FIFTH INTERNATIONAL CONGRESS ON SOUND AND VIBRATION
DECEMBER 15-18, 1997
ADELAIDE, SOUTH AUSTRALIA

FROM VIBRATION MONITORING TO ACOUSTIC SIGNATURE MONITORING OF A SHIP

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ABSTRACT

Very quiet ships are now built not only for military purposes (minehunters, ASW frigates, submarines...) but also for oceanography and fishery research. It is proven that fishing boats could catch more fish schools if they were quieter... However, the perfect vibro-acoustic control achieved by a careful design, the systematic introduction of rubber isolators, the use of large amounts of sound and vibration absorbing coatings and sound proofing materials is a costly investment to maintain.

As organizing adequate sea trials for measuring the ship radiated noise is very demanding - and sometimes even impossible if the vessel is quiet and the sea noisy - the only realistic solution for controlling periodically, or even better permanently, the vessel signature is to reconstruct it from on-board measurements.This is the function of a Ship Noise Monitoring System (SNMS).

Practical sea proven strategies for evaluating the sound radiation of a complete vessel from hull vibrations (accelerometers), machinery vibration (accelerometers), and machinery noise (microphones) is presented.

A sufficient emphasis is given to the delicate balance between a machine per machine monitoring philosophy (already widely used for machinery health monitoring in industrial plants), and a global approach of the vessel as an integrated system.

An original holography technique is recommended and will be presented in a companion paper (n° 379428 "Malice The Efficient Acoustical Imaging System for Precise Noise Source Loalization").

1. INTRODUCTION

The key functions of an ideal Ship Noise Monitoring System are listed hereafter, from end-users' requirements:

- a permanent assessment of the noise signature as radiated by the vessel at that precise moment (considering the operating equipments, manœuvres, speed, trawling activities, etc.),
- a cooperation with the critical acoustic systems of the vessel (underwater transmissions, echo sounders, sonars, etc.) to permit the precise identification and then the rejection of the ship induced acoustic disturbances (self-noise),

- the early detection of propeller cavitation, to prevent bales erosion and optimize the propeller driving parameters (speed, pitch, angle, etc.) and thus the overall propulsion efficiency,
- the early detection of abnormal flow conditions like induced by an excessive hull fouling, by a shape defect from a shock in harbour or on a flotsam, etc.,
- the machinery health assessment from vibro-acoustic signals (shaft unbalance or misalignment, wear of bearings, gearbox teeth damages, blades damages, electric problems, etc.).

Even if the best position to acquire the sound radiated signature is to listen to the manoeuvring vessel from some distance, supposing the ambient sea quiet and deep, it is clear that the permanent signature monitoring is to be done from sensors on the vessel itself for evident practical reasons.

However, as it will be demonstrated hereafter, recording the vibrational state of the vessel everywhere does not necessarly indicating its radiated noise; and this vibration monitoring would require a really unmanageable amount of sensors (several thousands) making the SNMS unaffordable... and unreliable.

Some basic vibro-acoustic physics are required to make this understandable.

2. FROM HULL VIBRATION TO SOUND RADIATION

The hull of any kind of vessel is made from a regular distribution of stiffeners (keel and timbers, frames, stanchions, etc.) then covered by a relatively thin plating. The ship is divided in some major sub-sections by watertight bulkheads, and then horizontally by a succession of bridges. As the water is a dense fluid, there is a **"strong coupling"** between the hull vibrational waves and the acoustic medium, described either as an important added inertia ("added mass") or by a significant change in the flexural waves speed (typically – 30 to – 50 %). From proper analytical equations, it is easy to demonstrate that **the flexural waves of the hull are always sub-sonic** whatever the material (steel, light alloy, GRP composite, wood...) referring to the sound speed in water (1460 m/s) at all audible frequencies.

This does not make ships quieter, unfortunately, but just makes sound radiation mechanisms more complex. Another complexity is due to the fact that the hull itself is only a small fraction of the vessel (max. 20 % of the global weight for a deep diving submarine), and thus appears widely disturbed by all the internal structures, vessel machinery, and payload, accounting for the remaining 80 % of the mass. As a consequence, the initial periodicity of the plating stiffening is extensively disturbed, reducing the propagation ability of the vibrations but also **increasing the sound radiation efficiency** as illustrated in figure 1.

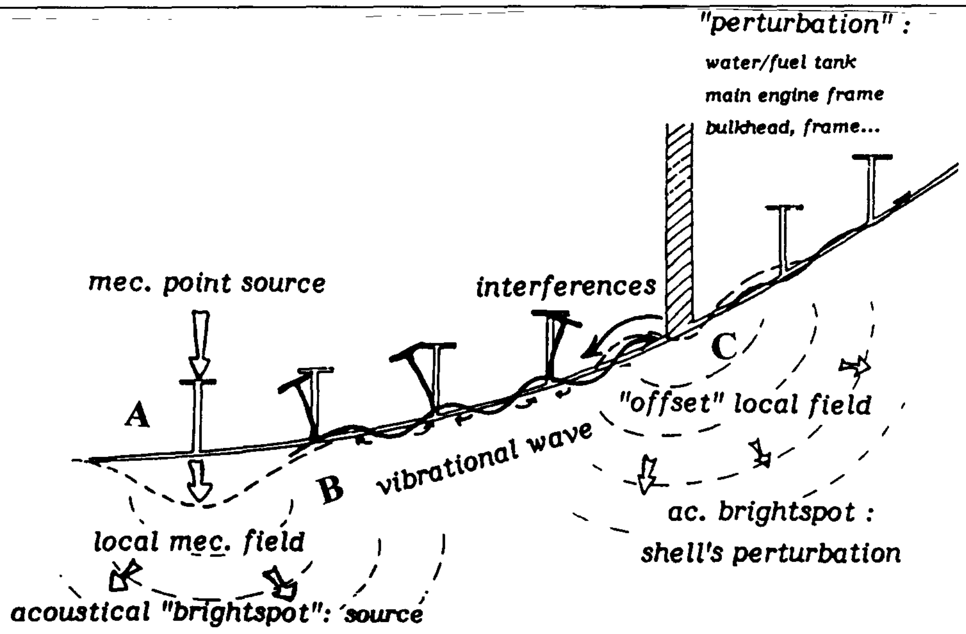
The second important characteristic of the sound radiation of an immersed vibrating hull is the very important **spatial filtering** of the vibration by the sound radiation mechanism, as illustrated in figure 2. This is relevant to the much larger wavelength of the sound (λ_{ac} = 1460/frequency in meters) compared to the plating or frames flexure. Very close to the hull, the pressure map is exactly reflecting the normal vibration velocity distribution, with a complex "punching" effect at the location of the driving force (here on the head of a rib) and visible flexural waves propagating symmetrically toward bow and stern. All this sound source even at distances as close as one fourth of λ_{ac} (i.e. 3.6 m at 100 Hz or 0.36 m at 1 kHz). But this will radiate audible sounds at hundreds of nautical miles, as the lower viscosity of the water and the 5 times larger wavelength compared to air make the sound propagation nearly unattenuated! Acoustic "rays" do not propagate in straight line underwater, explaining why vessels may remain undetected even being somewhat noisy,... but this is another story!!! Just state that if you can reduce the sound level by 6 dB, the huge distance of potential detection is divided by 2, i.e. a detection volume divided by 8 – a well motivating deal for military shipyards, but also for fishery research vessels, or even commercial trawlers, as fish schools are known to escape when hearing the vessel coming (cf. figure 3).

The internal noise issues are also very different from the radiated signature levels as the wave-length in air is only 340 m/s, and thus the airborne radiating contributions of the vibrational fields on hull, bulkheads, bridges, etc. are totally distinct from those efficiently radiating underwater, even if the radiation mechanics are similar. In particular, the fluid coupling is now negligible between the robust naval structures and the air, and many flexural waves are now supersonic ($c_f \geq 340$ m/s). This explains why equally comfortable vessels for crew and passengers may reveal radiating underwater levels differing by 30 to 40 dB in some frequency ranges! As an example, figure 4 presents the spread of the acoustic signatures underwater of 9 European Fishery Research vessels built over the last 30 years for very similar missions – military vessels signatures are not so easily diclosable but as well inhomogeneous…

The most essential aspects of this discussion for properly understanding the SNMS critical aspects are summarised hereafter:

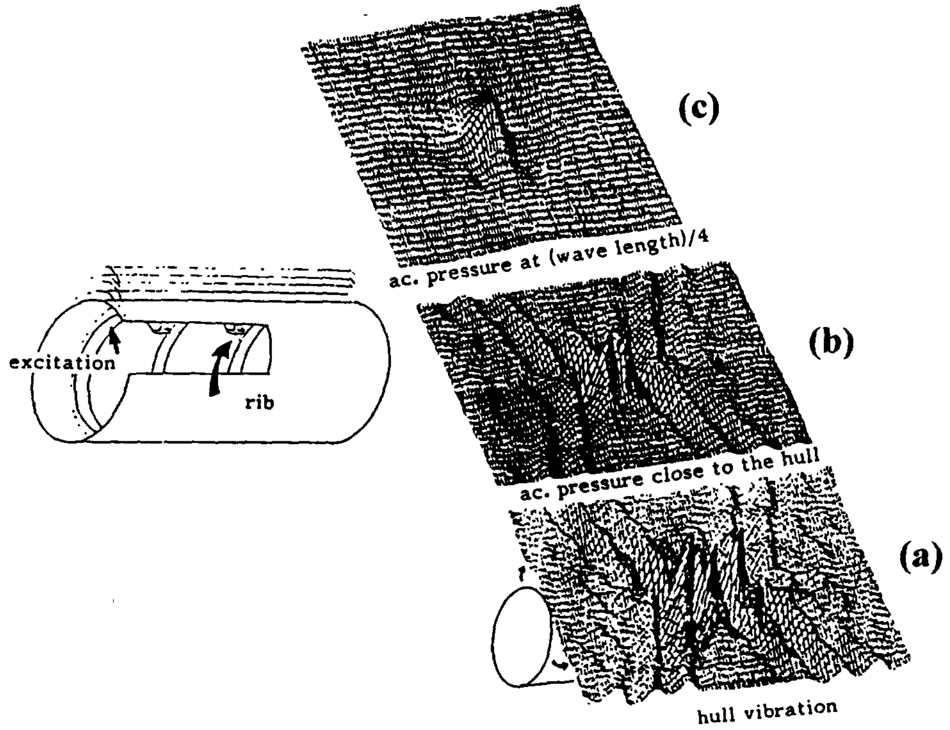
- The vibrational waves are very slow, and a complete sampling of the hull vibration in respect with the Shannon Theorem would require a network of several 10^3 accelerometers at a few hundred Hertz and several 10^5 above 1 kHz. As a consequence, calculating the sound radiation from the Helmholtz integral of a systematic hull meshing (even neglecting also the problem of sensors accuracy, etc., which also jeopardise the result) is definitively impracticable.
- The spatial distribution of hull vibrations is far from reflecting the noise radiation capability, and the noise cannot be supposed proportional to the vibration except right in the centre of a "hotspot" (cf. figure 2).

As a conclusion, monitoring the radiated noise signature from on board sensors is far from being a simple game, and the quality of the result totally depends on the "right choice" of sensors locations, i.e. the proper identification of the predominant emissive area of the hull and vibrational energy paths from the various sources.



A: direct radiation of a vibrating hull-mounted equipment
B: the vibration propagation does not radiate so much
C: the perturbation of the vibration wave by any other major structure or equipment now radiates as sound the vibration energy coming from 1

Figure 1: Acoustical radiation of shells



(a) map of the instantaneous hull vibration from a local dynamic force
(b) nearfield pressure map
(c) pressure map at a distance of $\lambda_{ac}/4$

Figure 2: From the hull vibrational field to the radiated sound (from GAP software modelling)

3. THE PROTIS SNMS

The PROTIS system developed by METRAVIB RDS and several other French Partners, the first of them being the French Directorate of Military Shipbuilding (DCN) is an integrated software + hardware paltform to achieve at low recurring cost the SNMS functions as listed above.

- The global acoustic signature is mostly assessed from hull mounted accelerometers. The sensors have to be placed at the exact location of the predominant noise paths from vessel machinery to hull and water ("hot spots" on the hull as detected from underwater acoustic imaging). At this condition, an average set of circa 60 accelerometers optimally distributed on the hull is typically sufficient to cover the variety of ship operating states. The second point is that the level of correlation of one of these "hot spots" to another is reducing with frequency, which means that the respective phases of the accelerometric signals become random. Parallel acquisition capabilities are thus essential at low frequency, at the vessel scale, but need just to be locally available at higher frequencies (from some hundreds to a few thousands Hertz, at the machinery compartment and hull section level, and in the upper frequency range, only for the very close sensors).
- The self-noise rejection issues are calling for accurate narrow band spectra (high resolution, zoom capabilities), and for the capability to provide good quality noise references to the sonar system: typically, an accelerometer signal on the noise making machine, to be provided as an analog time signal (for correlations, noise subtraction algorithms, etc.) is adequate.

- The cavitation detection issues are rather specific, supposing the implementation of dedicated sensors close to the propeller (generally hydrophones, but sometimes local hull accelerometers may reveal adequate and much more convenient considering the absence of cable water-tightening issues). High frequency acquisition capabilities are essential, but on a very limited number of channels. The same could be commented about flow noise issues. Hydrophones can preferably be used.
- Last but not least, the Health Monitoring issues of the ship machinery are preferable based on a machine per machine basis, with already well established industrial routines. The required band pass is limited, and there is generally no need for more than 1 or 2 channels synchronous acquisition capabilities as each machine is controlled one after the other (sequential scheme). A cooperation with the signature monitoring is however very beneficial, even if a noisier machine is not always a faulty machine, and vice-versa (e.g. rubber isolator failure will increase the radiated signature without raising any issue of machine health).

The PROTIS architecture is based on a distributed architecture from heterogeneous but fully developed processing entities (cf. figure 5).

- A first section corresponds to the management of all the machine mounted sensors (accelerometers synchros, DC status sensors like ON/OFF status, static pressure, supply power, etc.). For each machinery room, a PC based "SERIES 4" is successively interrogating each sensor, settling adequate filters, etc., and checking a first alarm status (level in excess of a pre-set threshold). Multiplexing units can be used to extend indefinitely (up to 100) the number of machines monitored by this unit; Each machine is controlled every 2 or 3 minutes in typical conditions.
- An Ethernet link is established to a central machinery health monitoring system, names "WIN'DIVA". This unit contains the "historical database" of all the machines inspected either automatically or from a portable collector for those not permanently monitored. It provides the latest states of the art of industrial computer aided maintenance and diagnosis (large collection of health criteria on the critical technological features of any kind of machine, statistics of evolution vs. Time, maintenance and repair suggestions). Even if no alarm occurs, it will provide the board chief mechanical engineer with answers to all its maintenance issues and related best practice advice, with a large potential of ship availability increase and maintenance cost reduction.
- A second section corresponds to the management of the acoustic signature monitoring from hull accelerometers, hydrophones, and eventual microphones. This is parallel acquisition system totally similar to any standard "Massively Parallel High Speed Acquisition System" option, but now down sized by a factor 3 typically without compromising the overall SNMS effectiveness:
  - a parallel acquisition with direct data throughput on disks are limited on the domains of number of transducers x frequency bands where the relative phases are really required later in the processing, reducing the overall data flow (and further processing load) by a factor 10 or more,
  - sequential acquisitions can be done for all the other situations as far as the overall signature assessment can be updated at a rate of c.a. every minute.
- The last system section is a global supervisor to provide the upper level system management and final user interfaces. The system operation follows this logic:
  - priority is given to the signature management with fast alarm confirmation capability and CIC overall reporting,

the diagnosis capability implemented in the form of an Ethernet link between the health monitoring section and the signature assessment section, the call for the

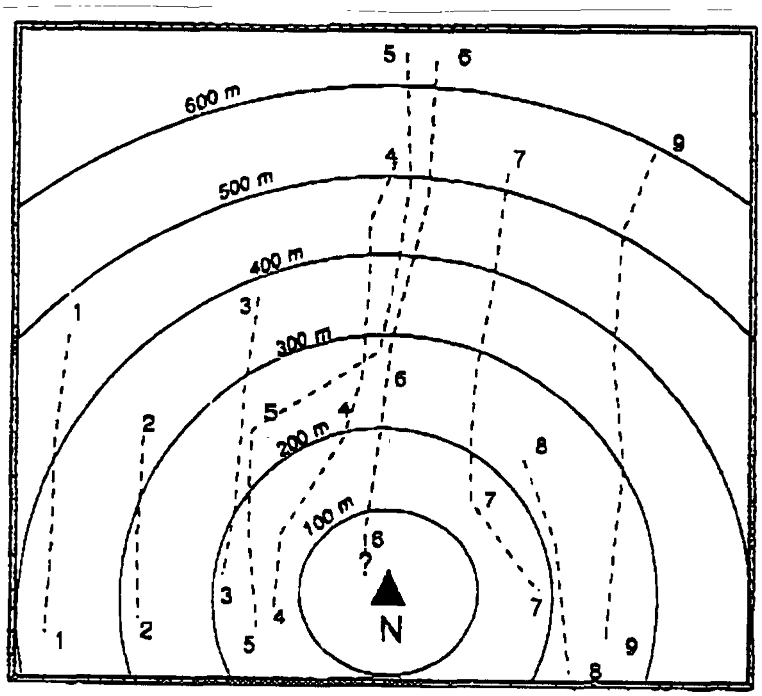


Figure 3: example of evidence of fish schools escaping strategy from the route of a noisy FRV is seen from the vessel sonars (N = vessel position) - (IFREMER document)

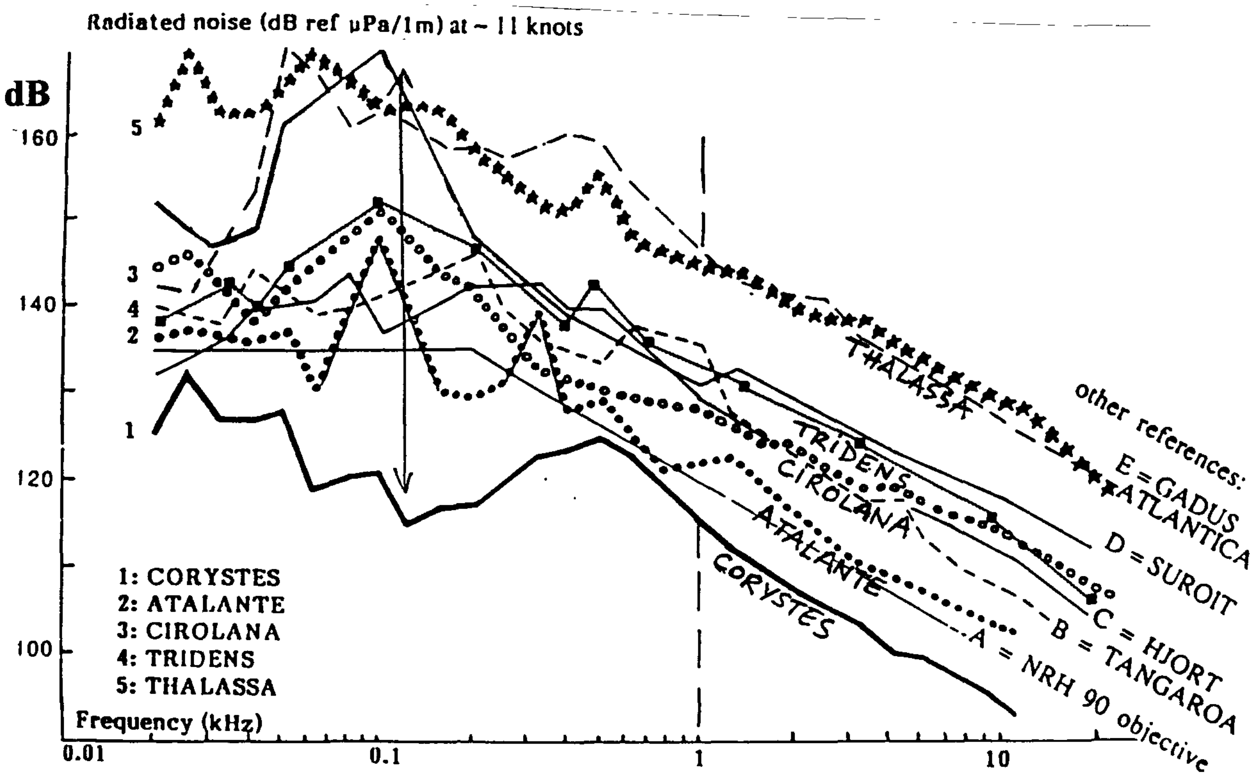


Figure 4: Example of the actual spread of the underwater signature of a collection of vessels built for a similar purpose (here, 9 European Fishery Research Vessels)

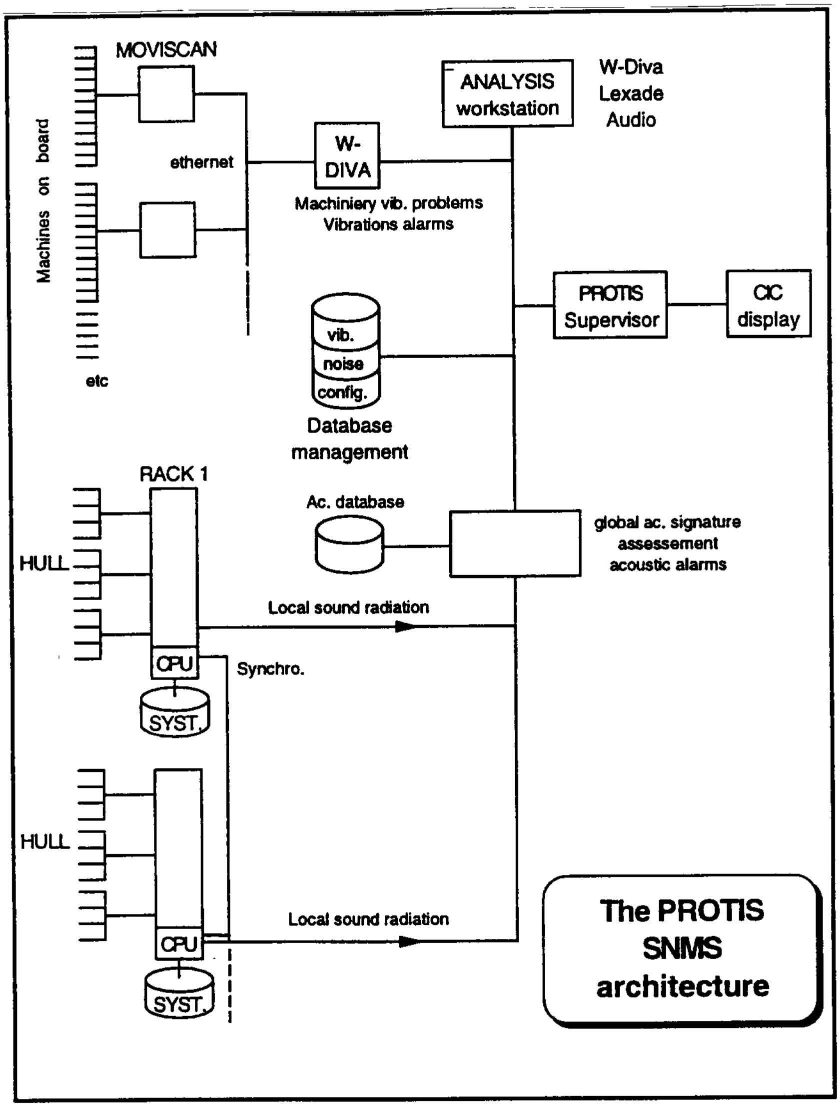


Figure 5: The PROTIS SNMS architecture

machinery signatures and their time evolution as a contribution of the Health Monitoring section to the Signature Management, as soon as they are detected in the hull signals.
An advantage of the PROTIS alternative is to offer three distinct man-machine interfaces:

- The "WIN'DIVA" unit, as an interface for all the Health Monitoring capabilities of the vessel machinery, not only for the permanently instrumented ones, but for every accessible item (servovalves, grease pumps, etc.), thanks to the wireless portable data collector; this interface is typically aimed at board mechanical engineers. It can include Artificial Intelligence for computer aided diagnosis and faster reaction (Expert System optional section).
- The PROTIS supervisor, as an interface for all the SNMS operation, alarm confirmation and overall recommendations and diagnosis; this interface is probably in a real proximity with the sonar systems operators.
- The specific CIC display, providing only the highest level of information for confirmed alarms (synthetic sound radiation patterns emphasising the sudden evolutions, synthetic localisation of the sensors in animated 3-D graphics of immediate legibility) but without requiring a fully interactive capability with the SNMS operating software in normal conditions.

4. SENSORS LOCALISATION AND SYSTEM CALIBRATION

It was previously explained that the hull sensors localisation decision process is critical for the effectiveness of an SNMS from physics.

Predominant paths to the hull can be determined sometimes from the vessel internal architecture; but they are potentially very numerous and cannot be easily ranked simply from drawings. The really best practice available to optimise the sensors location is the dockyard operated hull acoustic imaging developed by METRAVIB RDS and available through PNV in Australia in the form of the "MALICE" software package, presented in a companion paper. As final result, MALICE will provide a perfect picture of the "hot spots" on the hull related to every Ship Operating State, with a localisation accuracy of 0.1 to 0.3 m. Each of these hot spots is to be monitored by a hull accelerometer well centred on the spot. Additional sensors will be placed considering realistic signature degradation scenarios, particularly for the quietest operational states. Vibration shakers or loudspeakers may be added during MALICE surveys to reproduce the degradation of a particular critical machine or equipment and identify corresponding predominant paths towards waterborne sound emissions.

For each sensor, the MALICE processing will provide the explicit relationship vs. Frequency between the farfield contribution and the precise monitoring sensor successively for each "hot spot". From this, the system calibration is achieved for a complete class of similar vessels. Additional contributions from the propeller itself and the flow noise along the hull are finally extracted from the early sea trials. Alarm thresholds are refined and finally adjusted as a matter of practice from the vessel operators to optimally balance between an early failures detection capability and a low rate of false alarms.

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