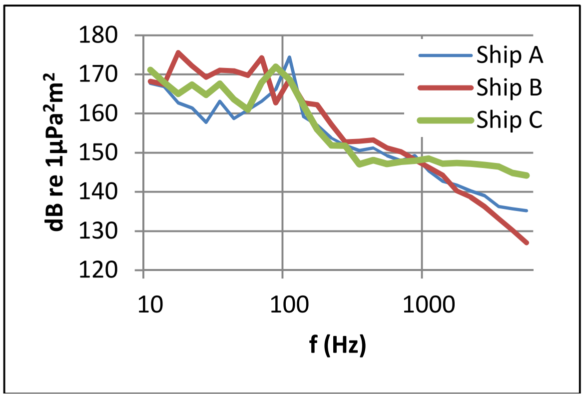

Figure 2. *Left* : application of the single hydrophone system – *Right* : third octave band noise levels.

6. Field application issues and limitations

After the recent releases of standard methods, researchers have undertaken measurements at sea of the noise radiated underwater from commercial ships, trying to fully comply with the requirements of the methods described in Section 3. However, many of these researchers have found problems fulfilling some of the specific requirements. Most of the critical issues are in relation to the special needs of commercial ships. In particular, contrary to military vessels, a long decommissioning of commercial vessel is generally not acceptable to the owners. This implies that, in general, measurements can only be carried out close to the dockyards or the commercial routes of existing ships, and within a short time window, through portable systems deployed and recovered in the space of one day. As a consequence, requirements on water depth, ambient noise, weather and sea conditions etc. often result real challenges, as discussed below.

In table 1 the principal quantities that can impact on the actual feasibility of the measurement are reported, with reference to the different standards. Some practical implications of the contents of table 1 are discussed in the following.

1) The recommended number of hydrophones is one or three, depending on the adopted standard. The advantage of using three hydrophones mainly consists in mitigating, through the averaging of the data across the three transducers, the Lloyd's mirror effect due to the reflections from the free surface (De Jong 2009, Ainslie, 2010). Examples of Radiated Noise Levels spectra from three hydrophone arrays got in sea trials are reported in figure 3. Radiated Noise Levels are the range corrected noise data, i.e. values referred to the reference distance of 1 m and not corrected for the presence of the sea surface (also known as affected source levels).

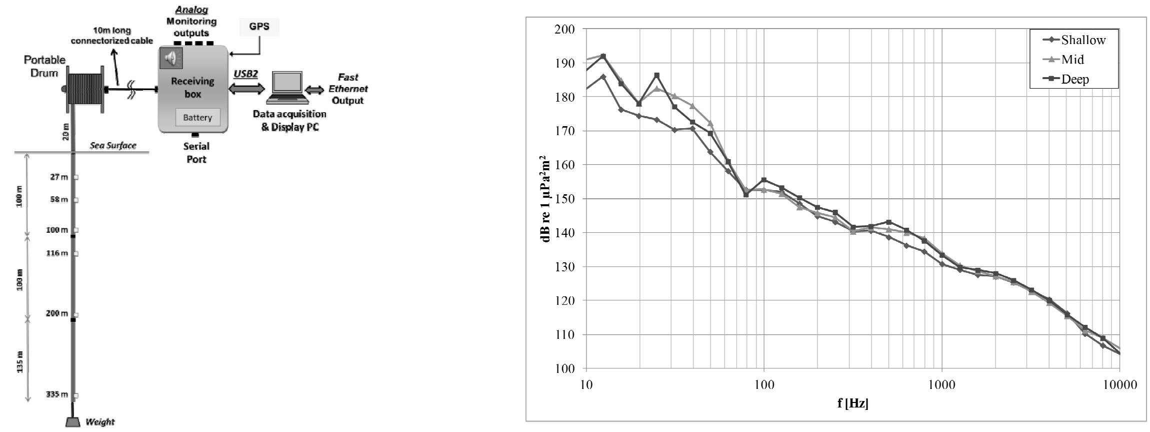

Figure 3. *Left* : variable length/spacing array – *Right* : Radiated Noise Levels from 3 hydrophones at different depths.

2) The use of a single hydrophone results in lighter systems when floating devices are adopted (especially when very long cables are necessary), and easier installations if bottom mounted solutions are chosen. As mentioned above, easier and faster solutions are often crucial requests when commercial applications are involved, so the use of a single hydrophone is provided by some standards, even if the comparability of the measurement can be lower in comparison with the adoption of a three hydrophone configuration, mainly due to the presence of the Lloyd’s mirror interference pattern.

3) As can be seen in table 1, only Classification Societies have standards which provide measurements in shallow waters. ANSI/ASA (Grade A) recommends minimum water depths of -300 m, down to around 900 m for example for large cruise ships, with the scope of avoiding any significant influences of the bottom on the measurements. This depth condition, as well as other lower values included in table 1, can be hardly matched for target ships built or operating within shallow water areas which extend for more than one day sailing. However, shallow water parts of some existing deep water standards are under development, which include recommendations for a proper acoustic characterization of the specific measurement site; their future release should be able to overcome the current issues.

4) The chance of waiting for the most favourable weather/sea conditions is a peculiarity of naval vessels. As highlighted above, as a matter of fact this opportunity is highly reduced when a commercial vessel has to be decommissioned to this scope or when a new ship has to carry out noise tests during the trials at sea prior to its delivery. This implies that often the weather condition limits are ‘stressed’ to be able to complete the test in time. The main effects on data can be an ambient noise increase at all frequencies (see further considerations below), and high levels of unwanted signal at low frequencies for the motion of the support vessel due to the sea surface conditions (this effect can be limited but not cancelled completely through proper provisions like an elastic tether between the support boat and the array, as well as through array sub-surface suspension devices).

5) Commercial ships have limited possibilities to reach the remote sea areas where very low ambient noise is in general found, if they do not already operate there – so we could state that the high noise levels that the measurement campaigns intend to partly mitigate are at the origin of the troubles of the measurements themselves. Even the possibility of simply reaching less noisy blue water areas is often limited by the target ship’s availability and/or by the capability of the support boat used to deploy the portable systems to stay at sea for more than a single day. This implies that broad adjustments for background noise are very common, mainly in the low frequency range, especially for measurements performed in coastal waters; sometimes entire datasets have to be disregarded due to the poor S/N ratio (see the limits in table 1). The alternative would consist in carrying out measurements at shorter CPA distances, to enhance the sound signal from the target ship, but at the

cost of weakening the prescription of most of the standards on the CPA distance (e.g. 100 m or one ship length whichever is greater).

6) As already mentioned, two different approaches are provided by the standards for the hydrophone configurations, i.e. bottom mounted/anchored systems and suspended systems. Bottom mounted solutions can be effectively implemented in fixed acoustic ranges. In this case the target ship is forced to go to a specific location to undertake the trials, but with the difficulty that installations close to all shipyards and commercial routes (to save decommissioning time) are not available. Mobile systems are more flexible as they can be moved to the measurement areas, but in practice bottom mounted hydrophones and anchored deployments can be adopted just in shallow waters, due to the troubles in arranging in deep waters the anchorages in short times and at reasonable costs. On the other hand, it's well known that as systems suspended to floating bodies exhibit limitations in the low frequency range due to the sea surface conditions affecting the noise levels (see above).

7) Another significant issue is the drift of the hydrophone array at sea, when systems deployed from the sea surface are used. The evidence from several trials at sea is that controlling the movement of the hydrophone cable within the limit angle of for example 5° is highly challenging in presence of strong currents. Even when each hydrophone is equipped with a depth sensor (see Section 4), this enables you to know if the above limit has been exceeded. The possibility of taking the drift angle into account to determine the actual slant range is precluded by the lack of information on the hydrophone positions in the horizontal plane; so the outcome is that it is not possible to include those measurements into a valid dataset.

Table 1. Main quantities included in the standards impacting practical aspects of the measurements.

	units	ANSI/ASA	ISO DIS/16554.3	ISO WD/17208-1	DNV	BV
N° of hydrophones	-	$3^{(1)} - 1^{(2)}$	1	3	1	3
Minimum water depth	[m]	300 or $3xL_{ship}$ 150 or $1.5xL_{ship}$ 75 or $1xL_{ship}$	$1.5xd_{CPA}$	150 or $1.5xL_{ship}$	30 or $> 0.64\ v^2$	$60^{(5)}$ or $0.3\ x\ v^2$ $200^{(6)}$ or $2\ x\ L_{ship}$
Sea/weather conditions	-	wind speed < 10.28 m/s	SS<3	wind speed < 10.28 m/s	Beaufort<4 SS<3	$SS<3^{(5)}$ $SS<2^{(6)}$
Min (S+N)/N ratio$^{(3)}$	[dB]	3	3	3	3	3
Type of deployment$^{(4)}$	-	SVD – BA – OBD	SVD – BA – OBD	SVD – BA – OBD	BM	$BA^{(5)} - OBD^{(6)}$
Maximum cable drift	[°]	5	not defined	5	not applicable	adequate to fulfil distance accuracy (±10 m)

(1) Grade A & B
(2) Grade C
(3) For which adjustments are no longer allowed – lower values to be so noted or discarded
(4) SVD = Support Vessel Deployed ; BA = Bottom Anchored ; OBD = Observation Buoy Deployed , BM = Bottom Mounted
(5) For shallow water trials
(6) For deep waters trials

7. Conclusions

The methodologies described in recent standards for the underwater radiated noise from ships in trial conditions can actually lead to a quite detailed assessment of the noise features of the vessel. Trials of this kind can also be useful to validate numerical techniques for noise prediction at the design stage, and to correlate model scale results and full scale results. At the same time, the outcome of experimental campaigns carried out on commercial vessels to date have highlighted some practical issues, discussed in this paper and linked to the exact application of standard methodologies in the real world. These issues often impose departures from the requirements of most of the current standards mainly in relation to the reduced decommissioning time of commercial vessels or to the short time available for trials of new buildings.

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