Real variability in ship systems' noise and vibration. Design and through-life management implications for underwater noise and habitability.

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ABSTRACT

Customers require completed ships to achieve acoustic performance relating to military stealth, standards for crew and passenger habitability and legislation for environmental protection. Design activity derives equipment and system specifications for machines, distributed systems and isolation treatments, since the whole ship performance achievability and sustainability relates directly to component noises and vibrations. The paper examines databases, compiled over many years, during noise rangings and supporting vibration surveys, for several ship classes. The databases allow for objective study of the statistical variability evident in a sample of typical machinery source mechanisms that relate to specific measures of performance. The evidence provides important findings. Critically, very significant variability exists in real underwater noise performance and the related vibrations when compared to median measurements and fixed targets. Technical and cost implications of this observation should be considered by initial ship designs or update programmes, where multiple systems and related mechanisms co-exist. Authorities planning condition based maintenance for system availability and the through-life management of onboard habitability or underwater noise are also encouraged to study the predicted or evidential behaviours using such an approach. Stakeholders in different disciplines should expect mutual benefits. Surveying is recommended, typically using available populations of systems on ships in-service.

Keywords: Ship, Underwater Noise, Systems I-INCE Classification of Subjects Numbers: 11, 13.5, 54.1, 54.3

1. INTRODUCTION

All organisations having an association with ships will find that they have an interest in the noise and vibration of associated machinery and systems. The degree of interest, and hence the relative importance in terms of systems requirements, will depend largely on the owner's and operator's needs.

Such interests may concern the ship's purpose and associated function(s), through-life activities and, finally, the relevant requirements and standards. Non-shipping, commercial organisations, such as those involved in oil and gas exploitation and renewable energy industries may also share these interests.

Organisations with a more direct interest may have overarching requirements for habitability and hence dedicated design activity for initial specifications and/or system availability that invokes detailed vendor negotiations in the procurement phase, dedicated acceptance trials, followed-by vibration based condition monitoring and maintenance strategies.

National Governments' defence and naval communities will typically have a more indirect interest in machinery and systems' noise and vibrations, where the primary requirements are to achieve and sustain military stealth requirements for underwater radiated noise, amongst other signatures. However, such government organisations are no longer immune to the long-reach of health and safety legislation with respect to noise induced hearing loss.

Developed national governments also carry responsibilities for a wide range of non-military activities requiring ships with respective roles and related functions. These are increasingly likely to be required to adhere to environmental protection requirements.

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Table 1 shows a simple breakdown of such considerations that demonstrates how direct or in-direct interests in systems' noise and vibration may arise.

Table 1 – Organisations, Capabilities, Requirements and Activities with an interest in machinery and system

<table>
<tr><th>Ship Customer/Owner/ Operator</th><th>Ship Capability/Function</th><th>Primary Requirements/legislation</th><th>Potential through-life relevant activities</th></tr>
<tr><td>Government</td><td></td><td></td><td rowspan="10">Build and Upgrade:
• Concept design and systems specification
• Detailed design
• Design assurance/ certification
• Machinery and systems supply chain specifications
• Delivery acceptance; systems and whole-ship

In-service
• Licensing, approval and certification
• Signature management
• Availability management including planned and/or condition based maintenance</td></tr>
<tr><td>Defence/Military</td><td>Major and Minor war-vessels
Support and auxiliary craft</td><td>Underwater radiated acoustic noise (mil.)
Habitability</td></tr>
<tr><td>Non-Defence</td><td>Hydro-graphic and environmental survey and research
Civil coastal security and safety</td><td>Underwater radiated acoustic noise (enviro.)
Habitability</td></tr>
<tr><td>Commercial</td><td></td><td></td></tr>
<tr><td>Cargo</td><td>Various, S/M/L</td><td>Habitability</td></tr>
<tr><td>Ferry</td><td>Passenger and/or vehicle</td><td>Habitability</td></tr>
<tr><td>Passenger/Pleasure</td><td>S/M/L</td><td>Habitability</td></tr>
<tr><td>Primary Industry</td><td>Oil, Gas and mineral exploration and production
Energy renewables: offshore wind, current and tide</td><td>Underwater radiated acoustic noise (enviro.)
Habitability</td></tr>
<tr><td>Private/pleasure</td><td></td><td></td></tr>
<tr><td></td><td>Motor/Sail/mixed</td><td>Habitability</td></tr>
</table>

The basis of this Paper is the long-term experience of signature management for the UK's Royal Navy ships over many decades. Signature management activities involving the UK Government Ministry of Defence (MOD), the Royal Navy (RN) and Industry are associated with the recognition that real signatures exhibit fluctuations (variability) over time and that requirements are subject to changes that impact new designs and in-service modifications.

Notwithstanding the basis of the paper relating to the experience of RN ship signature management, the work is of relevance to all commercial shipping interests and for other maritime sectors as described.

2. THE NATURE OF UNDERWATER RADIATED NOISE AND RELATED SHIP SYSTEM COMPONENT ASSESSMENT

2.1 Underwater Radiated Acoustic Noise composition, a brief summary

The description of mechanisms relating to ships' underwater radiated noise are well documented (1). Figure 1 provides a useful classical reminder of some of the contributions that are typically of interest. It can be seen that the component descriptions are associated primarily with the source disturbances within and around the vessel and the associated transmission paths. The total ship noise is typically a composite of many mechanical functions associated with the effective 'radiation surface' that in itself may vary spatially, depending on the nature of the mechanisms. In structural and hydro-acoustic physics, these mechanisms are the familiar monopoles, dipoles, quadrapoles and even more complex multi-pole effects.

Physical source disturbances associated with internal equipment and systems, having no direct interface with the sea, will produce underwater noise components that are also modified by one or more structural and/or volume transmission path mechanisms. Examples are the tonal effects resultant from the reciprocating forces associated with propulsion engines, or the out-of-balance forces from motor driven machines such as pumps, fans and centrifuges.

Some of the radiated noise may be purely hydro-acoustic, due to the sea flow interactions with the moving vessel and appendages, thus little affected by the transmission paths within the ship's structures or volumes. As an example, some broadband sub-components of the propeller noise are in this latter category. The rank significance of the physical source disturbances and the associated transmission paths, is determined by many factors including the variety of the vessel's design features, and the mode in which it is operated. The ship's operating speed, and the resultant behaviour of all the systems and features associated with the 'act of moving', are of overarching importance, and will tend to determine the total radiated noise level in most conditions.

The total radiated noise level as observed at any remote location is also determined by the in-medium propagation. The true source mechanism, transmission within the vessel and the radiation from the effective vessel surface can be considered as three energy conversions, such that each identifiable source disturbance may have an associated component amongst the total radiated noise. The total radiated noise is normally referred to as a signature in a defence or military context.

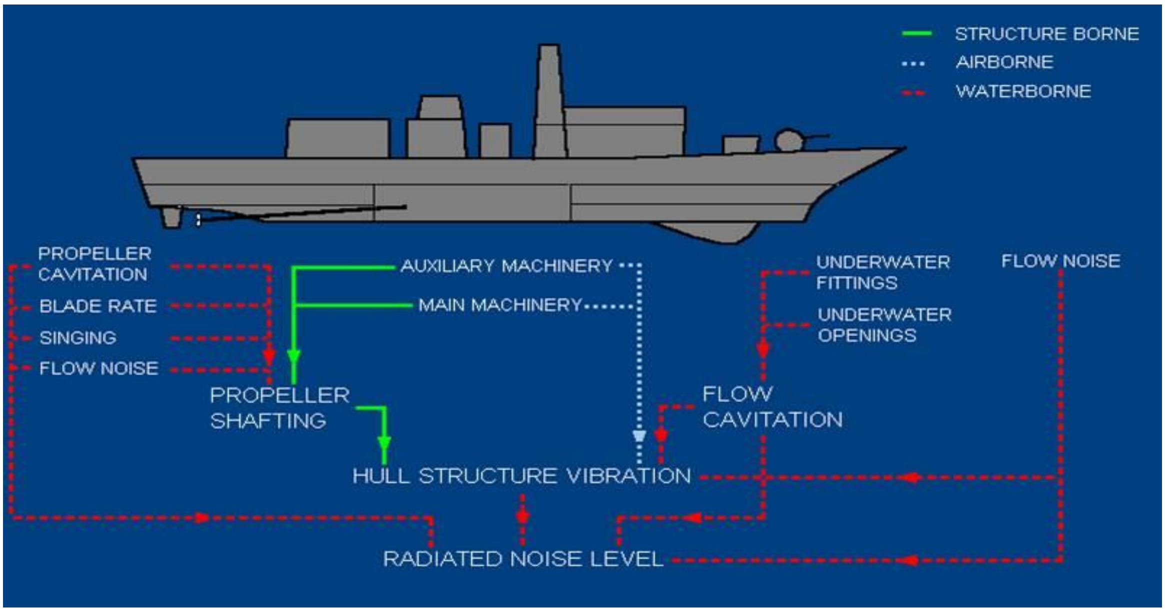

Figure 1 – A ship's underwater radiated acoustic noise components

2.2 Underwater radiated acoustic noise and related signature management

The UK MOD and RN have a signature management policy for all vessel classes and roles. This covers the entire life cycle from policy making, requirements setting and design, through to in-service update reductions and on-mission control. Underwater Radiated Acoustic Noise (RAN) is a significant signature influence for a number of vessel types in accordance with their associated capabilities and military tasking.

The signature management policy for in-service vessels consists of programmed activities such as noise ranging together with supporting activities conducted by the RN and Industry support, with the MOD in a coordinating role. The mix of activities and temporal programming is determined by the associated role of each class and specific vessel. In-service RAN signature goals, pertaining to vessel type and specific roles, are established and maintained by objective operational analysis. Requirements are typically developed using an understanding of the resultant farfield signature at a remote position and the wider considerations of the integrated platform survivability. In a military context, the performance of the potential threat platform's signature and sensor and own-ship sensor performances are also factored, amongst other considerations.

RN vessels signature requirements cannot be published, however the most basic of these take the form of frequency-domain spectra, for different vessel speeds. An open source standard in this format is referenced (2), detailing the ICES 209 noise limit proposed for specific environmental protection. Sound pressure levels expressed in broad-bandwidths, typically ISO standard one-third octaves, are generally utilised as these relate to the in-water property that can be most readily captured and also to recognised, comparable, analysis techniques. Non-military ship RAN performance requirements such as for survey and research vessels are also expressed in this format.

The UK has developed a number of fixed and transportable noise ranging capabilities designed to measure the RAN of different vessel types. Measurements are made using sensors and analysis procedures such as those detailed in references (3) and (4).

RN ships with the more developed RAN signature management policies include the classes associated with Anti-Submarine Warfare (ASW) and Mine-Warfare (MW). Current Royal Navy ship classes that fulfill these roles include the Type 23 Frigates, Hunt Class Mine Counter-Measures Vessels and Sandown Class Mine-Hunters. These are pictured in Figures 2, 3 and 4 respectively.

Figure 2 – UK Royal Navy Type 23 Frigate

Figure 3 – UK Royal Hunt Class Mine Counter-Measures Vessel

Figure 4 – UK Royal Navy Sandown Class Mine-Hunter

2.3 Assessment of ship system contributions to underwater noise

As described in the previous paragraph, the UK MOD's signature management policy for RN ships includes a number of activities that complement periodic noise ranging. Key amongst these activities is the exploitation of the Hull Vibration Monitoring Equipment (HVME) that is installed in those classes having more demanding requirements to achieve in-service signature goals.

HVME was developed by the UK MOD's Admiralty Research Establishment in the 1970s, initially for submarine applications, following a demand that certain vessels should have the ability to conduct 'organic self-ranging'. The system was subsequently designed-in to new classes or installed as a retro-fit to the surface-ship classes in-service today, which include the Type 23 Frigates and MCM vessels. Whilst initial and developed details of the HVME systems remain classified, it can be summarised that the systems comprise the following; vibration sensors, signal conditioning and digitising units, together with networked PCs for signal processing, information storage and man-machine interface functions.

The UK MOD and RN signature management activities include specific routines using HVME whilst vessels are deployed at sea. During routine noise rangings, the exploitation of the HVME systems is intensified by deployment of industry supplied subject matter expertise. Signature specialists are provided by QinetiQ Ltd, (previously DERA) the same organisation that maintains and operates the fixed and transportable ranges under the Long-Term Partnering Agreement, (LTPA). Specialist 'sea-riders' join the vessels for rangings and other exercises, to undertake tasks that include HVME based data acquisition, on-line analysis that includes correlation with the farfield range data, signature management training and defect investigation. The exploitation of the HVME systems and other activities has been developing for as long as the systems have been installed, which for some classes is approaching 30 years.

In addition to the data acquired from the HVME system itself, the onboard teams are also responsible for dedicated, signature component vibration surveys of identified machinery and systems. For each vessel class, the list has been extended to include appropriate and accessible vibration indications of the more significant components to the more important signatures, based on the vessels' mission profiles. Procedures for the surveying techniques and analysis are in accordance with UK defence standards as used by other stakeholder organisations such as those responsible for ship design, build and update programmes. Such HVME and transportable (hand-held) equipment vibration surveying is often extended to non-ranging activities, either in-port or in open-sea conditions where specific systems and machines may be operated over a wider range of operationally realistic duties.

The information databases derived from this in-service signature management activity are maintained on behalf of the MOD. They are themselves the subject of increasing exploitation to inform a wide range of knowledge needs that include; defect rectification, new build and class update design guidance and model validation. From the above discussion it is clear that the databases provide information regarding specific components of ships' underwater radiated noise as acquired at three notional measurement locations or 'surfaces':

1. Ship machinery and system representative source disturbance locations
2. Ship fitted management system (HVME); hull, structure and volume locations
3. Noise range sensor locations

2.4 Ship habitability and environmental protection considerations

Ships are places of work and many also carry paying passengers. As such they are subject to national and international regulations for the health and safety of both the work force and passengers. For commercial and military vessels, standards such as references (5) and (6) may apply. Private vessels such as luxury yachts may have more stringent performance requirements for internal noise and vibration.

In the UK, the Control of Noise at Work Regulations 2005 (7) came into force for all industry sectors in the UK on 6 April 2006 (except for the music and entertainment sectors where they came into force on 6 April 2008). Populated offshore structures such as fixed and transportable oil and gas installations, or ‘rigs’ are equally subject to habitability requirements and may also be required to meet limits on underwater noise.

Unmanned marine vessels and offshore structures may be subject to environmental impact assessment depending on the national or international regulations affecting the operational waters. These may be associated with oil, gas and mineral industries and increasingly with renewable energy industries. Such offshore wind turbines, current, tidal and wave energy devices are all potential sources of both underwater and above water noise, derived from the sum of the internal machinery and system contributions as converted by the associated structures and surrounding media.

3. COMPONENT VARIABILITY; EXPRESSION, EVIDENCE AND ANLAYSIS

3.1 Quantifying variability

There are four generally accepted statistical measures of variability in a population or distribution of measurements. In underwater noise and related noise and vibration analysis, it is important to consider the advantages and disadvantages of each measure or indicator:

(1) Range = R

The range is the simplest measure of variability to calculate. It is simply the highest value minus the lowest value.

$$\text{Range} = X_{max} - X_{min} \quad (1)$$

(2) Interquartile Range = IQR

The interquartile range (IQR) is the range of the middle 50% of the measurements in the distribution. It is computed as follows:

$$\text{IQR} = \textit{75th percentile - 25th percentile} \quad (2)$$

(3) Variance = σ^2

Variability can also be defined in terms of how close the scores in the distribution are to the middle of the distribution. Using the mean as the measure of the middle of the distribution, the variance is defined as the average squared difference of the scores from the mean. The variance is expressed as follows:

$$\sigma^2 = \frac{\sum(X-\mu)^2}{N} \quad (3)$$

Where: σ^2 is the variance, X is the specific measurement, μ is the mean, and N is the number of values in the distribution.

When using measurements expressed as decibels the median, $\tilde{X}$, should be used to represent the middle of the distribution:

$$\sigma^2 = \frac{\sum\left(X-\tilde{X}\right)^2}{N} \quad (3a)$$

(4) Standard Deviation = σ

The standard deviation is simply the square root of the variance. The standard deviation is an especially useful measure of variability when the distribution is normal or approximately normal. For such distributions it is always the case that approximately 68% of values are less than one standard deviation, 1σ, away from the mean value. In order to express a value that represents the spread (or range) of measurements that are within +/- one standard deviation from the middle of the sample, it is normal to present the 2σ result that is not to be confused with the spread of values lying within two standard deviations (~95%).

$$\sigma = \sqrt{\sigma^2} \quad (4)$$

The studies to interpret the noise and vibration information, provided by the UK MOD and RN signature management activities, have found that the most useful indicators of variability are the interquartile range and standard deviation measures in that order. These are typically used along with comparison of the distribution or actual measurement with the relevant target or goal, to inform design studies and in-service signature management decisions. The range measure is useful for identifying the effects of genuine machinery defects and transmission path degradations, represented by the maxima, as well as the occasional ‘outlier’ measurement where some potentially significant error in the data capture or analysis is present. The variance measure, although no doubt useful to other communities, is not as directly comparable with the others since it is in squared units compared to those of the actual measurements.

In order to express the relative significance of variability amongst different populations, statisticians use measures such as the coefficient of variation, C_v, that normally uses the ratio of the standard deviation divided by the mean. This has been adapted to use a preferred measure of variability, such as the IQR or 2σ value, and the median, to preserve the decibel measurements. Expression of this coefficient as a percentage has also been found to be useful. Perhaps of more use to the signature designer and manager, is a variability significance factor, VSF that compares the preferred variability measure with an established significant change, δ, that might represent a known impact or threat. In signature studies; values of 1, 2, 3 and 6 dB have been tested. For both the C_v and VSF terms, the 2σ may be used in place of the IQR.

$$C_v = \frac{\sigma}{\mu} \quad (5)$$

or

$$C_{v,IQR}(modified\ for\ dB, \%\ ) = \frac{IQR \times 100}{\tilde{X}} \quad (5a)$$

and

$$VSF_{IQR} = \frac{IQR}{\delta} \quad (6)$$

3.2 Evidence of machinery vibration variability derived from signature management activity

Table 2 shows a selection of example information, extracted from the databases described above, to illustrate the variability of a sample of five machinery vibration components associated with the underwater RAN of a specific class of ship. The data was acquired and analysed as a function of RN Fleet noise rangings over several years. All of the sample values were recorded in decibels with their respective engineering unit references; i.e. 1μPa at 1 metre for the RAN and $10^{-5}ms^{-2}$ for the HVME and machine point measured vibrations. These particular machinery component vibration examples are all tonal in nature. In order to deliberately declassify the information, the absolute RAN and vibration values, in terms of both frequencies and amplitudes, have been removed by normalising each sample set to having a zero value median. The zero value medians are not equivalent, in real amplitude terms, across the five components. The A to E ordering of the components is not intended to convey any information about their distribution in the frequency domain; however it is possible to state that the tones span approximately three octaves. For each component the three measurement populations would ideally be ‘coherent’, such that a mechanism’s instant vibrations and radiated noise are measured at the same time. This is rarely the case, particularly whilst the data capture is still reliant on significant manual activity. Careful selection of components, attention to data capture procedures and the avoidance of non-stationary effects is required to ensure the quality of the information that can be derived. Recording of trial conditions, procedures, local limitations and assumptions is standard practice and these are recorded in the relevant databases.

Table 2 – Example UK RN ship underwater RAN and associated vibration level variability, dB

Component id	machine source	Measurement location	Samples N	Min	lower quartile	Median $\tilde{X}$	upper quartile	Max	SD σ	Range 100%	IQR 50%	2σ ~68%
		RAN	17	-8.0	-4.0	0.0	5.0	9.0	5.2	17.0	9.0	10.4
A	Fuel Centrifuge	HVME		-9.5	-3.0	0.0	8.3	11.5	7.6	21.0	11.3	15.3
		Mc point		-10.8	-3.8	0.0	3.7	11.5	5.7	22.2	7.5	11.5
		RAN	38	-10.5	-6.3	0.0	4.3	11.5	6.3	22.0	10.5	12.6
B	LP SW pp	HVME		-6.5	-3.5	0.0	3.5	14.5	7.0	21.0	7.0	14.0
		Mc point		-27.1	-5.4	0.0	3.6	14.2	8.1	41.3	8.9	16.2
		RAN	22	-5.0	-0.8	0.0	4.5	8.0	4.1	13.0	5.3	8.2
C	Lub. Oil pp #1	HVME		-8.0	-3.3	0.0	2.5	3.0	4.1	11.0	5.8	8.2
		Mc point		-13.5	-3.3	0.0	2.8	12.6	6.4	26.1	6.1	12.7
		RAN	18	-10.5	-2.5	0.0	2.3	8.5	4.5	19.0	4.8	9.0
D	Lub. Oil pp #2	HVME		-2.0	-1.0	0.0	7.0	10.0	5.4	12.0	8.0	10.8
		Mc point		-7.2	-2.2	0.0	2.9	8.9	4.3	16.1	5.2	8.5
E	Chilled FW pp	RAN	17	-7.0	-1.0	0.0	7.0	15.0	6.0	22.0	8.0	12.1
		HVME		no data	no data	no data	no data	no data				
		Mc point		-21.3	-2.6	0.0	2.5	6.3	6.3	27.6	5.1	12.7

Figure 5 provides a histogram of the information from Table 2. Component RAN and vibration measurement ranges are presented with error bars used to exhibit the preferred measures of variability; Range, IQR and 2σ. Again, the information has been declassified by using zero value medians and these are not related between the samples for each component or between components. The population count for each component is provided by the figures in brackets. The measurement and variability axis has been scaled using 3dB divisions to illustrate an example of the significant steps, or deltas, in RAN requirements and the associated component signature and vibration performance.

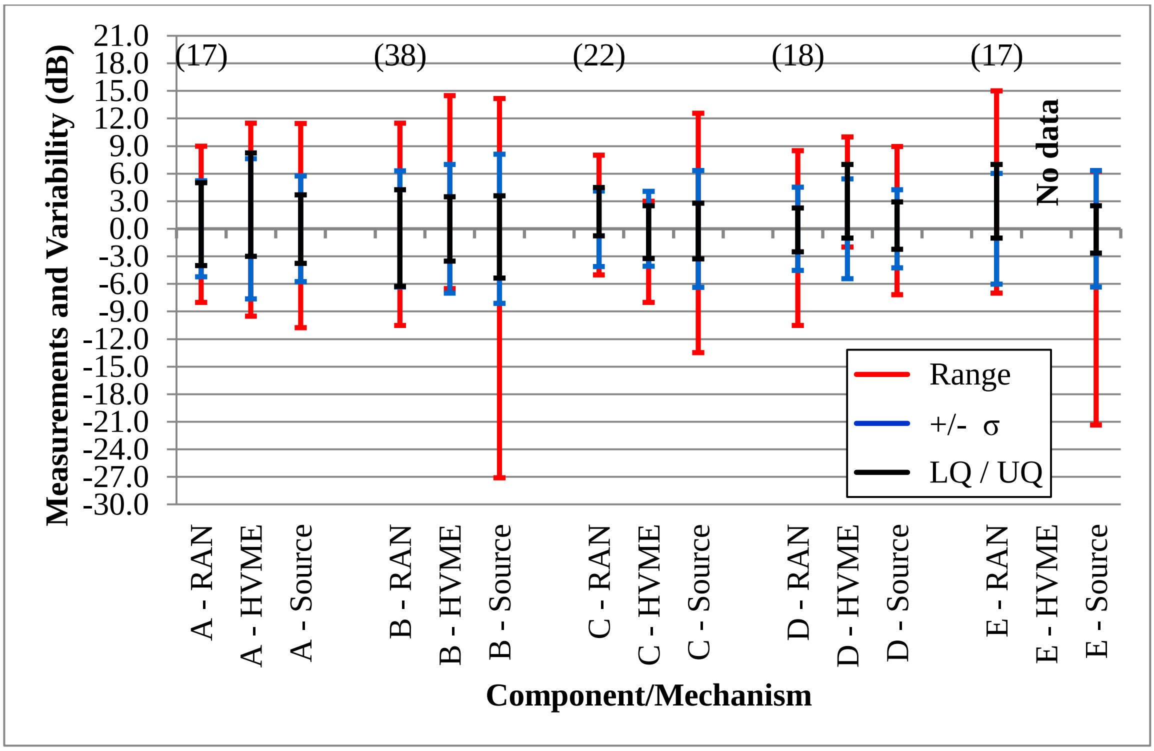

Figure 5 – RAN component variability compared to a normalised family of requirements

The graph makes it relatively straightforward to compare the variability indications for the three measurement types for each of the five components. For a perfectly linear 'system' with no transmission path or propagation changes over time, one might expect any particular variability indicator to have the same value across the three measurements. Clearly this is not the case and the temporal misalignment of the measurements, however short-term, is assumed to have played a significant part in the observed differences.

Notwithstanding these observed differences, it is clear that the variability associated with a particular mechanism, tends to extend across the three measures. Components C and D for example, exhibit relatively lower variability than do components A, B and E.

3.3 Potential impacts of total performance component variability

When all 14 combinations of the example components and measurements are compared, the median values of variability are 7.2dB and 11.8dB using the IQR (50% of values) and 2σ (~68% of values) measures respectively.

The C_v values using the IQR vary between; 3.5 and 11.9, and when using 2σ; between; 6.6 and 21.6 and the useful VSF (δ=3dB) values vary between 1.6 and 3.5 using the IQR and between 2.7 and 5.4 using the 2σ results.

The observed variability and related significance can be shared between signature design and management organisations but also with organisations, such as industrial equipment suppliers and maintenance authorities, who may not be allowed access to the more classified absolute performance figures.

Signature design work and through-life management activities are generally considered within a framework of higher-order integrated survivability considerations, where the cost and programme implications of a range of parameters are considered. Examples of other such parameters are the effectiveness of a ship's sensors, payloads and communications.

Signature design options may be considered and in effect traded against possible choices for the other parameters; for example an improved or lower signature might be considered cost-effective when paired with a reduction in underwater sensor performance. Traditionally, the signature designer might use a typical e.g. median measured or modelled performance to compare against a single target or goal. The selected signature can then be used to derive machinery and system noise and vibration specifications, amongst others, that can subsequently be used to seek costs from the relevant supplier chains. Analogous activities would be applied where the key design aims are more related to meeting environmental standards or habitability requirements as outlined earlier.

The example variability measurements and significance factors demonstrate the importance of understanding this real life performance of machines and systems. The whole ship's signature performance relates to a summation of the effects of individual mechanisms, each having potentially very significant variability, compared to a significant step that discriminates between options – the chosen 3dB delta, for example. In terms of a machine's or system's noise and vibration performance and/or that of their isolation systems, such a 3dB margin can be related to significant cost differences for both procurement and maintenance. Hence it would now appear to be unwise to conduct such business using simple fixed 'single value' descriptions of signatures and their related noise and vibrations, without factoring the margins of real, and hence expected, variability.

4. CONCLUSIONS AND RECOMMENDATIONS FOR INTERESTED ORGANISATIONS

Some example evidence has been provided by the paper from the measurements of auxiliary machinery in a class of UK RN ship, relating to radiated acoustic noise and the related component vibrations, as measured at machine source points and at the ships' hulls by the HVME signature management system.

Traditionally, signature design and subsequent management activities, that have their parallels in habitability and environmental control domains, are concerned with the comparison of the absolute component performance. Typically the observed or expected performance, represented by the median components or whole ship values, would be used. A typical complication of using such observations and the related modelling is that the data can carry a significant protective marking in security grading, as the information may be sensitive, militarily if not commercially.

As the paper has demonstrated, the absolute signatures and related noise and vibration measurements can now be supplemented by indicators of their variability, and the significance of that variability, when measured against potential advantage and disadvantage, and costs, in other key areas of performance.

Critically, the variability, when compared to the typical or demanded measure, is often very significant. The observed variability in the example machine components was between 1.6 and 5.4 multiples of the selected 3dB performance discriminator using the IQR and 2σ indicators that have been discussed.

The inevitable nature of such variability, if shown to be relevant to a particular business or enterprise, warrants critical attention by all concerned. Measures of statistically significant variability are recommended to be used in place of median measurements in design and through-life management activities.

It is recommended, to organisations across a wide range of disciplines, that study of such variability information associated with their own systems, will yield design and through-life management knowledge for customers and suppliers to the ultimate benefit of ship or platform capabilities, operators, passengers, and the environment, depending on the relevant demands. Experience of working with the related data and information will determine the indicators and measures that are most meaningful to each organisation.

The technical and cost implications of these observations, and the potential demands for human and equipment resources, should be considered by initial ship designs and update programmes, where multiple systems and related mechanisms co-exist.

Authorities planning condition based maintenance for system availability and the through-life management of onboard habitability or underwater noise, are also encouraged to study the predicted or evidential behaviours using such an approach. Mutual benefits are foreseen between stakeholders in the identified fields of defence, industry and private ventures.

Noise and vibration surveying is recommended, typically using available populations of machinery and systems on ships in-service. Co-incident radiated noise ranging, if relevant (certainly in defence) and available, will provide the added confirmation that the component variabilities warrant attention and to prioritise actions for operational ships and design work accordingly.

An overarching recommendation is for targeted data mining and fusion activities that are intelligently managed from the outset, to permit analysis of the suggested variability measures. Valuable knowledge will result that may be shared by like-minded organisations and interest groups where permissible.

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