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ON SITE PROPAGATION LOSS MEASUREMENTS THROUGH NON-IMPULSIVE SIGNAL DECONVOLUTION

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The recent concern about the impact of underwater noise emitted by ships, pushed national and international bodies to face the problem of setting limits to ship noise emission. In order to set new limits, a deep knowledge of the three elements of the noise chain (i.e. source, transmission path and receiver) is needed. In this context it is therefore important to measure the acoustic signature of a ship, in order to characterize it as noise source. To this aim, dedicated measurements may be carried out during sea trials, which usually takes place in an area close to the building shipyard. The measurement layout foresees a series of hydrophones deployed in the water column placed at a distance of a hundred metres from the ship that passes abeam the hydrophones on a straight course. Such far field measurements are to be referred to the reference distance of 1 metre in order to ensure results comparability. Sound propagation from the ship to the hydrophones is therefore to be carefully taken into account also considering the fact that measurements are carried out in a continuously changing environment. In the present paper, an experimental technique to characterise the environment frequency response function is presented together with results of its onsite application.

Keywords: propagation loss; ship underwater noise; signal processing

1. Introduction

The problem of assessing the impact of ship traffic on the marine fauna has recently become a hot topic in the shipping field. Both ship builders, ship owners, ship operators, Classification Societies and the scientific community are discussing about this issue from different viewpoints (see e.g. [1], [2]). A common denominator is represented by the need of having an experimental procedure to characterise the underwater acoustic emission of ships in full scale. In the light of this, the main European Classification Societies issuing their Class notations to certify the low underwater noise emissions of the vessels included a measurement procedure. Moreover the Acoustical Society of America [3] in 2009 issued a standard for the measurements of underwater sound form ships in deep water and within ISO (International Standardisation Organisation) the committee ISO/TC 43/SC 3 is working on the matter and produced two standards on the matter [4],[5]. The above mentioned standards are aimed at giving procedures for comparison purposes. Due to this, the propagation losses of noise are taken into account using the standard spherical law even if ships are typically tested in different geographical areas, seasons and daytime and therefore in areas where noise propagates differently. If on the contrary measurements are aimed at a real characterisation of the noise emitted by the ship for modelling purposes or to assess the impact on the marine fauna, noise propagation has to be carefully taken into account. Propagation losses can be therefore estimated either by using ad-hoc mathematical models or by on site measures. In the present paper an easy technique to measure propagation losses at the site where the ship is measured is presented. The technique foresees the use, of a relatively cheap noise emitter in addition to the normal instrumentation needed for the underwater noise signature test.

2. Instrumentation

2.1 Emitting equipment

The noise generation system consisted of a laptop computer, used to reproduce a "pre-packaged" .WAV file (illustrated below), so as to ensure the absolute reproducibility of the test signal. The output signal was then amplified by an 80W/channel stereo amplifier (Impact LK 602). The left output channel of the amplifier was sent directly to the Clark Synthesis AQ339 underwater loudspeaker, while the right channel was coupled to the ITC 1001 transducer via a 1:10 transformer to adapt its impedance. The following figure shows the block diagram of the transmitter unit described above. The use of a 2-way system allows to cover a wide range of frequencies emitted (20-48000 Hz), specifically the low frequencies (from 20 Hz to 10 kHz) were reproduced by the Clark loudspeaker, while the high frequencies (from 10 kHz to 48 kHz) by the ITC source (see scheme in Figure 1).

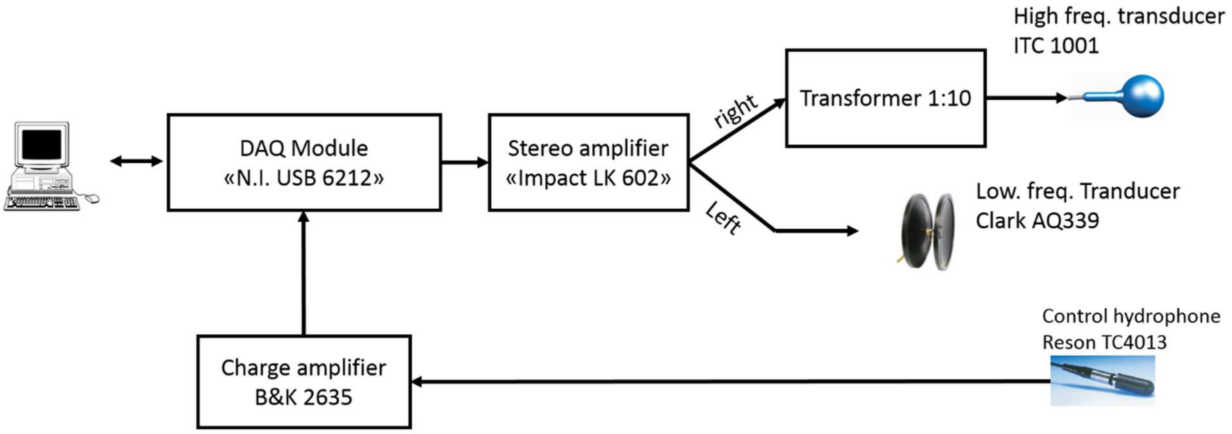

Figure 1: Scheme of the signal emitting equipment.

In such a way a sort of natural cross-over between the two channels is created, exploiting the two underwater transducers in their optimal frequency ranges. The signal levels used were such that the transducers could function correctly without distorting them.

The signal used for the measurements is an exponential sine sweep going from 20 Hz to 48 kHz with a duration of 30s. More details about the advantages of the adoption of this kind of signal are given in section 3.

2.2 Receiving equipment

The underwater radiated noise measurement is carried out through a vertical array, consisting of:

- up to 3 digital broadband hydrophones;

- an underwater cable, which can be divided into 2 sections and equipped with 3 fixed connection points for hydrophones in order to easily configure the array geometry before deployment;
- 2 antennas placed on the support vessel and on the target vessel respectively in order to exchange the data;
- a multi-channel data receiver.

Each hydrophone includes an electronic calibrator and a depth sensor, in order to monitor the actual position of the hydrophones during measurements.

One GPS antenna is installed on the surface buoy (used to decouple the cable from the motions of the sea and the supply vessel) and connected to the multi-channel data receiver, in order to exactly know the position of the array during the test.

A second GPS antenna is installed on the target vessel, in order to calculate the simultaneous distance between the target vessel and the hydrophones during the test.

In Figure 2 the cable with the hydrophones, the surface buoy and the GPS antenna are positioned on the supply vessel.

Figure 2: receiving equipment picture.

The array is lowered and recovered by a support vessel; all machineries on-board the supply boat remain switched off during the trials. All the instruments of the measurement set-up on-board the supply boat are battery powered, in order to avoid any acoustic self noise from the supply vessel.
The hydrophones are omni-directional sensors, with the characteristics reported in Table 1.

Table 1: Receiving system data.

Parameters	Values
Receiving Sensitivity (dB re 1V/µPa at 10 kHz)	-200 (± 1 dB)
Linear Frequency Range	5 Hz – 90 kHz
Directivity - Horizontal Plane	Omni (± 1.5 dB) @ 10 kHz
Directivity - Vertical Plane	240° (± 2 dB) @ 10 kHz

3. Technique description

In order to characterise the propagation losses at the test site a non-impulsive signal deconvolution technique has been adopted. This technique, described in details in [6], allows to calculate in a simple and fast way the impulse response (or the transfer function) of weakly non-linear systems and approximately time-invariant, as shown for example in [7] applied to the measurement of the transfer function of a cavitation tunnel.

To understand how it works, let's consider a system ("black box") with a single input and a single output (shown in the following figure), in which by introducing a signal x(t) you get a signal y(t) at the output. For simplicity, we assume that the system is linear and time-invariant. Within the system itself, noise n(t) can also be generated and added to the output signal. Typically this noise is assumed as a Gaussian white process completely unrelated to the input signal.

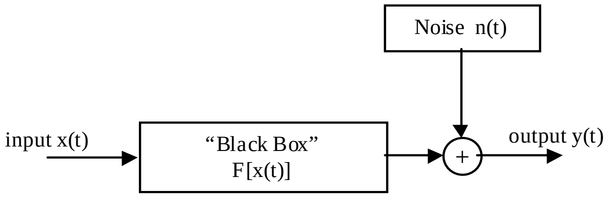

Figure 3: System block diagram.

The output signal can be written as the sum of noise and a deterministic function of the input signal:

$$y(t) = n(t) + F[x(t)]. \quad (1)$$

If, as assumed, the system is linear and time-invariant, the function F of the previous formula can be written as the convolution between the input signal and the impulsive response of the system h(t), that is:

$$y(t) = n(t) + x(t) \otimes h(t). \quad (2)$$

To calculate the unknown transfer function, typically what you do is to measure the output response from the system y(t) when a known x(t) signal has been applied to the input.

In particular, with the sine sweep technique, a pure tone (sinusoid) is used as an excitation signal, whose frequency increases over time:

$$x(t) = \sin(f(t)). \quad (3)$$

Such a signal is commonly called sweep, and according to the law governing the frequency variation we may have Linear Sine Sweep or Exponential Sine Sweep. In this work the Exponential Sine Sweep has been used, here the frequency increases exponentially with time, therefore very slowly at low frequencies, and then more and more rapidly at high frequencies.

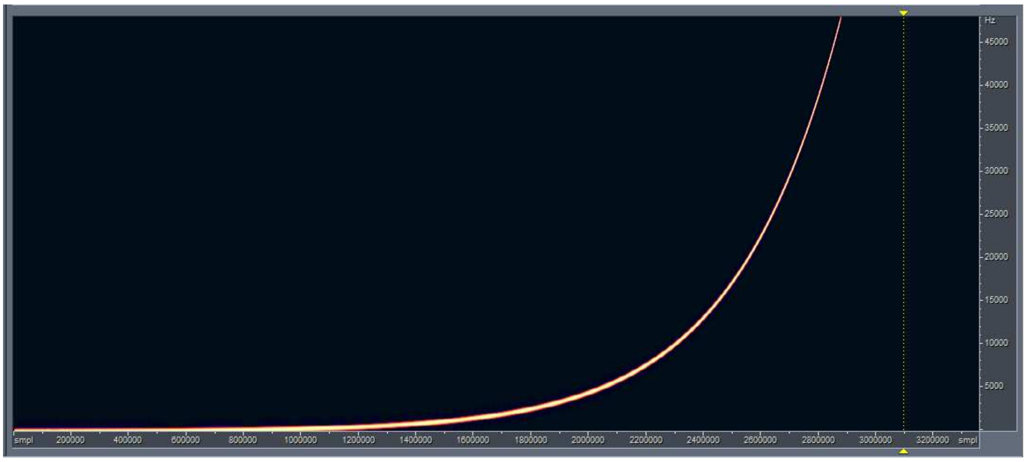

Figure 4: Spectrogram of the exponential sine sweep.

Using the sine sweep technique, it is possible to increase the signal-to-noise ratio (SNR), simply by averaging over time several recordings of the output y(t), suitably synchronized. From now on we will indicate with $\hat{y}(t)$ the average time of these recordings.

This concept is very important because it allows, averaging over a large number of recordings, to consider $\hat{y}(t)$ as the system response in the absence of noise n(t). Mathematically, what has been said can be expressed as follows:

$$\hat{y}(t) = x(t) \otimes h(t). \quad (4)$$

At this point, through a process of linear deconvolution over time, it is possible to calculate the impulse response (IR) of the system under examination. Deconvolution actually consists in convolution with a suitable inverse filter f(t), designed in such a way that it, carried out with the input signal x(t), gives rise to a Dirac Delta δ(t):

$$f(t) \otimes x(t) = \delta(t). \quad (5)$$

By applying this inverse filter to the $\hat{y}(t)$ system response, you can obtain the impulse response you are looking for:

$$h(t) = f(t) \otimes \hat{y}(t). \quad (6)$$

When the excitation signal is a sweep, its reverse filter is simply the sweep itself reversed along the time axis, so the frequency decreases progressively, as shown in Figure 5

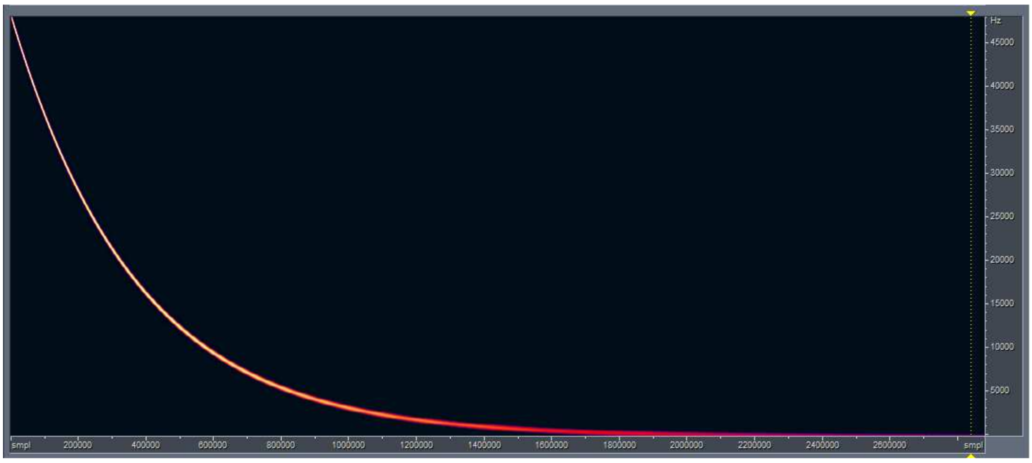

Figure 5: Spectrogram of the inverse filter of the exponential sine sweep.

Note that in the case of the exponential sine sweep inverse filter, amplitude modulation must be added to compensate for the fact that exponential sweep gives more energy at low frequencies.

In this way, by convolving the exponential sweep with its inverse filter, you get a Dirac's delta.

One interesting advantage of this technique is that the convolution with the inverse filter increases the signal to noise ratio of the sweep signal, packing the energy of the sweep in a short impulse response.

The propagation loss measure slightly differ from the above described technique as the real impulse response of the ambient at different distances it is not directly evaluated. Nevertheless, some of the technique advantages are anyway used. The scheme of the studied system is reported in Figure 6.

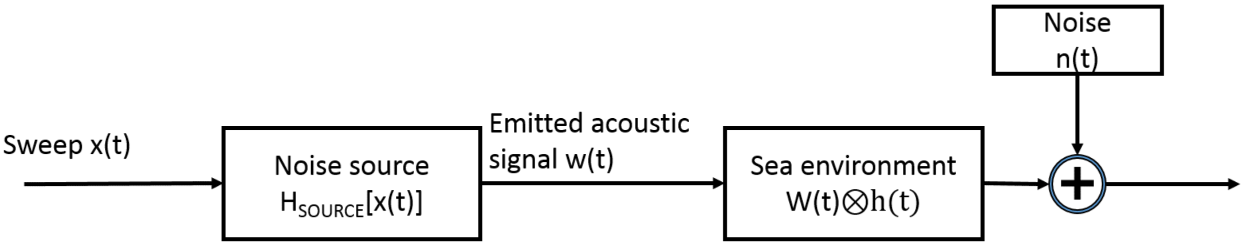

Figure 6: Scheme of the technique chain.

The above described technique allows to deconvolve the impulse response of the entire system that comprises the propagation effects in the surrounding environment and the source response that usually presents a linear part, the so called Transmitting Voltage Response (TVR) and a non-linear response that generates unwanted harmonic distortions. As the technique allows to separate the distortions in principle the response of the marine environment could be directly estimated knowing the

TVR. For the present work the frequency range studied did not allow to have a robust measure of the TVR as the reference distance of 1 meter from the source felt in the nearfield for some frequencies. In the light of this the impulse response measured is the response of the marine environment plus the source effects and to obtain the response of the marine system only a differential approach among the different measures at different distances is used. Practically the IR of the system is measured at a first distance that becomes the reference distance. Successively the same measure is carried out at increasing distances. The difference among the spectra of the responses are due to the propagation losses taking pace in the environment as it is considered that the source effects do not change with time. Finally, the reference measure may be scaled to 1 m deriving from data the most suitable propagation law. In the following the results for some significant third octaves bands are reported.

4. Measurement Results

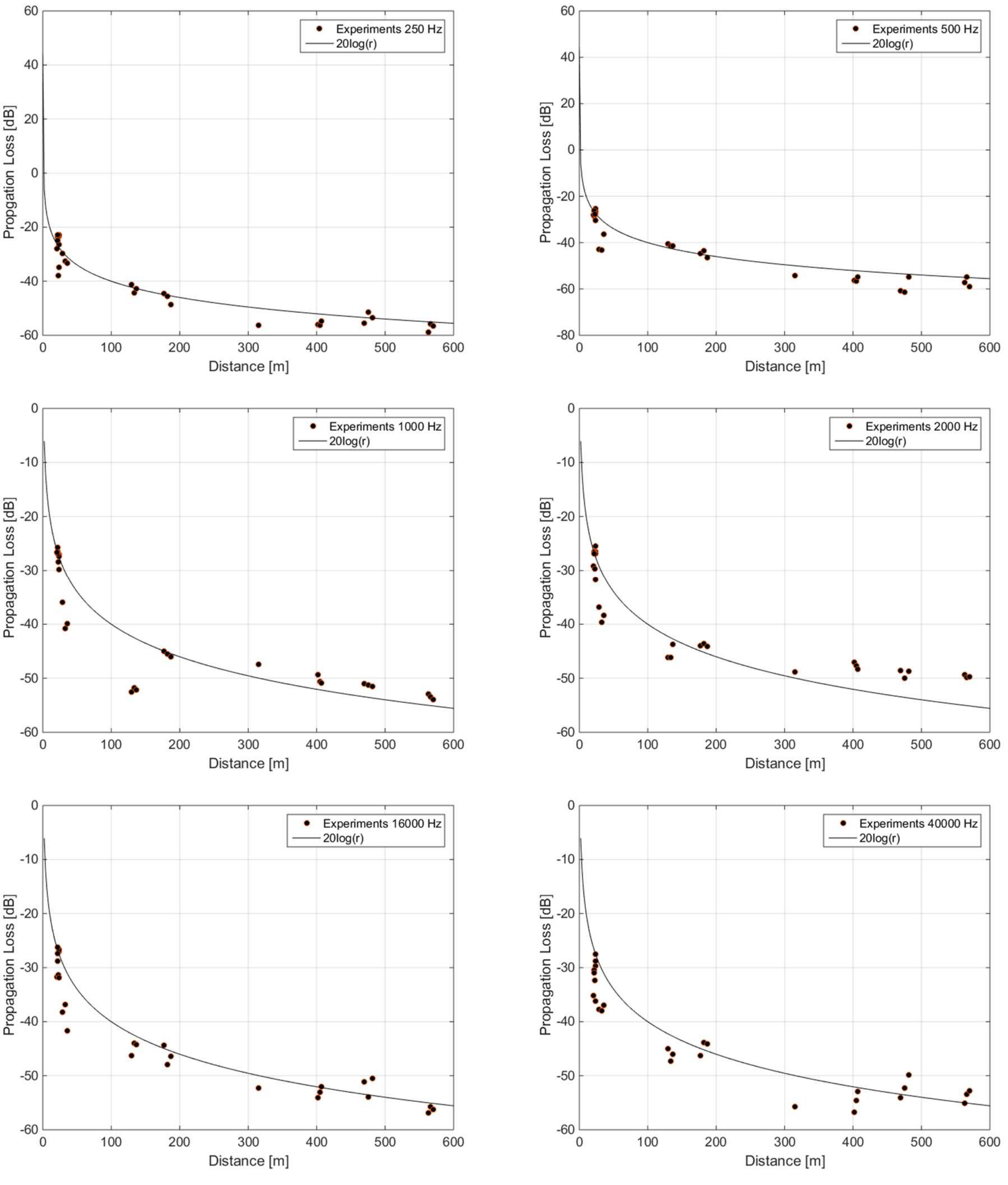

Figure 7: Measured propagation loss vs. spherical spreading law.

In Figure 7 the measured propagation losses are reported for some frequencies together with the spherical propagation law. The measurements have been carried out with the boat from which the hydrophones were deployed anchored while the boat with the source was free to drift and therefore gradually departing. It is assumed that the characteristics of the surrounding environment are constant in the investigated range allowing to consider this approach equivalent to the situation with fixed emitter and moving receiver. At each distance three signals were emitted in rapid sequence as it can be seen for Figure 7 where families of three points are reported. The differences among the three points can give a picture of the uncertainties in the evaluation of propagation losses with the above described technique. In almost all the cases the three points are located within 5 dB. Looking at the reported frequencies it can noticed that for lower frequencies the Llloyd's mirror effect can be seen for distances less then 200 meters where displacements for the spherical law are more consistent. For greater distances, a transition from the zone where the destructive/constructive interference pattern and a logarithmic decay is present. This transition can be seen for 1000 Hz at 200 meters and for 2000 Hz at around 300 meters. As expected for higher frequencies such transition zone is close to the source as almost all the measurements are closer to the spherical curve.

5. Conclusions

In this paper a technique to measure propagation loss at sea has been presented. The adopted setup is characterized by the simultaneous presence of an emitting system and some receivers, whose relative distance is varied during tests. Between the broadband signals suitable for similar applications, the exponential sine sweep has been used. The presented technique basically consists in evaluating the impulse response of the system at varying distances between the source and the receiver in order to derive from data the laws governing propagation loss in the target area. The impulse response of the system is evaluated by the linear deconvolution with a proper inverse filter exploiting the characteristics of the sweep signal. This allows obtaining satisfactory results on a wide frequency range with relatively short signals.

The technique described has been applied during in situ measurements and some example of results have been presented.

Trends observed in the experimental data are in good agreement with underwater noise propagation theories, showing also evidences of the occurrence of Lloyd's mirror effect.

Collected information may be used for the correction of noise levels measured during ships sea trials in order to estimate ships source strength levels. In addition experimental results will be used for validation and fine tuning of mathematical methods used to model noise propagation in the sea at short range.

Further measuring campaigns will be carried out in the future in order to get a deeper insight into the problem and to investigate the effects of different environmental parameters on noise propagation.

REFERENCES

1. Badino, D. Borelli, T. Gaggero, E. Rizzuto, and C. Schenone, Acoustic impact of ships: Noise-related needs, quantification and justification, in Sustainable Maritime Transportation and Exploitation of Sea Resources - *Proceedings of the 14th International Congress of the International Maritime Association of the Mediterranean*, IMAM 2011, vol. 2, pp. 961–969, (2012).
2. C. Audoly et al., Mitigation of underwater radiated noise related to shipping and its impact on marine life: A practical approach developed in the scope of AQUO project, *IEEE Journal of Oceanic Engineering*, vol. **42**, (2), 373–387, (2017).
3. ANSI/ASA. ANSI /ASA S12.64-2009/Part 1. Quantities and Procedures for Description and Measurement of Underwater Sound from Ships - Part 1: General Requirements. Acoustical Society of America, (2009).

4. ISO 17208-1:2016 Underwater acoustics -- Quantities and procedures for description and measurement of underwater sound from ships -- Part 1: Requirements for precision measurements in deep water used for comparison purposes
5. ISO 18405:2017 Underwater acoustics – Terminology
6. Farina, A., Advancements in impulse response measurements by sine sweeps. In: Proceed-ings of the 122nd AES convention, Audio Engineering Society (AES): Vienna, 5-8 May 2007.
7. Tani, G., Viviani, M., Armelloni, E., Nataletti, M., Cavitation tunnel acoustic characterisation and application to model propeller radiated noise measurements at different functioning conditions. *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment* 17. doi:10.1177/1475090214563860, (2015).