

Estimation of Hydro-acoustic Signatures Originated from Ship's Hull Vibration

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Abstract - The origin of shipboard hull vibrations is dominantly determined by vessels propulsion system, main machinery, auxiliary systems, pumps, breaking of the waves at the ship hull, etc. All of these peripherals and systems origin the static and dynamic induction of underwater sound in water environment. As a source of underwater sound, individual vessel has displayed unique characteristics of directivity and diversity of hydro-acoustic spectrum. Many researches had been completed on identification and quantified estimation of the noise or the multiple vibrations resulted from ship and machinery. The paper is focussed on to study the hull transferred vibration of the vessel's structure to sea and are analysed using vibration spectra using onboard measurements of a naval vessel.

Sea trials at following conditions had been carried out.

Sea State : 1-2, 2-3;

Loading Condition : Full Load, Half Load;

Wind Condition : Moderate < 15 knots;

Sea Direction : Ahead, Astern

The measuring of the radiated hydro-acoustic noise was done simultaneously with multi channel measurements of the vessels vibrations at few characteristic positions of the vessel. The hydro-acoustic signals that are transferred through water column is to be analyzed using spectra and higher order spectral analysis bispectra with under water transducers / hydrophones was not performed due to financial constraints and limitations of underwater measuring technology in Sri Lanka. Numerical relationship was established using similar study outcomes performed by Poland Navy.

Key words: hydro-acoustic signal, vibration spectrum, bispectra, Vibration analyser

I. INTRODUCTION

Shipboard vibration phenomena are caused mainly by the following sources of excitation:

- a. the propeller (periodic vibration)
- b. engine and auxiliary machinery (periodic vibration)

c. effects of the sea (random vibration)

The vessels hull will transfer/ emit the damped vibration received at propeller, thrust block, keel or the underwater appendages directly to the water column underneath, as the next immediate medium to damp/ absorb/ neutralise the signature of vibration. The topic hydro-acoustic spectrum of ships has long been an important scope of research in the merchant community worldwide. Especially, the navies of modern day found it vital and its application in various naval combat systems, this assertion is critical. Knowing the parameters of hydro acoustic signals is of particular importance when the goal is detection and identification of the vessel on the basis of its radiated hydro-acoustic noise.

The main aim of a naval vessel is to perform her activities quiet as much as possible. The unique hydro-acoustic spectrum generated of her may not only unveils her presence but might disclose the ships identity if the data could be collected and filtered from a universal data bank. The vibration spectra assessment is to be performed after every major hull refit, machinery maintenance work, modification, or installation of new equipment in order to reveal any changes of acoustic signature of the vessel. The acoustic signatures of the new vessels are measured to confirm that the radiated noise is within the limits stipulated by the project specifications, and to ensure they are in accordance with safety and habitability regulations.

II. METHODOLOGY

Vibrations of the vessel are analyzed using Fast Fourier Transform (FFT) algorithm in two frequency bands, the first from 0 to 100 Hz, and the second from 0 to 1 kHz. Taking into account the overall linear dimensions of the vessel, low frequency range of the vibrations is of particular interest, and therefore the limits of the above frequency bands are defined. Particular interest is in the low frequency band, which is defined from zero to 100 Hz. Vibrations - acceleration were measured during the movement of the vessel in the measuring points defined.

A. Vibration Analyser and Software

The trial team used 02 Nos vibration data analysers (Frequency Range: 0 – 40,000 Hz) integrated with supported software system. The averaging used is 5 times and FFT uses Hanning window method for data filtering. One analyser is having two channels and the sampling frequency for each channel is 102.4 kHz.

B. Measurement Conditions

Measurement data is obtained, during performance sea trials of the ship. The data was recorded using at following uniform and favourable measurement conditions:

- a. Free-route test on a straight course: The ship sailed on a straight course with minimum rudder deflection. (i.e. +/- 2 degrees Port to Stbd rudder angle)
- b. Constant representative engine output; Generally the power output on the propeller shaft(s) shall correspond to contractual normal seagoing condition, or at least 85% of maximum continuous power available on the propeller shaft(s). All other machinery was run under normal operating conditions during the tests.
- c. Sea state 3 or less
- d. Full immersion of the propeller
- e. Water depth not less than five times the draught of the ship

C. Measurement Procedure (As per ISO 6954: 2000)

- a. Measurements were recorded in all three directions at a minimum of two locations on each deck. At other locations, measurements are only required in the vertical direction.
- b. The combined frequency weighting curve according to ISO 2631-2 was applied to all measurements irrespective of their direction.
- c. The frequency range evaluated was 1 Hz to 10000 Hz. (Analysed separately in low, medium and high frequency ranges)
- d. The measurement duration was above 1 min. for all machinery locations. For hull locations measurement duration of at least 2 min is required.
- e. The result of each measurement shall be the overall frequency-weighted r.m.s. value.

A similar procedure is applicable for the frequency weighting of velocity spectra. The highest value in any direction could be used for the evaluation of habitability in another study.

D. International Standards Followed

Following international standards have been adhered during the data recording and conduct of sea trials.

- a. ISO 10816-1, "Mechanical vibration-Evaluation of machine vibration by measurements on non-rotating parts, Part 1: General guidelines".
- b. ISO 6954: 2000, "Guidelines for the measurement, Reporting and Evaluation of Vibration with regard to Habitability on Passenger and Merchant Ships"
- c. ISO 20283-2: 2008, "Mechanical vibration-Measurement of Vibration on Ships, Part 2: Measurement of Structural Vibration"

Following rules and classifications published by Det Nordske Veritas (DNV) in "Rules for Classification of Ships" July 2004 (Revised in July 2009) also considered during the data recording and conduct of sea trials.

- a. Part 6 Chapter 11 – Hull Monitoring Systems
- b. Part 6 Chapter 15 – Vibration Class

D. Locations for Data Recording

Table 1. Locations on board Ship

Sr No	Location	Direction
Machinery Locations		
1	Gear Box Free End (G/B F/E)	Vertical Horizontal Axial
2	Gear Box Drive End (G/B D/E)	Vertical Horizontal Axial
3	Main Engine Free End (M/E F/E)	Vertical Horizontal Axial
4	Main Engine Drive End (M/E D/E)	Vertical Horizontal Axial
5	Stern Gland	Vertical Horizontal Axial
6	Plummer Block	Vertical Horizontal Axial
Hull Locations		
7	Rudder Top	Longitudinal Transverse
8	A Bracket (Aft)	Vertical Longitudinal Transverse
9	A Bracket (Fwd)	Vertical Longitudinal Transverse
10	Stern Tube	Vertical Longitudinal Transverse
11	Stern Tube	Vertical Longitudinal Transverse
12	Quarter Deck	Vertical Longitudinal Transverse
13	Middle Deck	Vertical Longitudinal Transverse
14	Mast	Vertical Longitudinal Transverse

E. Loading Condition of the Ship

Table 2. Loading Condition

Sr No	Description	Half Load	Full Load
1	Fuel (Low Sulphur Diesel)	150000 ltrs	360000 ltrs
2	Lubrication Oil	2800 ltrs	5000 ltrs
3	Fresh Water	72000 ltrs	150000 ltrs
4	Crew	100	120

F. Ships Particulars

Length overall	-	102 m
Length between perpendiculars	-	96.00 m
Breadth, moulded (max)	-	11.5 m
Depth to main deck at mid ship	-	6.00 m
Draught (mean) at Max	-	4.5 m
Half load	-	3.3 m
Min	-	3.1 m
Displacement at full load	-	1928 Ton
Trial displacement (half load)	-	1700 Ton
Max. Speed at 100% engine	-	20 kn (knots)
Class	-	Offshore Patrol Vessel

III. CONDUCT OF SEA TRIALS AND SALIENT RESULTS

The trial team mainly focused on recording data at a fixed engine RPM and analysing the spectrums resulted from earmarked machinery and hull locations.

A. Machinery Vibration Spectra at 600 rpm

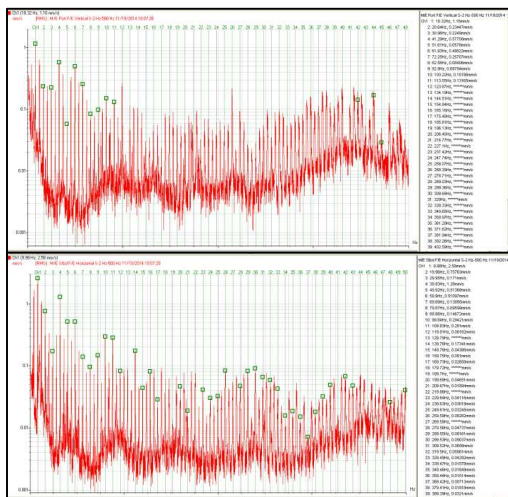


Figure 1. Machinery Vibration spectrums radiated from main engine

B. Hull Vibration Spectra at 600 rpm (At after steering position)

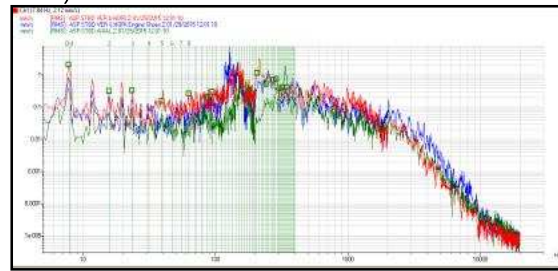


Figure 2. Hull Vibration spectrums radiated from propeller end

The underwater radiated spectra have its origin in vibration from ships components. This can be done by simultaneous measurements of underwater vibrations and then comparison of results using coherence function. Poland Navy had conducted a series of researches on subject matter using a vessel anchored between buoys which determine the area of range. An array of hydrophones was positioned one meter above the sea bottom and under the keel of the ship. Accelerometers were installed inside important locations to measure vibration.

The directional vibration signature from the vessel is injected into the water medium, where acoustic propagation occurred till the array of transducers.

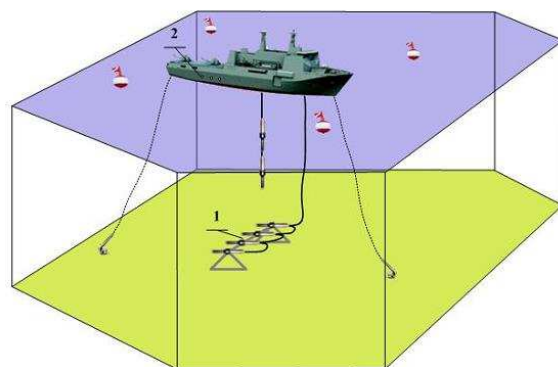


Figure 3. Static method of placing underwater transducers, Andrzej Żak (2008), Ships Classification Basing on Acoustic Signatures, p. 138

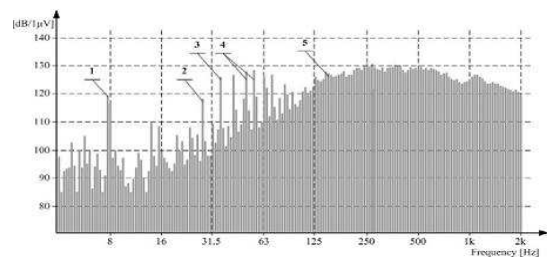


Figure 4. Underwater noise spectrum of a moving ship; 1) shaft, 2) diesel generator, 3) propeller blades, 4) main engines, 5) propeller. Andrzej Żak (2008) p. 141

The ship was made to propel at various speeds to identify the co-relation of signature transferred to bottom.

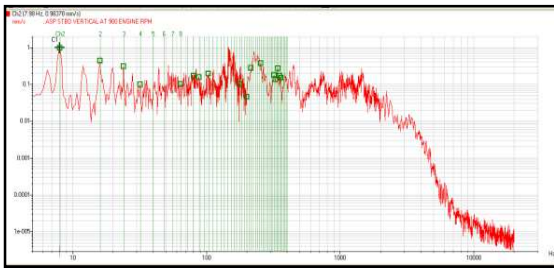


Figure 5. The sound spectra radiated by moving ship with different speeds; 1) 3.8 kn, 2) 8 kn, 3) 11 kn Andrzej Żak (2008) p.141

Another research done by Naval University of Gdynia, Poland has collected underwater hydrophone data and spectrum whilst ships on passage and on various speeds. A remarkable proportional relationship in vibration/ noise levels had been observed with the increase of speed.

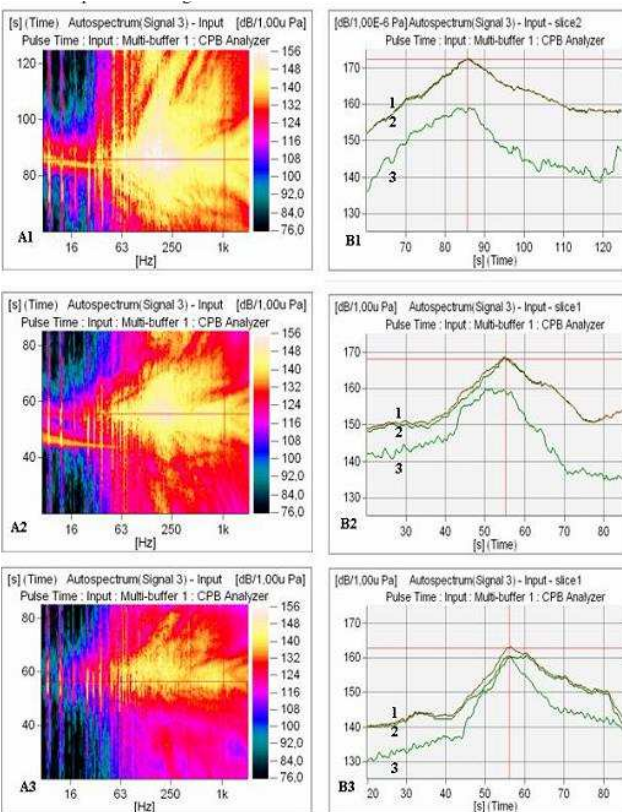


Figure 6. Behaviour of noise levels in function of different ship speeds, A1-4.8 kn and A2-6.4 kn, A3-7.6 kn
1 – hydro-acoustic signature of ship hull, 2 – signature of propulsion machinery, 3 - signature of propeller.
Domagalski J. et al (2010)

IV. ESTIMATION OF RESULTS

It is to be determined how much vibration energy is radiated by a running ship through the water column and the relationship/ proportionate value of the initial vibration energy emitted by the vessel while propelling through the water.

This can be done by measuring vibration aboard the ship as the initial phase of this study (inside the ship) and compare it with the underwater spectra and magnitude. As found out during the study by Poland Navy, the similarities between the vibration signals originated onboard within the hull and the ship, the underwater acoustical pressure in the water could be represented by a logical coherence function.

For two signals of pressure $p(t)$ and vibration $v(t)$ the coherence function is described as follows.

$$\gamma_{pv}^2(f) = \frac{|G_{pv}(f)|^2}{G_p(f)G_v(f)} \dots\dots\dots(1)$$

Where:

G_p and G_v denote the corresponding spectral densities of signals $p(t)$, $v(t)$ respectively;
 G_{pv} denotes the cross spectral density

Coherence function is a real function from the range of:

$$0 \leq \gamma_{pv}^2(f) \leq 1 \dots\dots\dots(2)$$

Table 3. Vibration and coherence function of hydro-acoustics pressure and vibration

Frequency [Hz]	Coherency function	Vibration on the hull [$\mu\text{m/s}$]
16.5	0.8	13
25	1	80
37.5	0.8	69
50	1	42
62.5	0.9	8.4
75	1	72
87.5	1	64
100	0.8	23

The identification of various frequencies and spectrum harmonics could be done from following formulae.

Table 4. Basic frequencies and harmonics of vibration

Vibration	Frequency		Harmonics
	Formula	[Hz]	
Unbalanced parts	$f_n = k f_0$	15	30, 45, 60, 75...
Diesel firing rate	$f_n = \frac{kz_c f_0 s}{4}$	10	20, 30, 40, 50 ...

Where:

- $k = 1, 2...$ is the number of next harmonics;
- f_0 is the main frequency;
- s is the coefficient of stroke (equal 0.5 for four stroke engines);
- z_c is the number of cylinder;

Relations between mechanical vibration and hydro-acoustics field of a ship are presented by transmission coefficient of the mechanical vibration α :

$$\alpha = \frac{L_{1m1Hz}}{\rho cv} \dots\dots\dots(3)$$

Where:

- L_{1m1Hz} is sound pressure level relative to $1\mu Pa$ at 1 m for 1 Hz;
- ρ is fluid density for sea water;
- v is vibration velocity;
- c is propagation velocity of sound wave.

$$L_{1m1Hz} = L + 20 \log R - 10 \log \Delta f \dots\dots\dots(4)$$

Where:

- L is acoustic pressure level under ship (dB re μPa);
- R is the distance between a ship and a sensor (m);
- Δf is the width of an applied filter (Hz).

The proportionality factor ρc is the acoustic resistance (specific impedance) of the fluid and for sea water is $1.5 \times 10^5 \text{ g/cm}^2 \text{ s}$. The results were reduced to a band of 1 Hz by applying a bandwidth reduction factor equal to 10 log of the bandwidth used.

V. CONCLUSION

The results of measuring vessel vibration suggest that the main engine of the vessel is the biggest generator of vibrations of the vessel structure. The most pronounced vibration component is at 10 Hz. The spectral analysis of radiated hydro-acoustic noise of the vessel shows the existence of some localised peaks in low frequency and medium frequency range. These signatures are of other structural and reciprocating components of the ship and could be analysed as separate harmonic series for individual component. Same will be transferred to the bottom water column with the proportionate corresponding value as discussed in paragraph IV, thus enables SLN to estimate and quantify the hydro-acoustic signatures of their vessels with a rough estimation derived from the shipboard vibration signature.

Ship noise is a major part of the field of underwater acoustics. In naval operations the radiated noise is an important source of information, leading to stringent requirements for passive listening systems. Radiated noise is an important contributor to ocean ambient noise, and is a factor in oceanographic research and geophysical

exploration. Ship noise reduction and control is an important factor in the safety and habitability of the vessel and crew.

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