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RESEARCH ARTICLE

Source Contribution Analysis Of Vibration Operational Responses on Full Scale Ship Data Measurements

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Abstract

The demand for enhanced passenger comfort on cruise ships has increased, emphasizing the need to reduce excessive vibrations that affect both onboard livability and environmental noise emissions. Structural vibrations contribute significantly to underwater radiated noise, making vibration control a key challenge. This study develops a method to analyze vibration propagation and identify individual source contributions to ship responses. Proper characterization of transfer mechanisms between sources and receivers is essential for effective vibration control, minimizing negative effects, and improving onboard comfort. The approach helps pinpoint critical sources and optimize their isolation by refining hull interfaces and energy transfer paths. After reviewing existing techniques, a methodology for source contribution analysis is proposed and applied to a cruise ship with dual electric propulsion engines and propellers. The study employs insertion loss functions to experimentally quantify vibration transmission between sources and target locations. The findings support optimized vibration control strategies, leading to improved passenger comfort and reduced underwater noise.

Keywords Full scale ship measurement; Vibration signals; source separation; vibration transmission characteristics of source; vibration monitoring and control

1 Introduction

Reduction of noise and vibration remains a critical issue for marine vessels. The trend in ship design towards high-speed, larger dimensions, and lightweight constructions has necessitated higher power outputs from propulsion systems, intensifying structural vibrations in these vessels (Kim, 2003; Spence and Fischer, 2016; Det Norske Veritas, 2006; Silvestri et al., 2021). A ship is a multi-sources complex dynamic system and therefore, isolation technologies and vibration reduction are challenging and key requirement problems.

The vibration sources inside the hull cause the operational vibration of the whole mechanical structures, which may affect both the reliability and the physical and mental health of the relevant staff and passengers and create exterior noise problems.

In a structural complex dynamic system as ship, harmonic contents generated by rotating sources as propellers and diesel generator and propulsion engines are generally the main vibrational sources providing deterministic contributions responsible of most vibrational energy transfer to passenger areas and to water through the hull.

Techniques capable of reducing vibration levels in marine vessels, even by a few decibels, are well worth pursuing (Zhen and Cheuk, 2018; He and Xu, 2013; Niu et al., 2005a; He et al., 2014). Conducting vibration analysis is essential in this field to evaluate the dynamic behavior of vessels under operational excitation forces, providing critical insights that aid design engineers in addressing and mitigating significant dynamic structural issues during operation.

Vibrations generated by sources, such as propeller blades and engines, propagate from source locations to the target

Article Highlights

- A methodology is proposed for analyzing vibration propagation phenomena in a vessel and for identifying individual source contributions from mixed observed operational signals.
- The proposed method has been validated through application to full scale operational measurements on a ship.
- The method allowed to quantify vibration transmission between sources and specific receiving target locations by experimental definition of path insertion loss functions.
- The presented approach allows the identification of the most critical vibration sources whose isolation should be improved to enhance onboard comfort and reduce the ship's underwater radiated noise.

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points (e.g. hull, bulkheads, decks where the passenger areas are located, ⋯) through transfer paths, involving connections or coupling elements between structures and produce the vibration responses at the target points. Within structural paths, mechanical energy is transferred from the source to the structure and propagated towards the receiver as vibrational energy.

To meet specific design requirements, the vibration control problem must be addressed through the following three key aspects: vibration sources identification, transfer paths optimization, and implementing passive control measures to mitigate vibrations at the receivers (Kai et al., 2014; Niu and Song, 2011).

In the 1960s, numerous studies addressed the mitigation of noise and vibration transmission from ship and submarine engines, through passive control strategies adopting dynamic vibration absorbers and decoupling mechanisms to minimize the vibro-acoustic transmission between the interfaces of the ships and enhance stealth characteristics (Ramos and Pisanelli, 2021).

The measured structural vibration response signals are composed of a mixture of multicomponent signals, which contains the vibration components excited by internal excitation sources plus the environmental noise that degrades signal quality. Accurately identifying not the sources themselves but their individual contributions to the system outputs is an interesting and challenging problem useful for identifying the most critical ones and improving their isolation acting on their interface with the hull and related energy transfer paths (Silvestri et al., 2021; Zhen and Cheuk, 2018). This enables the identification of specific components and structures requiring modification to effectively address targeted issues and improve the overall vibration operational behaviour of the system.

In naval field, extensive research has been focused to investigate vibration transmission dynamic properties of different structures, such as beams (Lee et al., 2007), girders (Senjanovic et al., 2007; Senjanovic et al., 2009), rafts (Niu et al., 2005b), casings (Otrin and Boltezar, 2009), and plates/shells (Chapman and Sorokin, 2005; Renji, 2005; Efimtsov and Lazarev, 2009). Additionally, some studies have directly addressed the vibration behavior of the overall ship structure (Iijima et al., 2008; Lin et al., 2009), which means that the entire structure of a ship is analyzed as one whole continuous component (Cheng et al., 2014).

This paper focuses on developing a methodology for evaluating source contributions at a vibrational target which related to diesel generators, propellers and propulsion electric motor drives can be applied on experimental full scale vibrational measures of a ship. A source separation technique is proposed to be applied on system responses in order to extract the different vibration components of interest and main sources information directly from mixed observed signals.

This was achieved through a combination of synchronous averaging, spectral kurtosis analysis and Wiener filtering techniques.

First, every periodic source is extracted from each observed signal by the time synchronous averaging method to identify deterministic discrete harmonics and suppress noise from observed signals.

Second, random content is assessed. This is achieved as time synchronous average signals can be compared with the original signal to evaluate a residual content with the exclusion of the deterministic part (Randall and Antoni, 2011). This has been performed using a proper estimation of coherence function to evaluate how a considered response is related to a source periodicity.

Third, random stationary and random non-stationary sources are separated by means Wiener filtering based on the spectral kurtosis. This allows to identify that part of the signal with the highest level of non-stationary burst components and enhance the detection of impulsive events associated with specific sources (e.g. propeller cavitation).

The proposed method is applied for its validation on full scale vibrational operational measurements acquiring during a cruise ship sea trial.

The separation of source contributions enables the identification of key transfer paths between vibration sources and targets on emitting hull, desks and bulkhead surfaces. This approach enables tracing vibration transmission and optimizing transfer paths to enhance the ship's acoustic and vibrational operational behaviour.

A method for calculating transmissibility using only experimental operational response measurements is also introduced and applied with the objective to find experimental relationships between the set of input sources and the set of output responses. As inputs are often very difficult to be measured directly or correctly estimated as they correspond to sources operational excitation forces, the method is based on system outputs only by defining a relationship between responses at source and target points. The method has been previously applied by the authors in a large pleasure superyachts providing promising and consistent results for system dynamic characterization (Silvestri et al., 2024a) and so suggesting its application on bigger size units to check its robustness in presence of a complex and massive unit as cruise ships (Silvestri et al., 2024a, Prato et al., 2023). Considering only the extracted principal components related to each specific source, the concepts of path Insertion Loss (IL) is utilized to quantitatively assess the path contributions quantitatively from source to the receiver vibration responses within the frequency domain. In this way it is possible to clearly recognize a vibration energy amount wholly involved in the transmission from a source to a target through all possible structural paths and so to be able to evaluate the structural insulation significantly.

Given the highly challenging environment, character-

ized by a massive, dynamic, and convolutive structural system with coupling phenomena between sources, classical methodologies available in the literature seem to be not easily applicable. In this context, the proposed approach in the present paper may provide a significant contribution to the naval sector, which constitutes its primary field of application.

2 Material and methods

Full scale structural vibration measurements were conducted on-board a cruise ship with a double propulsion electric engine and double propeller during sea trials. On the collected data, the proposed methodology for source separation and path transmission identification has been applied in the experimental case study presented hereafter. This allowed to check the reliability of the proposed method in evaluating the operational vibration transmission characteristics of the ship hull.

2.1 Main ship specifications

The investigated ship has a length of 223 meters, with its key specifications summarized in Table 1. Its electric propulsion system is obtained by installing an electrical drive for each propeller driven through a power electronic converter. The required power is supplied by four thermal diesel generators operating at constant speed.

Table 1 The main specifications of the cruise ship taken as case study (Pais and Silvestri, 2024)

Name	Investigated cruise ship
Length, overall	225 m
Beam moulded	31 m
Gross tonnage	55×10^3 t
Propellers (two)	6 blades
Installed power	4 diesel generators 4 × 8 MW 8 cyl 516 r/min
Propulsion (electrical)	2 electrical drives 2 × 9 MW 141 r/min
Speed, service/max	19.5/20.5 kn

The study focuses on one of the two vessels analyzed in (Pais and Silvestri, 2024), where operational modal analysis was applied for the experimental identification of the vibration modes. Relevant structural identification data from (Pais and Silvestri, 2024) are utilized in this work to enhance the interpretation of the presented results.

2.2 Measurement Equipment

The acquisition and processing of signals were performed using the measurement and analysis equipment listed in Table 2. The measurement campaign has been conducted using two LMS SCADAS data acquisition systems controlled by LMS Test.Lab software and configured in a master-slave mode which permitted synchronized measurements driven by one data acquisition system.

Piezoelectric monoaxial accelerometers with a sensitivity of 100 mV/g were employed to measure the operational vibration responses. Additionally, 10 mV/g triaxial accelerometers were used to measure the vibrational responses of the diesel generator engine block. Employed accelerometers have an error of ±5% in the range 3 Hz−5 kHz and a broadband resolution minus than 0.000 2 g rms.

Table 2 Measurement equipment (Pais and Silvestri, 2024)

Equipment
1 × 24 channels, LMS SCADAS (master data acquisition system)
1 × 16 channels, LMS SCADAS (slave data acquisition system)
Mono axial ICP PCB accelerometers, 100 mV/g
Triaxial PCB accelerometer, 10 mV/g
LMS Test.Lab 17 Structures acquisition software

Vibration response measurements were carried out in proximity to the onboard sources under investigation (diesel generators, propellers, and drive electric motors) to capture the maximized vibration signals from sources themselves and so obtain information on their operational dynamics.

In addition, the vibrational response was measured at receiving targets.

Figure 1 shows the positioning of the adopted mono axial accelerometers. Red markers refer to source points, green ones to receiving targets. The figure also shows the considered input operational sources acting on the physical system generally unknow and not collectible. The measured output responses at sources and targets will be used for defining path contributions quantitatively from source to receiver and identifying the transfer characteristic of mechanical structure.

The adopted acquisition time was set to ensure the collection of system responses suitable for accurate data processing.

The acquisition duration was selected to achieve both adequate frequency resolution in the spectral analysis and a sufficient number of statistical averages, in order to reduce the variance of the results. Specifically, the system outputs under steady-state ship conditions were sampled over 300-second intervals.

Vibration data were recorded through a sample frequency equal to 8 192 Hz s enabling the analysis of most significant contents in system vibrational response (including propeller cavitation phenomena). Trigger on both propeller shafts were measured adopting an induction sensor: in this way it was possible to detect a pulse per revolution signal useful for synchronous processing. Diesel generator engine block vibrational response provided an affordable trigger to identify diesel engine cyclicity.

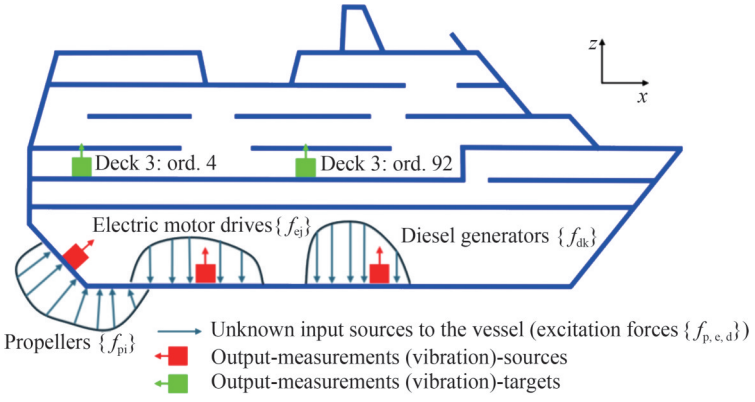


Figure 1 Positioning scheme of the considered mono axial accelerometers (normal to surface axis oriented) and spatially distributed input sources on a longitudinal-vertical plane parallel to the ship's centerline (longitudinal view)

In this way both for left and right propellers and diesel sources, it has been possible to define and average together series of signal segments each corresponding to one period of the synchronizing signal.

For a correct application of the proposed methodology it is mandatory to ensure the correct phase relationships among all acquired signals (both vibration and triggers). This implies the use of a single data acquisition system collecting all channels - or multiple systems sharing a common clock, as in the current case. Such a solution may not be easily implementable in complex and very large systems as it often requires extensive cabling throughout the vessel, and this may represent a limitation to the easy implementation of the method.

The following Figure 2 shows the adopted point for source response measurement at the left electric motor drive foundations (left photo): the accelerometer was placed downstream the resilient supports connecting the engine to its foundations on the passive side of the vessel; in addition (right photo) accelerometer position for target response at deck: 3 (ordinate 4) measurement point near a steel vertical girder.

The vibrational measurement points were placed as close as possible on the main structural elements of the hull in order to minimize the influence of the system local vibration modes and be more representative of the dynamic behaviour of the whole system.

2.3 Data collection

The shipbuilder defined and executed specific operating conditions to allow the collection of data fine for this analysis. All measurement runs were executed in the presence of harmonic contents from the propellers and engines as well as broadband excitation contributions generated by the wave impact as well as vortex and turbulent flow. A stationary operating condition was considered characterized by a constant rotational speed of the propellers. In addition, an astern propeller revolutions condition where an additional vibration source with marked burst characteristic is present acting on the system generated by cavitation phenomenon. Vibrational signals were collected while the sea state was 1 to avoid the effect of the ship motions on the acquired data. Moreover, weather conditions during

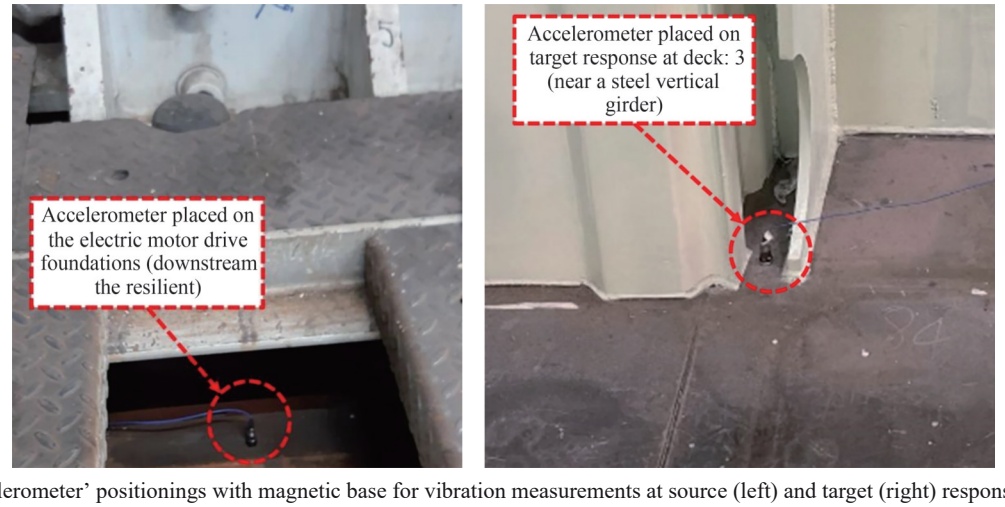


Figure 2 Accelerometer' positionings with magnetic base for vibration measurements at source (left) and target (right) response points

the sea trials were with very light winds and no precipitation. Ambient temperature and barometric pressure were within normal operational ranges. The encountered weather conditions were deemed to have had a minimal influence on the measurements carried out during the tests, and were therefore considered suitable for a correct vibrational characterization of the ship.

2.4 Source contribution analysis and propagation paths of mechanical vibration

The study of vibration sources and propagation paths is essential for proposing effective modifications and improvements to minimize vibration in critical regions of complex dynamic systems, such as ships. Traditional signal processing techniques, including FFT and wavelet transform, can reveal valuable insights within certain spectral bands; however, they fail to capture all relevant information about the sources.

However, as vibration signals are transmitted from sources to measuring points through mechanical structures, the source signals are mixed each other and coupled with structural and environmental noises: the previously cited traditional signal processing methods are generally not able to extract correctly source signals from acquired mixed vibration signals.

As a result, dedicated signal processing approaches are required to help extract the source specific information and trace the major components of the vibration signals. This enables a detailed analysis of the vibration transmission characteristics of the ship structures and transmission paths facilitating the redesign of the structures to reduce vibration transmission.

In the following a recall of the two main techniques for transmission path and source contribution analysis: transfer path analysis (TPA) and operational TPA (OTPA). Classical TPA is based on a load-response relationship, whereas OTPA is based on a response-response relationship model.

Both approaches must address the dynamic coupling effects among paths which can complicate accurate system identification and source contribution evaluation. This is a key problem to be solved as the measured operational response of a source point is influenced not only by the source acting at that point but also by other sources in the system. This leads to a lack of not a simple one-to-one relationship between responses and sources making the correct transmission path identification difficult.

2.4.1 Load-response method

The load-response approach enables the separation of individual source contributions to system responses by employing a dynamic model that considers the input dynamic loads generated by the sources and the associated transmission paths. The method is able to provide the output system vibrational responses at the target points jointly the single contributions of the considered sources (Seijs et al., 2015).

Model identification can be developed either through theoretical formulation or via an identification process based on experimental data, such as frequency response function (FRF) measurements. Dynamic forces can be determined using direct measurement techniques or indirectly by solving an inverse structural dynamics problem in conjunction with measured system operational responses (Elliott et al., 2013; Seijs et al., 2014).

However, this method may present some limitations in naval field as generally it is not easy to establish reliable physical models and correctly evaluate dynamic loads for complex equipment and especially for massive system as a vessel.

TPA is a well-established load-response technique that utilizes the load-response approach, based on an experimental model identified through FRF measurements (Pais and Silvestri, 2024). Over the past few decades, TPA has been increasingly applied in structural engineering, particularly within the automotive and aerospace industries, in response to growing consumer demands for enhanced vibratory comfort (Seijs et al., 2015).

It permits to break down a vibration problem into its key contributors. These contributors are identified using input system source loads and FRF from a source to the response location where unsuitable vibrations are perceived.

In applying TPA, the initial step is to construct a TPA model. The mechanical system is divided into two subsystems: the active part which includes the excitation sources and the passive part which contains the target points.

Energy from the active part is transmitted to the passive part via connecting elements, which induce vibration at the target point. Each connecting element at the interface between the active and passive part is a path which transmits vibration energy and have to be identified through a FRF measurement.

A schematic representation of the TPA model is shown in Figure. 3 with reference to a vessel and a diesel generator acting as a source. In the described layout, at the interface between the two parts coupling is obtained adopting mounts and structural excitation loads are generated propagating to the receiver points in the vessel through the mounts acting as transfer paths. In the scheme a_{ai} and a_{ai+1} are the responses at the active side while a_{pi} and a_{pi+1} at the passive one (the latter refers to the data collected during the experimental activity). The latter ones are the responses at the input degree of freedom of the passive subsystem. Additional response locations, a_q and a_v are also indicated representing possible indicator points that can act as target points. A physical interconnections between the two transfer paths is also take into account in the scheme generating cross coupling phenomena at the input degree of freedom of the passive subsystem.

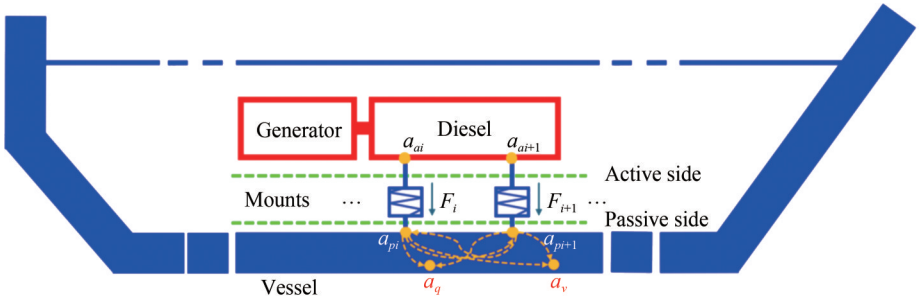


Figure 3 Transfer path between active and passive side (a: operational accelerations at both sides of mount)

The second step involves identifying the operational forces at each excitation point on the passive part under operating conditions. Dynamic loads are defined at the interface between the active and passive part. Various techniques can be used to determine the operational forces, including the direct measurement method, the mount stiffness method, and the matrix inversion method (Seijs et al., 2015).

Once the FRFs and operational forces are obtained, the individual contributions of each transfer path can be calculated. This enables the identification of the dominant paths that significantly influence the target point, providing valuable insights for vibration and noise reduction strategies.

In this way, TPA enables multiple input and multiple output (MIMO) systems to be divided into distinct excitations and transfer paths, offering better comprehensive dynamic information for operational system behaviour optimization.

In systems with multiple transmission paths between source points and responses, accurate identification of transfer paths requires measuring the FRF of the uncoupled system. Therefore, it is necessary to disassemble the system in order to isolate each transfer path. Subsequently, a known artificial force must be applied to each individual link to eliminate the influence of flanking paths.

In this way it is not allowed that the same input causes responses on multiple paths and output points generating crosstalk among transfer paths in the system. By isolating paths, the contribution of each transfer path can be accurately assessed through response measurements.

For massive and complex systems, such as vessels, this process involves extensive testing, is time-intensive, and in addition dismantling process may modify system boundary conditions, the results may not be reliable.

In some cases, it is deemed acceptable to approximate by keeping the system assembled, assuming that crosstalk effects are negligible. While this significantly simplifies the experimental setup, the validity of this assumption must be confirmed by validating the results through analysis of the reconstructed signals at the target responses (Seijs et al., 2015). In naval field another challenging aspect in the FRF experimental definition, it is hard to create and measure enough energy to induce significant vibrations artificially without causing local plastic deformation on the impact point of the vessel (Jiang et al., 2011). Moreover, artificial excitation is not the actual excitation normally, and the accuracy of the FRF and the analyzed results could not be guaranteed (Zhonghua et al., 2022; Orlowitz and Brandt, 2014; Soal et al., 2015; Van Zijl and al., 2021).

In addition, especially in massive equipment and for complex mechanical structures source dynamic operational load identifications necessary for the evaluation of source contributions are also challenging. Direct method is not always feasible due to the difficulty in find adequate force sensors for correct measuring, while the application of indirect force estimation methods is not always reliable providing correct results (Orlowitz and Brandt, 2014).

For these reasons listed above, the TPA is costly or even not very feasible for massive structures like ships, submarines, and offshore platforms unlike cars and planes as it was initially developed (Seijs et al., 2015).

2.4.2 Response-response method

The response-response method utilizes a statistical signal processing technique to estimate source contributions with minimal prior knowledge of the system's dynamic behavior and vibration transmission properties. This approach requires vibration response measurements at both source and target locations and it relies on the concept of transmissibility or path transfer ratio, defined as the ratio of the spectrum response at a target point to the response at a source point under real operational conditions (Zhonghua et al., 2022). The method involves decomposing of the operational signals received at the targets using transmissibility data, which provides insights into the relative strengths of the transmission paths (Zhang et al., 2005; Gajdatsy et al., 2010). This measurement technique is cost-effective as only the system's operational responses are used and no loads estimation is required. Moreover it eliminates the need to disassemble sources or machine components for isolating each transfer paths, thereby preserving accurate boundary conditions throughout the measurement process.

The OTPA method is a widely used response-response approach. A difference compared to TPA is that while TPA considers both the active and passive parts of the system under analysis, OTPA is focused exclusively on the passive part. The FRF's linking the targets to loads adopted in

TPA are replaced with transmissibility functions (e.g. path insertion loss). By employing OTPA, system identification can be performed without the need for artificial excitation to experimentally evaluate FRFs, as only transmissibility functions are needed evaluated from operating vibrational responses (Jiang et al., 2011). The transmissibility-based approach offers a simplified and fast setup, significantly reducing measurement time and complexity compared to FRF approaches adopted in TPA, which are often impractical in naval applications (Maia et al., 2001; Janssens et al., 2011).

An additional key advantage of the method is that using operational data, real operational effects are considered, and real boundary conditions are applied making the evaluation of vibration transfer paths representative of true operating conditions (Li et al., 2021).

However, transmissibility measurements can be susceptible to errors when the input signals are highly coherent between each other. Coherence degradation, often caused by unavoidable crosstalk between simultaneously sampled measurement vibrational responses, can reduce the accuracy of the results.

Removing crosstalk implies that the response contributions associated with the considered source are taken into account omitting the ones related to the other sources acting on the system.

Crosstalk is typically unavoidable due to physical interconnections within the system, and while optimized signal acquisition schemes can help minimize its impact, they cannot eliminate it entirely.

A schematic representation of the crosstalk model is shown in Figure 4 where F_p and F_d are exciting forces generated by two sources (e.g. propeller "p" and diesel generator "d"), T_{pd} and T_{dp} are structural transfer paths between reference points at the input degree of freedom of each source at the passive subsystem. T_{py} and T_{dY} are transfer paths between reference points and target point Y.

Thus some arrangements such as a reasonable signal acquisition scheme can reduce crosstalk but cannot remove it. In presence of cross-talk, the relationship between responses and sources is not a simple one-to-one relationship (Schünemann et al., 2021; Cheng et al., 2021). To address this issue, statistical separation methods and procedures can be applied before calculating the transmissibility of each critical path.

Singular Value Decomposition (SVD) and Principal Component Analysis (PCA) are commonly utilized (Bendat and Piersol, 2012) to mitigate crosstalk by decomposing the total signal into distinct independent components while simultaneously filtering out measurement noise. This enables accurate identification of transfer paths and source contributions to the overall response at the receiver (Zhang et al., 2005).

While SVD and PCA perform well for linear systems, OTPA often encounters non-linear crosstalk, particularly in complex structural or vibrational systems. Non-linear phenomena, such as resonance, damping effects, frequency-dependent interactions, correlated sources and convolutive mixtures, can significantly reduce the reliability of OTPA in such contexts. These aspects are generally particularly marked in dynamically complex structure as vessels.

Additionally, the neglect of certain transfer paths can further compromise the accuracy of OTPA in some specific scenarios (Schünemann et al., 2021).

2.4.3 Source separation methods at the system outputs for cross-talk cancellation

As reported in the previous section, OTPA measurements are conducted during real operation with all sources acting on the system simultaneously and cross-talk between measurement channels caused by strong sources is expected. If cross-talk is not effectively mitigated during analysis, this can lead to inaccurate and erroneous results.

SVD and PCA are powerful tools for data decomposition, separating signals and reducing dimensionality, but neither can fully solve or remove cross-talk in OTPA (Bendat and Piersol, 2012). To handle these complexities, more advanced techniques are typically required, along with detailed modeling of the physical dynamic system.

Blind Source Separation (BSS) is a well-established technique in the field of communications, enabling the extraction of source signals only from observed signals without requiring prior knowledge of the sources and how they are constructed (Cheng et al., 2014; Comon et al., 1991; Jutten and Herault, 1991; Sorouchyari, 1991; Almeida et al., 2006; Antoni, 2005).

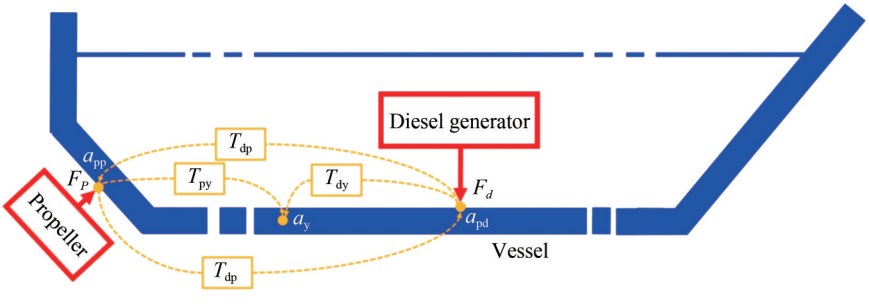


Figure 4 Crosstalk among sources in the system (e.g. propeller and diesel generator in the vessel)

The objective is to reconstruct the contributions of n statistically independent sources, $s(t) = (s_1(t), \cdots, s_n(t))$, from m observed signals, $x(t) = (x_1(t), \cdots, x_m(t))$, which represent "mixtures" of the original sources. The separation algorithms are designed based on the nature of the mixtures, which can be classified as instantaneous, delayed, or convolutive (Comon et al., 1991).

To achieve separation, it is essential to hypothesize the independence of the sources and employ a statistical function that quantifies the independence of the extracted components. This function serves as the objective in an optimization process, maximizing statistical independence without requiring prior knowledge of the system's structural transmission characteristics. Numerous studies have proposed methods to isolate waveform information and quantify the contributions of source signals from mixed vibration data based on enhanced separation algorithms.

Mechanical vibration signals exhibit significantly greater complexity compared to communication signals, for which BSS was initially developed. In the context of vibration analysis, it is common to encounter measurements that result from mixtures of many excitation forces.

The subsequent discussion highlights the main difficulties BSS is faced with when dealing with vibration signals.

As reported in (Antoni, 2005), the first challenge arises from the fact that mechanical systems are rarely described by a simple algebraic relationship. Mechanical systems generally present high levels of complexity and actually include inertia and dynamic coupling effects which give rise to a system of differential (rather than algebraic) equations.

For this reason in mechanical system the measured vibrations are most often mixture of dynamic or convolutive type opposed to a static or instantaneous mixtures as generally in telecommunication cases where "mass less system" are involved.

In particular, vessels represent complex dynamic systems with high modal density and significant coupling phenomena and so this difficulty is realistically present and makes the mixing process complex.

The second challenge lies in the uncertainty and often high number of individual sources contributing to the mixture, as is typical in complex systems like vessels (Antoni, 2005). Effective separation generally requires that the number of sources does not exceed the number of measurement points, a condition that may not always be met in some cases. In vessels, the presence of numerous individual sources, some of which may also exhibit dynamic coupling, further complicates the identification and characterization of their interactions.

The third significant challenge is the presence of noise in vibration measurements, which can complicate analysis (Antoni, 2005). Additionally, a critical difficulty arises from the nature of the sources themselves, which are typically spatially distributed rather than localized pointwise forces or torques. The assumption of pointwise sources is fundamental condition for BSS to work correctly (Antoni, 2005). For instance, in a vessel, the propeller acts as a significant distributed source, exciting the hull both through the inflow pressure field induced by its operational and through the shaft bearing generating constrain reactions.

These previously cited difficulties can significantly weaken, if not entirely compromise, the effectiveness of most separation algorithms available in literature so far (Comon et al., 1991; Jutten and Herault, 1991). Achieving complete separation of all sources linked to the various components of a mechanical system, is, although ideal, often impractical and may not align with engineering objectives. Instead, maybe sufficient clustering sources with similar characteristics, such as grouping random sources and harmonic sources together, may provide a sufficiently effective solution in many practical cases of interest (Antoni, 2005).

In naval field a useful separation criterion for vibration signals might be distinguish between harmonic (engine/propeller) and random components (waves, wakes), and then between random stationary and random nonstationary components (burst transient phenomena as cavitation).

A vibrational response signal can be decomposed into a summation of a deterministic part and a random part (Anderson, 2011). For operational vibration signals in a vessel, the deterministic part principally embodies periodic harmonic components mainly from kinematical forces induced by rotating machinery such as diesel and propulsion engines and propellers. Then the random part is the residual after extraction of the deterministic part introduced by stochastic sources as wakes and wave impact forces generating broadband random energy in the system responses. Figure 5 shows the three main clusters of sources sharing similar characteristics for a vessel considered in this work.

Periodic vibration signals generated by rotating sources can be extracted from raw data using the synchronous averaging (SA) technique. This approach involves averaging the signal in synchronization with a periodic reference, typically associated with the rotation of machinery or other repetitive events. Starting from a time-domain signal, angular resampling at constant increments of the shaft angle is required to produce synchronously sampled data suitable for order tracking analysis (Fyfe and Munck, 1997).

Consecutive segments separated by the exact reference period are averaged. Any periodic content, synchronous with this reference period, is thus unchanged, any other will be reduced and converge asymptotically towards zero. This can be done in either the time (angle) or frequency (order) domain (Fyfe and Munck, 1997; Silvestri et al., 2019).

Formally in angle domain:

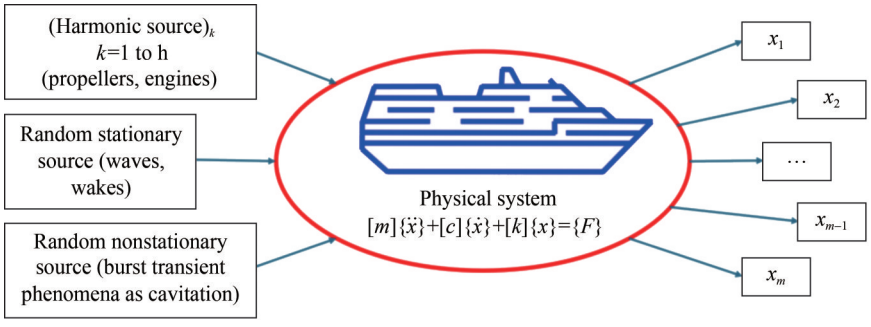


Figure 5 Identification of the main clusters of sources sharing similar characteristics in a mechanical system (vessel) from output-measurements x_i in presence of convolutive mixtures of sources

$$y(\theta) = \frac{1}{N}\sum_{j=1}^{N-1} x\left(\theta + j\Delta\theta_{\text{reference}}\right) \tag{1}$$

Where $\Delta\theta_{\text{reference}}$ is the main reference period, N is the number of sections averaged, $y(\theta)$ is then a sequence spanning one reference period of the averaged sections.

After the extraction of the periodic components from the raw vibration signals, individual sources can be easily identified through conventional spectral analysis, adopting adequate frequency resolution. This is feasible because the rotating elements of a machine can be exactly assigned to known characteristic frequencies. The application of this method typically requires the system to operate under stationary conditions for a suitably long time, ensuring the collection of sufficient data to perform an adequate number of averages to obtain reliable results.

Following the extraction of periodic components, the remaining residual content can be attributed to random stochastic phenomena. This residual, however, requires further separation to identify the various sources it gathers. A practical strategy is to first separate those source contents characterized by the highest degree of impulsiveness, because they are likely to relate to specific sources acting inside the system such as propeller cavitation and other transient phenomena of interest in operational vibration analysis of a vessel.

To achieve this, statistical techniques based on Spectral Kurtosis (SK) analysis (Antoni and Randall, 2006; Antoni, 2007; Antoni et al., 2004) may be used to highlight burst components linked to transient impulsive phenomena (Buzzoni et al., 2017).

SK is defined as the energy normalized fourth-order spectral cumulant. Its estimator can be calculated from the Short Time Fourier Transform (STFT) $|X(t,f)|$ of a signal $x(t)$ according to (2):

$$\text{SK}(f) = \frac{\left\langle |X(t,f)|^4 \right\rangle}{\left\langle |X(t,f)|^2 \right\rangle^2} - 2 \tag{2}$$

where $\langle\cdot\rangle$ means the time averaging operator. The SK allows to identify and extract by optimal filters nonstationary or non-Gaussian contents related to transient source characterized by the highest degree of impulsiveness (Antoni and Randall, 2006; Antoni, 2007; Antoni et al., 2004).

The remaining stochastic content can then be attributed to the combined effect of more "gentle" sources, i.e. to those sources commonly classified as "stationary random content".

Figure 6 shows the proposed processing procedure for evaluating source contributions at system vibrational responses (both reference points at the input of each source at the passive subsystem and target points). The scheme includes in the first stages the mixing process in the physical system (vessel). The following section describes the application of the adopted method on cruise ship vibration operational responses for source contribution analysis.

3 Application of the method on a cruise ship

The proposed technique is used for source contribution analysis of vessel vibrational responses on full scale ship data measurements collected during sea trials.

Periodic components have been extracted in measured vibration operational responses adopting a Linear Synchronous Averaging (LSA) computation. LSA calculates the arithmetic mean of all the values and include phase in the averaging process. The LSA highlights harmonic deterministic components associated with the periodic reference phenomena under consideration, such as propeller rotation or diesel engine cycles, while reducing the energy of frequency contents originating from both random processes and non-synchronous phenomena (Fyfe and Munck, 1997; Silvestri et al., 2019). LSA is an effective technique for separating harmonic source contributions within the vibrational system responses. LSA can help reduce the effects of cross-talk in OTPA by averaging out random components and enhancing synchronized harmonic sources. In this way it is possible to isolate the harmonic components of the considered source, reducing the influence of unrelated noise or non-harmonic interference.

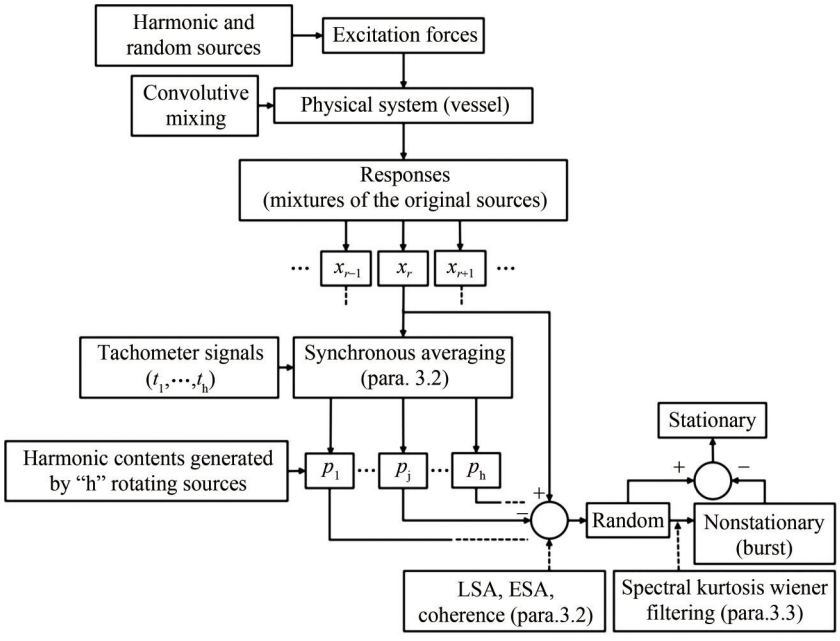


Figure 6 Diagram of the proposed signal processing procedure for evaluating source contributions in measured x_r responses

In contrast, Energy Synchronous Averaging (ESA) calculates the averages of the squared values of all values and provides overall information of the measured vibrational response, encompassing contributions from other not considered sources and non-harmonic and random contents (Fyfe and Munck, 1997; Silvestri et al., 2019). ESA does not use phase in the averaging process as squaring process removes the phase and so all contents are taken into account in the obtained result.

LSA and ESA perform synchronous averaging by focusing respectively on the amplitude and on the energy content of the signal.

A comparison between LSA and ESA allows to evaluate the amount of the random energy (stationary and transient) plus non-harmonic contents in the measured response.

This is done in the following by means coherence function evaluated starting from the LSA and ESA computatiuon. Coherence is a powerful indicator of how much the response is actually linearly related to the excitation. For two signals, $a(t)$ and $b(t)$, the coherence function γ_{ab} is described as follow in Equation 3:

$$\gamma_{ab}^2(f) = \left|G_{ab}(f)\right|^2 / G_a(f) G_a(F) \tag{3}$$

where G_a and G_b represent the spectral densities of signals $a(t)$ and $b(t)$, respectively, and G_{ab} denotes the cross spectral density. Coherence function is a real function defined within the range $0 \leqslant \gamma_{ab}(f) \leqslant 1$, higher values indicating a stronger correlation between the signals at the corresponding frequency.

With address to a synchronous average process a coherence function may be defined and estimated according to Equation 4:

$$\gamma_{ab}(f) = \frac{\left(\frac{1}{N}\sum_{j=1}^{N}\left(X_j\right)\right)^2}{\frac{1}{N}\sum_{j=1}^{N}X_j^2} = \frac{X_{LSA}}{X_{ESA}} \tag{4}$$

where X_j represents the complex spectrum j with the phase referred to the reference.

As synchronous averages are generally performed with reference to the kinematic trigger related to the reference period, considering the ratio between LSA and ESA spectra is equivalent to estimate the coherence between the quantity under examination (response vibration) and the trigger signal used for the synchronous average, which is exclusively attributable to the reference.

Both steady random phenomena and transient phenomena (such as dynamic events as cavitation) and not synchronous contents contribute to reduce the coherence value. Coherence function defined in this way may be an indicator of the amount of these contents with reference to the deterministic synchronous parts and makes possible to identify them in the frequency domain.

3.1 Ship source' characteristics

In the following, an analysis on the main vibration sources of a cruise ship is reported. Diesel generators, propellers and propulsion electric motor drives typically have the greatest power output on board a vessel, thus they are often found to be the main sources of vibration energy.

In the analyzed system, all the diesel engines can be

treated as a single source due to their interconnection through the electrical grid, which imposes synchronized coupling on the generators to which diesel engines are mechanically linked. This coupling ensures both identical operating cycle frequencies while preserving the phase relationship among all diesel engines.

Conversely, the propeller and propulsion electric motors are two sources correlated due to their direct mechanical connection via the direct drive shaft, which prevents them from being treated as two independent and therefore separable sources using a statistical approach. However, the signature analysis revealed spectral components that are well-separated in frequency. The propulsion electric motors generate a significant high-frequency harmonic content (drive switching frequencies and harmonics up to the audio frequency range: 46X and 96X), while the propeller induces energy in the response at the blade passing frequency (BPF), order 6X, which decreases significantly at higher multiples. This allows contribution separation of the two sources in the measured responses.

The non-deterministic (random) content is considered a single separable source in the measured responses. A subsequent analysis will be conducted on this content involving the computation of spectral kurtosis enabling the identification of random components with pronounced impulsive transient characteristics (e.g. cavitation phenomenon) and distinguish them from the stationary random ones.

For SA technique application, a signal phased-locked with the angular position of the propeller shaft was recorded, providing a reference angular position on shaft both for left and right propellers. The diesel engine generator's reference trigger signal was obtained mounting an accelerometer on the engine block. This signal was processed using a band-pass filter centered on the crankshaft's synchronous frequency to capture engine periodicity for subsequent synchronous analysis.

SA spectra were calculated for both propellers and engine sources on 350 signal segment extracts.

This sample size was determined to be sufficient to effectively remove all non-deterministic contents of the signal and keep periodic components. This permitted to correctly reconstruct the key original sources.

3.2 Results Periodic and random contents identification

The vibrational response signals were analyzed to identify both periodic and random components. Endurance trial is initially considered where the ship operated in a steady-state condition and is run at maximum continuous rating power for an extended period. In the specific case the duration was equal to 6 hours and the propeller rotational speed was kept fixed at 141 r/min corresponding to a 20.5 kn constant vessel speed. Results are presented in the subsequent figures where the LSA vibration angular resampled traces are shown. On the base of the adopted reference for the average process (diesel generators, propeller left and propeller right), the harmonic content was separated and plotted vs the reference angle of rotation.

Figures 7 and 8 show the LSA waveforms (each obtained on the base of the adopted reference) of the vibrational response measured on the hull shell above the right propeller and diesel generator foundations, respectively (see points propeller: 1 and diesel generator foundations: 1 in Figure 0).

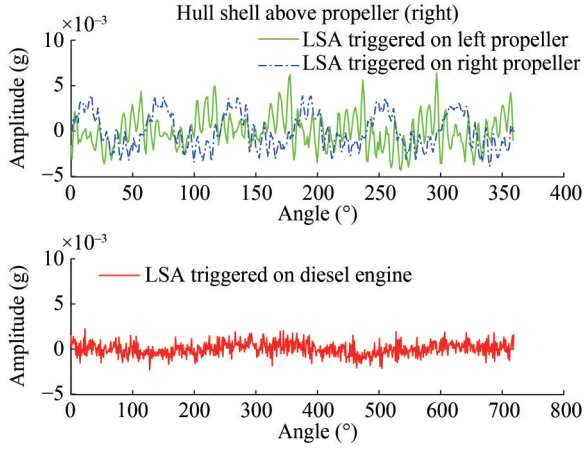


Figure 7 Hull shell immediately above a propeller–right side of the vessel-harmonic contents extracted by LSA adopting different references (diesel, left and right propellers)

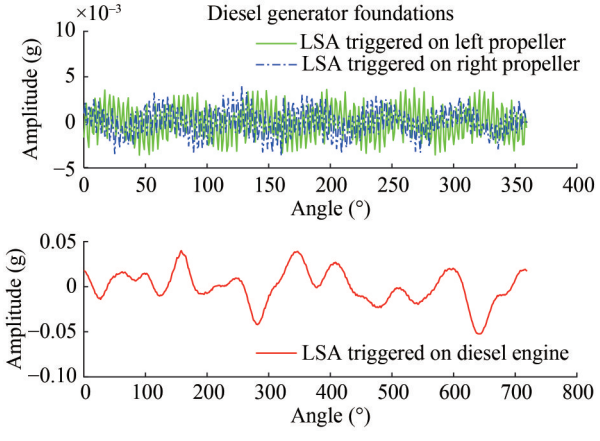


Figure 8 Diesel generator foundations–harmonic contents extracted by LSA adopting different references (diesel, left and right propellers)

In Figure 7, the synchronous average separation process, referenced to the propeller rotation (see solid green and dashdot blue traces in the upper panel) shows that most of the signal energy on the hull shell immediately above the right propeller is mainly due to periodic propeller loads, most likely related to BPF (in the traces, a 6 cycles periodicity in a 0–360° interval corresponding to a whole shaft revolution is well detectable). Higher orders harmonic con-

tent is extracted in the measured response and seems to be related to the electric propulsion engine which is directly mechanically connected to the propeller shaft and so synchronous with it.

The harmonic content from the left propeller is also evident in the response measured near the right propeller, even if it is generally lower than the analogous one induced by the right propeller. This is justified as the considered measured source response was detected on the right side of the vessel in correspondence of the right propeller. Additionally, harmonic diesel engine content is lower even if it is not negligeable (see engine reference solid red trace in the lower panel). These findings indicate cross-talk phenomena among diesel, left propeller and right propeller sources present in the measured operational raw signal may be separated by the use of the synchronous averages.

Figure 8 refers to the vibrational response measured on diesel generator foundations. As expected, the dominant contribution in the measured response originates from the diesel engines which are directly connected to the hull through resilient mounts (see engine reference solid red trace in the lower panel). The contributions from the right and left propellers are detectable, although at significantly lower levels, indicating the presence of cross-talk effects (see solid green and dashdot blue traces in the upper panel: different y-axis limits are adopted in the two panels).

The root mean square (RMS) of the LSA angular traces referring both to the diesel and left and right propellers sources are computed. The obtained RMS values, included in the following table, are representative of the energy harmonic energy content in the system response associated with each extracted source component.

Table 3 depicts the corresponding analysis for the kurtosis excess (Bendat et al., 1992), i. e. the centered fourth-order moment minus 3 (the latter being the kurtosis value of the Gaussian distribution, which is thus subtracted).

Kurtosis (excess) values were significantly negative underlining the deterministic nature of the obtained signals for all the extracted waveforms except for diesel component on the hull shell above propeller where the obtained value was slightly negative near 0, to indicate a signal pattern that approach a symmetrical Gaussian distribution. In this case it seems averaging processing is not able to extract clearly the deterministic part of the signal and this may be related considered source energy contents is not very high in the considered response point.

The following figures show LSA and ESA narrow band complex order spectra with a frequency resolution equal to 0.5 Hz computed for previous considered endurance condition at propeller speed 141 r/min. Energy averaged process doesn't take into account the phase and the obtained spectra are the same regardless of the reference adopted.

Figure 9 refers to the vibrational response measured on the hull shell immediately above the right propeller triggered on diesel engine cycle (solid red trace) and both left (green trace) and right (dotted blu trace) propeller rotation.

The results are in agreement with those obtained in the previous reported average angle domain traces analysis.

In both cases, an elevated energy content is observed in the "LSA reference propeller" complex spectrum corresponding to the propeller BPF (see green dotted cursor and 14.1 Hz). The second multiplier is not negligible. As could have been expected, the right propeller reference provided higher BPF component energy values than the left one to indicate a greater contribution of the right propeller on the considered structural response. Propeller shaft fundamental content at 2.3 Hz is detectable and also its second order. One can clearly see that only the first two BPF periodic components account for a large part of the signal energy in low frequency range.

At higher frequency values (≅130 Hz) a high shaft propeller order is detectable, which may be related to electric propulsion engine. Diesel harmonics are not marked except the fundamental one related to crank shaft rotation cycle.

The ESA spectrum reveals power continuously distributed across the whole frequency domain, indicating that the system response measured on the hull shell above a propeller includes significant random components.

Figure 10 presents the vibrational response measured on the diesel engine foundation. At the crankshaft rotational frequency, as indicated by the dashed blue cursor at 8.6 Hz a noticeable peak is evident in the "LSA diesel" complex spectrum. This peak is associated with the connecting rod assembly movement that generate synchronous forces on the system. Additionally, the half order diesel engine cycle frequency shows significant energy in the measured response at 4.3 Hz as shown in the figure. Modulation effects are also evident, involving interactions between the diesel engine cycle frequency (0.5X) and the crankshaft rotation

Table 3 RMS and kurtosis (excess) values of the average waveforms

Point	Syncr. ref. prop (left)		Syncr. ref. prop (right)		Syncr. ref diesel	
	rms (g)	kurtosis	rms (g)	kurtosis	rms (g)	kurtosis
Hull shell above propeller (right)	0.00191	−1.2172	0.00196	−1.2313	0.00075	−0.0846
Diesel generator foundations	0.00187	−1.0838	0.00159	−1.1036	0.01795	−1.5547

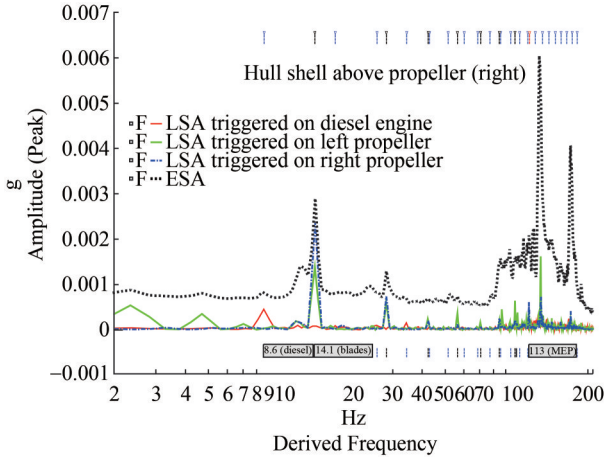


Figure 9 Average responses spectra measured on the propeller source-endurance condition-LSA computed with diesel and left and right shaft propeller references, ESA)

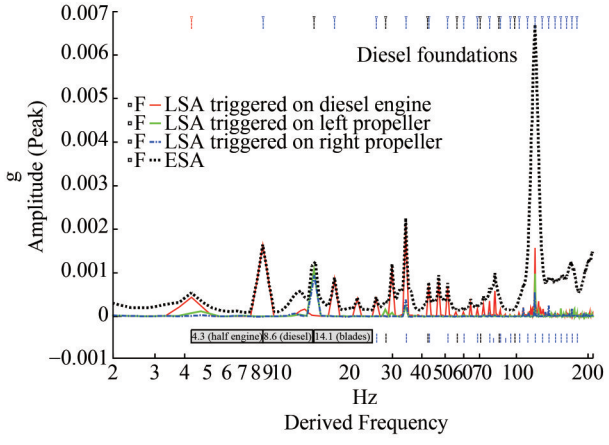


Figure 10 Average responses spectra measured on the diesel source-endurance condition-LSA computed with diesel and left and right shaft propeller references, ESA)

frequency (1X), leading to the generation of significant harmonic contents (see dotted blue harmonic cursor). Combustion cycle content at 4X (≅35 Hz) is well detectable. From reference propellers LSA spectra, only the fundamental BPF harmonic is significant and higher orders are negligeable. The dotted black line cursor is referred to the BPF content, while the short red line cursor is referred to the diesel engine cycle frequency.

The previous spectra reveal evident cross-talk phenomena as a response measured closer to one source contains not negligeable contributions from others. This effect is evident in the measured vibrational response on the propeller source (Figure 9), where energy attributable to the diesel engines appears to be non-negligible. This is inevitable due to coupling between sources, facilitated by the hull structure, which allows perturbation energy from one source to propagate to others. A cross-talk effect is also present due to the contribution of the BPF in the measured diesel foundation response (see peak at 14.1 Hz in Figure 10).

Figure 11 presents ESA and LSA complex spectra computed on the response measured respectively on the propulsion electric engine foundations.

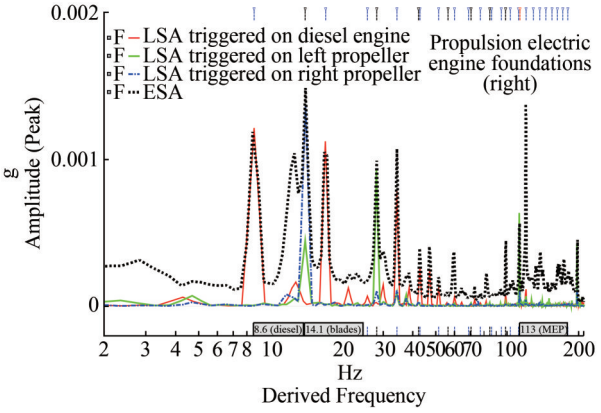


Figure 11 Average responses spectra measured on electric propulsion engine source foundations–endurance condition-LSA with diesel and left and right shaft propeller references, ESA)

LSA technique effectively separates harmonic contents associated with propulsion electric engines from the acquired mixtures. In this case, cross-talk between source contributions is also evident.

At BPF frequency content (14.1 Hz), the contribution from left and right propellers exhibit partial cancellation due to destructive interference caused by phase differences between the two sources (not mechanically coupled). As a result, the LSA value of the BPF content (see dashdot blue trace referred to right propeller) exceeds the corresponding ESA value (black dotted trace).

The following section presents the computed averaged synchronous spectra for target locations corresponding to passenger areas, aiming to identify the harmonic contributions from diesel engines, propellers, and electric propulsion engines. Additionally, the ESA spectra are included.

Figures 12 and 13 show the spectra corresponding to measurement points on the deck 3 of the vessel at two different abscissa value near the ship's stern (lowest abscissa value 4) and in a central area vertically aligned with the installation in the vessel of the diesel generator engines (abscissa value 92).

In ESA spectra (see dotted red traces), marked energy peaks are evident in the low frequency range (below 10 Hz); these contributions may be related to vessel structural vibration modes that endurance operation condition is able to excite in a marked way as reported in (Pais and Silvestri, 2024). The not synchronous origin of such spectral contents may be confirmed as they are evident only in the ESA spectrum and not in the LSA one.

The comparison between averaged response spectra in linear and energy modes allowed to evaluate how the con-

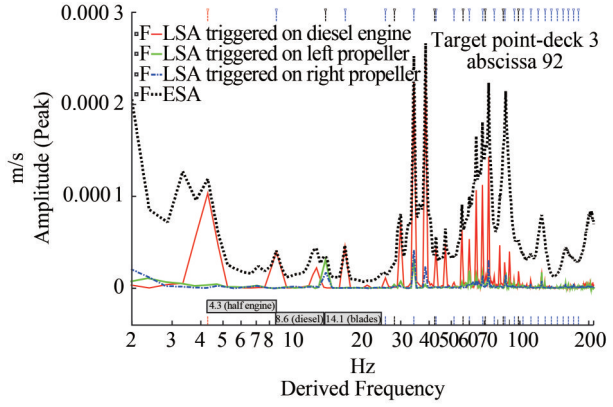


Figure 12 Average responses spectra measured on the deck 3, abscissa 92 target 1 – endurance condition-LSA with diesel and left and right shaft propeller references, ESA)

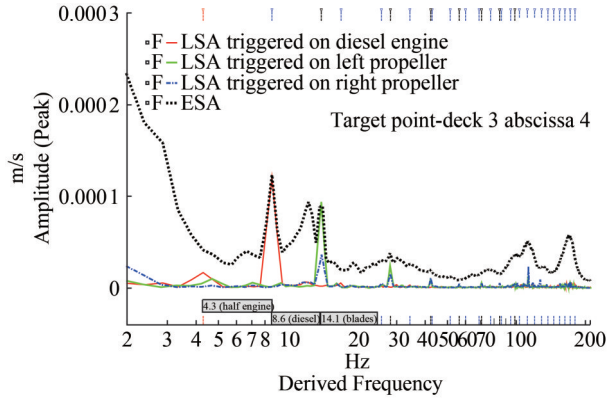


Figure 13 Average responses spectra measured on the deck 3, abscissa 4 target 2–endurance condition-LSA with diesel and left and right shaft propeller references, ESA)

sidered response is coherent with the adopted harmonic sources for averaging process, giving useful information for source contribution identification.

The vibration response measured near a source generally exhibit harmonic components produced by the source itself, characterized by high coherence values. These values indicate that the harmonic response can be attributed exclusively to the source itself.

For the diesel engine source, harmonic peaks at 1X, 2X and 4X (see short line dotted blue cursors) present the same values both in LSA and ESA spectra when evaluated on responses measured on diesel generator and electric propulsion engine foundations (see Figures 9 and 10). This indicate a high coherence of the measured previous vibration harmonic contents with the operation of the diesel engine. On the contrary, responses measured closer to the propeller source show significantly lower coherence values for the diesel engine-related harmonics.

In the case of BPF content, discrepancies between LSA and ESA and consequently lower coherence function values were found considering the propeller source response (see spectra in Figure 4). This seems to indicate increased randomness, particularly at high propeller rotational speeds where additional stochastic contributions, such as vortex, turbulent flow and in some cases cavitation, may be present generating a not correlated energy with propeller rotation.

In the higher frequency range, the coherence values related to harmonic sources contents generally decrease and this may be related to an influence increasing of a random distributed energy contribution in the measured responses.

The following figures display ESA spectrum and LSA spectra represented in third-octave bands computed for endurance condition at propeller speed 141 r/min at higher frequencies values (up to 2 048 Hz). In the third-octave band spectrum of the propeller response (Figure 14), the band containing the BPF content exhibits high energy levels when either left or right propeller references in average process is adopted. Vice versa the same third octave band is characterized by negligeable values when diesel engine is used as reference. In the foundations third octave band vibrational response spectrum (Figure 15), analogous considerations can be applied to the third octave bands containing harmonic diesel engine contents, which display high energy values. A frequency band near 200 Hz is char-

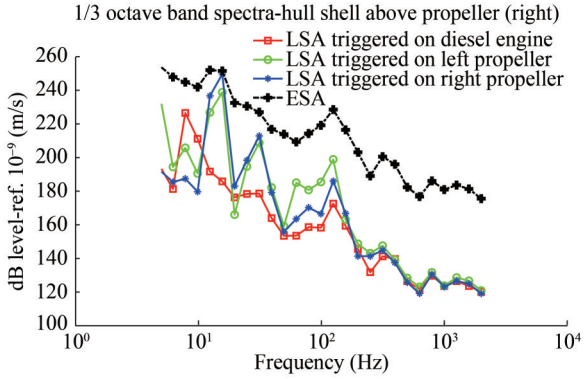


Figure 14 Operational structural response spectra for the 141 r/min condition with third-octave representation measured on the hull shell immediately above a propeller

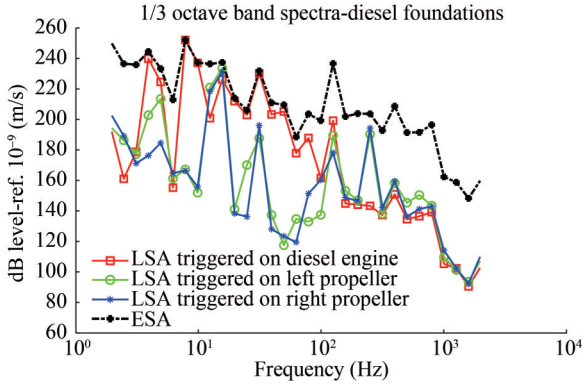


Figure 15 Operational structural response spectra for the 141 r/min condition with third-octave representation measured on the diesel generator foundations

acterized by high values only when both propellers are adopted as references. Its energy content may be related to electric propulsion engine contributions included in the LSA process referred to propellers.

In Figure 16 and 17 are reported the coherence values evaluated between the two considered vibration targets and diesel, propeller left and right sources.

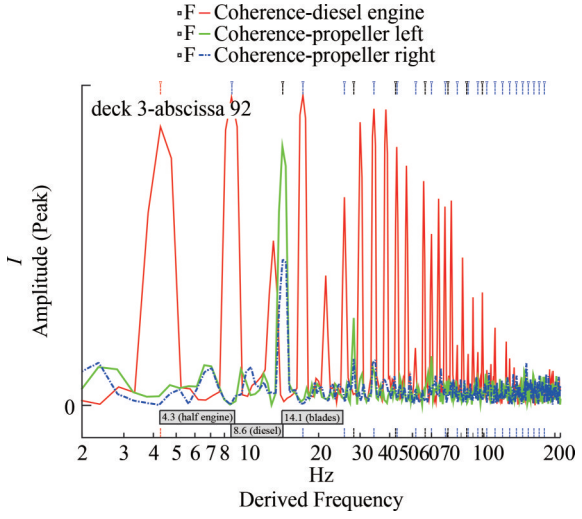


Figure 16 Coherence function between vibration target 1 and diesel, propeller left and right sources

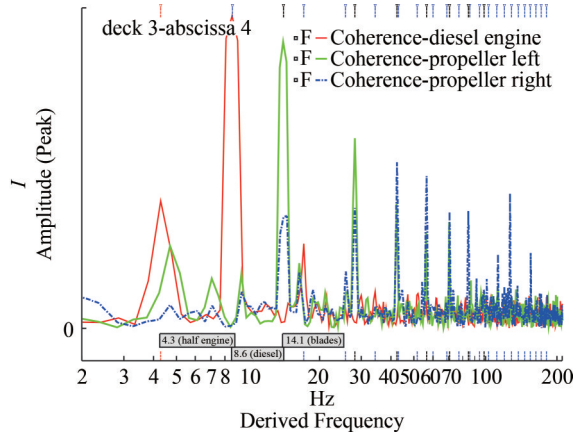


Figure 17 Coherence function between vibration target 2 and diesel, propeller left and right sources

The components exhibiting the highest coherence values are those of the diesel generator for Target 1 at abscissa 92, while for Target 2 at abscissa 4, they correspond to the propellers (both left and right), in accordance with the spatial arrangement of sources and targets on the ship.

At higher frequency, lower coherence values seem to be attributable to a lower influence of deterministic contributions and at the same time to the greater influence of random contributions in the system response, which lead to a degradation of the coherence function.

3.3 Results-highest degree of impulsiveness random contents identification

Comparison between LSA e ESA allows detecting in a measured vibrational response both not harmonic content and random one. To further deep the analysis of the source contributions it'd be significant to be able to separate the burst energy vibration content can be related to sources characterized by high impulsiveness behaviour.

Currently, various indicators, such as sparseness, kurtosis, entropy, spectral coherence and spectral kurtosis, etc (Lv et al., 2018; Zhang et al., 2019) are commonly employed to identify bursting components associated with specific sources related to transient excitation (e.g. propeller cavitation). However, no single indicator is universally effective in addressing these challenges. For example, changing the nature of burst source such as its periodicity, duration, or intensity, an indicator may reduce significantly its strength in burst component separation (Hu et al., 2018).

In mechanical vibration analysis, spectral kurtosis (SK) has proven to be an effective tool for isolating phenomena of different natures in the acquired system's forced responses (Antoni and Randall, 2006).

SK is defined as the kurtosis of the signal spectrum at a particular frequency and providing a frequency-dependent measure of the nonstationarity in a vibration signal. Its use enables the extraction of transient components from measured data (Antoni and Randall, 2006; Antoni, 2007). It is a statistical tool based on the moment of order 4 can be used to assess the degree of signal deviation from normal distribution. When a signal exhibits significant transient content and impulsive characteristics, the SK value becomes notably high.

The SK is applied locally in different frequency bands to generate the kurtogram, a two-dimensional map that identifies regions where kurtosis is maximized. This approach enables the analysis of the entire frequency domain and highlights those frequency ranges where the burst components are mostly present (Antoni and Randall, 2006; Antoni, 2007).

He et al. (He et al., 2016) utilized spectral kurtosis for the detection of multiple bearing faults, while it has also been applied to identify tooth cracks in gears (Antoni and Randall, 2006). Additionally, McDonald et al. introduced the concept of maximum correlated kurtosis deconvolution for machinery condition monitoring (McDonald et al., 2012).

In the naval field, the spectral kurtosis technique can be employed to detect sources such as propeller cavitation, which generate higher levels of impulsive responses and contribute to increased nonstationary and non-Gaussian behavior in the system (Silvestri et al., 2024b).

Once the deterministic harmonic components such as diesel generator engines and propellers have been identified and removed, the most impactive transient part is

effectively extracted and so available for further analysis aimed to identify additional sources acting on the system e. g. propeller cavitation phenomenon and other burst anomalous sources generating impulse-like contents.

The proposed separation method based on SK for burst content extraction has been applied to a ship operation condition when propeller cavitation happens and results are reported hereafter.

Signal response extract refers to the phase when the propellers go on astern revolutions during a crash stop maneuvering leading to a marked cavitation condition.

Under these conditions, the tip vortex cavitation happens generated by bubbles produced at the end of the propeller blade tip. The blade load distributions exhibit anomalous impulsive phenomena and random fluctuations with periodically modulated broadbands energy by the propeller rotation and blade passage (Silvestri et al., 2023; Han et al., 2018; Maines and Arndt, 1997).

Figure 18 illustrates the computation of the Fast-Kurtogram using Antoni's algorithm (Antoni and Randall, 2006; Antoni, 2007), evaluated on the vibration response measured on the hull shell immediately above a propeller. SK proves effective for detecting and isolating transient burst phenomenon contents in the propeller measured forced vibrational response.

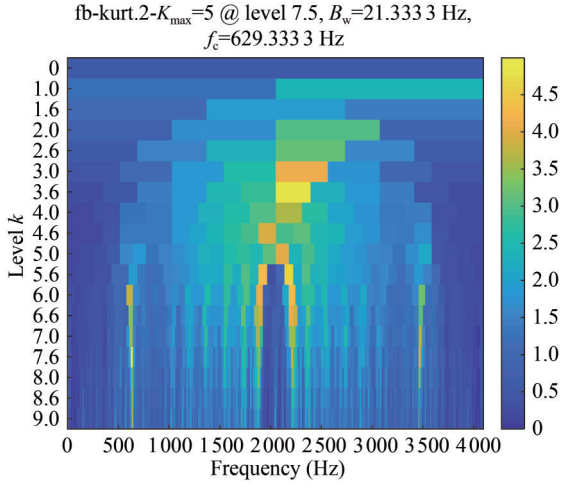


Figure 18 Fast-kurtogram for the vibration signal measured on the hull shell immediately above a propeller in the astern revolutions phase of a crash stop maneuvering

Analysis of the SK colormap enables the identification of frequency bands characterized by abnormally high values, indicating the potential presence of impulsive random contributions in the system's response. The kurtogram highlights the main maxima at a central frequencies 629 Hz, 1 881 Hz and 2 022 at the levels 7.5 for the first frequency (bandwidth of 24 Hz) and 6 (bandwidth of 64 Hz) for the last two ones. By means of the kurtogram, it is possible to define frequencies bands with highest signal-to-noise ratio, optimal for deconvolving the sequence of impulses in the signal.

The previous frequencies with the highest spectral kurtosis may correspond to the natural frequencies of the cavitation vortex cavities oscillation modes (Silvestri et al., 2023).

In this way it is possible to extract a component from the acquired signal characterized by high level of impulsiveness and so separate the contribution in the forced system response related to burst sources. An optimal bandpass filter can then be adopted on the raw signal that uses the information coming from the SK to maintain the high kurtosis contents related to the burst source.

In Figure 19 the blue and red traces represent respectively the raw and the residual vibration propeller signal obtained with the SK based filtering process for the considered astern revolutions operating condition. Residual vibration signal highlights the impulsive contents may be associated to the cavitation phenomenon source. The impulses are extracted with a rate of repetition related to propeller shaft rotation generating a modulation phenomenon.

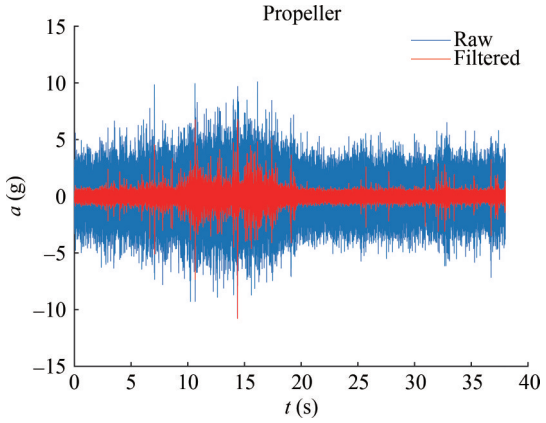


Figure 19 Raw and filtered signal based on SK computation

This can be highlighted by envelope spectrum analysis conducted on the filtered residual signal which allows to identify the presence of modulation phenomena and better define characteristics of the burst extracted contents (Silvestri et al., 2024b).

In the specific case it is possible to detect the presence of not a single transient response, but a pattern of the series of transient responses. This enables to better describe the impulsive nature of identified burst source contribution to system vibrational response and its repeating impact-like characteristic.

Figure 20 shows the squared envelope spectra where it is well detectable a low-frequency content related to propeller rotation (see cursor at 9.6 Hz), implying the vortex cavities are sufficiently developed in the whole propeller. This means when cavitation occurs, the excitation of the cavities modulates synchronously to the propeller shaft rate. This method allowed to put in evidence also the presence of a modulation behaviour in the system's dynamic

responses generated by two coupled sources (cavitation and propeller shaft rotation).

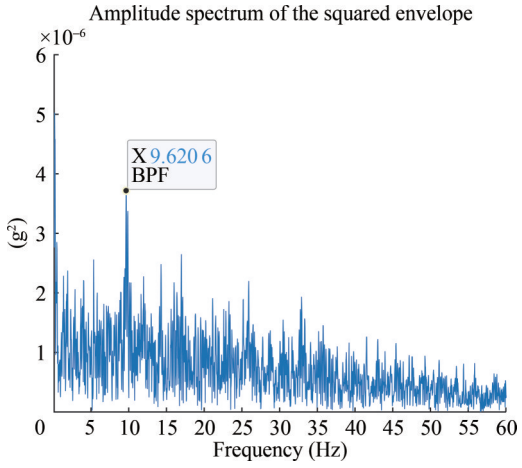


Figure 20 Magnitude of the squared envelope spectrum analysis for the optimally filtered signals from SK analysis

The proposed methodology, which enables the separation of high-energy burst content from raw acquired signals, is considered potentially applicable as a data pre-processing tool for condition monitoring systems (also including real time applications). Its use could enhance diagnostic performance by reducing noise and minimizing the influence of contributions from other sources in the diagnostic inputs.

3.4 Ship vibration insulation properties experimental identification

Following the separation of source contributions from the originally acquired raw signal, the information on how vibration propagates were determined using a response-response method. This approach uses the transmission analysis to assess how components of operational vibration signals are changed as they go through the ship hull from sources to the receiver through the transmission paths. The vibrational structural insulation properties of the ship is quantified by means of the experimental assessment of the path insertion loss function which quantifies the energy content from a source transmitted to a receiving target (Silvestri et al., 2024a).

The proposed approach relies on operational measurements and deterministic identification of harmonic components related to specific deterministic sources (e.g. rotating sources such as propellers and diesel engines) through the average synchronous technique. It enables the evaluation of how a principal harmonic component associated with a specific source is modified and attenuated as its vibration energy propagates along structural paths to the receiving target.

This methodology effectively split a MIMO system into an equivalent set of single-input multiple-output (SIMO) systems. Each SIMO system corresponds to an identified source and transmission path between the source reference response point and the signal measured at target points making possible the definition of transmissibility functions (Silvestri et al., 2024a).

This method employs operational system responses and exploits synchronous averaging techniques to separate harmonic contributions at both the source and receiving targets avoiding cross talk phenomena and enabling the correct assessment of vibrational energy transmission strictly related to the considered source through the structure. The D_{harmonic} vibration insulation descriptor is adopted which is an indicator of vibration transmission loss evaluated on the transmission of source harmonic contents passing through structural paths to the receiving target.

For each principal harmonic component associated with a source, operational spectra are determined at both the source and the receiving points. These spectra typically exhibit numerous peaks corresponding to the specific harmonic components generated by the considered source. The descriptor D_{harmonic} is then calculated as the difference in the power levels of the source's harmonic components between the source and the receiving targets representing a path insertion loss related to structural vibration energy. In the application reported hereafter diesel generator engine, electric propulsion engine and propeller sources have been taken into account.

Harmonic frequency content values related to the considered source are used as x-coordinates in the descriptor curve representation. Due to the discrete characteristics of descriptor due to the discrete nature of propeller and engine harmonic contents, a method is proposed to generalize their applicability across the entire frequency range of interest. This approach assumes that harmonic frequencies contents can shift in frequency and move along the envelope of source and receiving target spectra, i. e. along the curve that links, point-by-point, source harmonic peaks.

In the considered application case of a ship this is possible due to the complex dynamic structural characteristics of the system under consideration with significant modal overlap and high vibration modal density. In this way the energy differences are computed at frequency contents where the energy vibrational responses are significant, and the signal-to-noise ratio is high. The chosen descriptor can be extended across the entire frequency spectrum through linear interpolation, enabling representation in third-octave bands as well.

Given the potential non-uniform spatial distribution of vibration levels, it is essential to identify a representative measurement location for both the source and target responses that accurately reflects the forced response induced by the source. For evaluating the source response, an effective empirical strategy to minimize the influence of the dynamic behavior of source structures and foundations is to position the accelerometer as close as possible to the

excitation. Adopting this approach, the structure cannot influence the dynamic response in a significant manner and the measured vibrations more accurately represent the source behavior.

Also for target response measurement it is important to take into account the crucial role of the accelerometer positioning. In cases where this is challenging, it could be necessary eventually to take into account additional and redundant response points and to compute an average value to ensure reliable data.

Figures 21 and 22 show the principal component FFT spectra for the source, associated with the propeller and electric propulsion engine (two mechanically correlated sources treated as a single source, see section 4.1) and target (deck 3, abscissa 92 in Figure 1) and the corresponding envelopes evaluated on sources harmonic contents at the previous considered steady-state operating endurance condition featuring a constant propeller rotation speed of 141 r/min.

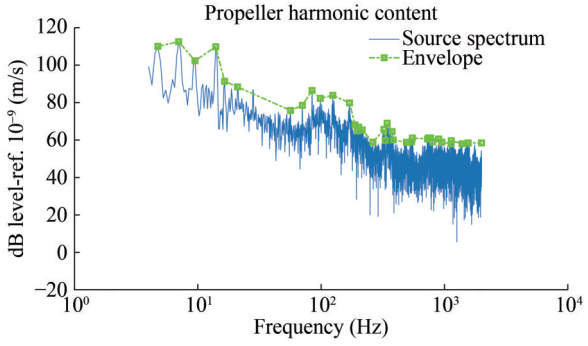


Figure 21 Propeller source principal component spectrum and envelope

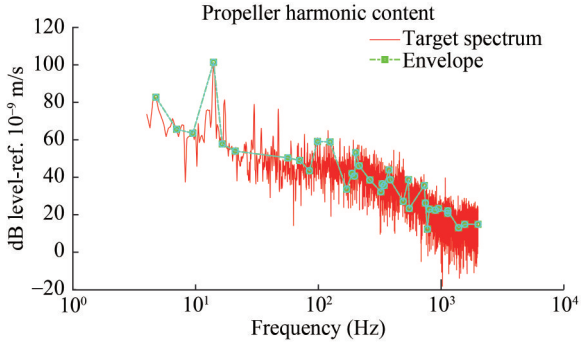


Figure 22 Target 1 (deck 3 abscissa 92) principal component spectrum and envelope

By calculating the differences between corresponding harmonic vibration levels, a representation of harmonic vibration insulation D_{harmonic} is achieved as shown in Figure 23 (blue trace). This index is specific to the source harmonic frequencies and provides a measure of the vibration transmission loss of a single harmonic content through the structure from the considered source (propeller in low frequency range and electric propulsion engine at higher frequencies values) to the receiving target.

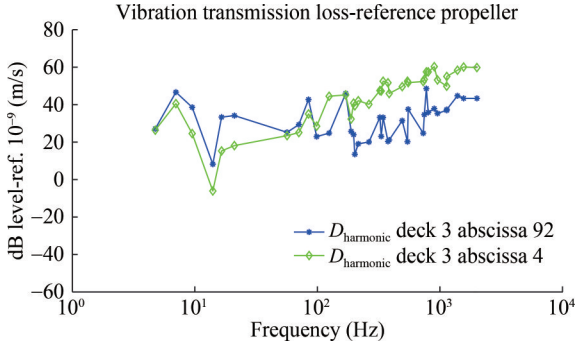


Figure 23 Source and target principal component envelopes differences representing the harmonic vibration insulation descriptor extended to the whole low frequency range-source propeller

The resulting curve characterizes the structural vibration insulation of the investigated unit in a frequency range determined by the minimum and maximum frequency harmonic component significantly excited by the investigated source. The isolation curve can thus be defined over a sufficiently appropriate frequency range, where the source energy is significant and an assessment of the system's dynamic isolation performance has to be adequately explored.

D_{harmonic} curve in Figure 23 indicates the path insertion loss i.e. the source energy content modification passing to the receiving target (deck 3 abscissa 92) from propeller and propulsion engine sources.

High descriptor values in high frequency ranges underline how the presence of viscoelastic materials coupled with the deck steel structures generating good level of isolation at these frequency values.

The application of the method allows to obtain insulation curves may be obtained for other structural paths related to the same source and referred to different receiver points or other harmonic sources acting in the system. On the same graph is reported the same indicator computed between the same source (propeller) and the target 2 on the deck 3 at abscissa 4 (green trace).

A better isolation in the vibration energy transmission path at higher frequencies can be observed for target 2 at ordinate 4 of deck 3. This could be attributed to a more complete outfitting of the ship at target 2, where passive vibration isolation materials were properly applied differently from target 1.

Figure 24 shows the D_{harmonic} evaluated in the case of the previous two targets measured at the deck 3 with reference to diesel generator source.

The presented curves are representative of a structural characteristic of the analyzed unit related to the vibration insulation. They indicate the path insertion loss i. e. the source energy content modification propagating to the receiving targets (deck 3 at abscissa 92 and 4) for both pro-

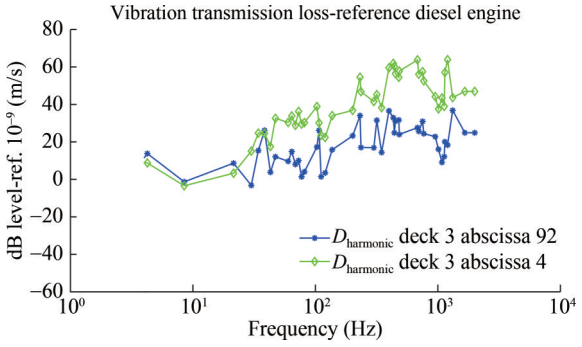


Figure 24 Source and target principal component envelopes differences representing the harmonic vibration insulation descriptor extended to the whole low frequency range-source diesel

peller and diesel engine sources.

These curves will allow to predict the operational responses at the target points for an operation condition of the ship starting from the source measurements response content (harmonic, stationary random or burst).

To validate the proposed method, an experimental verification was conducted to assess whether the path insertion loss values based on the propagation characteristics of harmonic components are almost invariant and are not strongly dependent on the specific vessel operational conditions considered.

Figure 25 shows a comparison of one of the previous D_{harmonic} descriptor (reference propeller, target deck 3 abscissa 92) evaluated using experimental data collected at two propeller rotational speeds: the previous one at 141 r/min and a reduced speed of 96 r/min (corresponding to a 16 kn constant vessel speed).

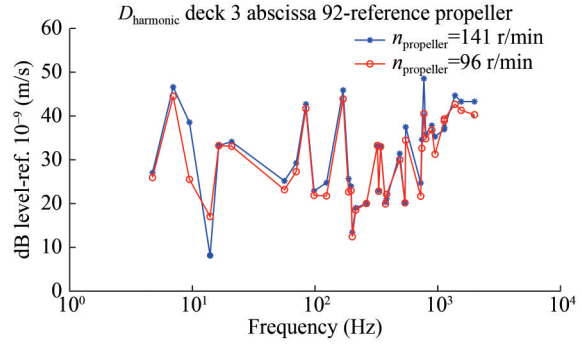


Figure 25 Comparison between harmonic vibration insulation descriptors computed at two different operational speed of the ship (reference propeller)

Similar D_{harmonic} values are obtained in the two cases to indicate its computation not strictly related to the specific considered operational data and this appears to support the generalization and validation of the proposed methodology. Results obtained at lower rotational speed results indicate slightly lower insulation values.

Figure 26 shows the previous descriptor evaluated with reference to the diesel engine, estimated on the two previously considered experimental datasets at two propeller rotational speeds. A significant correlation appears to be observed in this case as well. Possible discrepancies may be attributed to the effects of nonlinearities within the system.

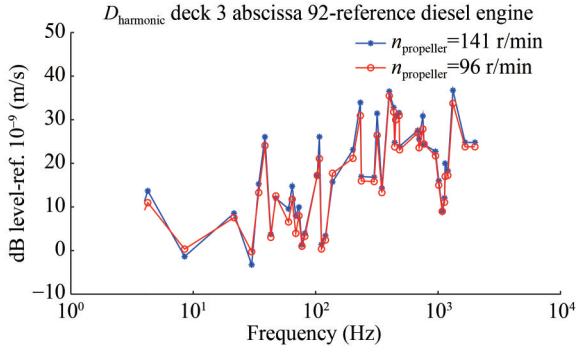


Figure 26 Comparison between harmonic vibration insulation descriptors computed at two different operational speed of the ship (reference diesel engine)

The experimental definition of this property provides valuable information to improve comfort onboard ship and reduce underwater radiated noise by evaluating improvements by acting on the most critical propagation paths of vibration energy.

4 Conclusions

The presented activity aims to define a systematic framework for identifying and evaluating the transfer paths of structure-borne vibrational energy from excitation sources to specific receiver locations in a ship during operation. The method quantifies the various sources contribution and their paths throughout the transmissibility concept.

A screening on two main vibration separation techniques is reported, highlighting their applicability, constraints, and limitations in naval contexts. The method delivers quantitative results by separating in a vibrational response signal the contributions of periodic, random stationary, and random nonstationary sources. While not without limitations, this separation approach has demonstrated significant practical value in relevant naval case studies (Antoni, 2005).

The proposed method has been applied to separate and identify the vibration source signals from the mixed signals on the hull of a cruise ship to evaluate its feasibility and effectiveness.

It was possible to identify subsets of components strictly associated with periodic kinematic sources such as propellers and diesel generator engines, stochastic contents as vortex and impact waves forces and in some operations impulsive random part due to burst source phenomena (e.g. propeller cavitations).

LSA were performed on synchronously resampled angle domain signal and complex operational spectra providing insights into deterministic components. By comparing the spectra obtained from ESA and LSA spectra, the energy contributions from random and non-synchronous sources were quantified. Deconvolution method based on SK was applied in a ship propeller cavitation condition and permitted extracting burst response components by means of a band pass filter that uses a prior SK knowledge.

The concepts of transmissibility analysis linked to path transfer ratio/insertion loss functions were utilized to quantitatively assess the path contributions from source to the receiver vibration responses within the frequency domain. A harmonic-based methodology for assessing vibration insulation properties in ships, relying exclusively on operational response measurements, has been developed and implemented. A specific descriptor is evaluated (D_{harmonic}) derived from the harmonic operational principal component contributions of the sources and employed to quantify the transmission loss to the receiving targets through the vessel.

This approach improves the analysis of vibration transmission characteristics within the ship hull, supporting the implementation of control strategies to mitigate vibration sources and minimize radiated noise and vibration.

An experimental verification of the method has been done and similar path insertion loss values obtained in different cases seems to indicate computation not strictly related to the specific operational data validating the proposed approach.

It is important to highlight that the proposed method relies on accurate phase alignment among all acquired signals (vibration and trigger) and this implies the use of a single high sampling frequency data acquisition system collecting all channels (or multiple systems sharing a common clock, as in this case). This often requires extensive cabling, especially in large or complex vessels. Implementing such a setup on large structures like cruise ships can be challenging, potentially limiting the method's practical applicability.

However, this method offers comprehensive insights into vibrational behavior, enabling expedited troubleshooting, improved product optimization, and a systematic framework for vibro-acoustic design.

Nevertheless, a limitation of the proposed separation technique is its resolution into only three component subsets, which may necessitate additional methods to further identify independent contributions.

Competing interests The authors have no competing interests to declare that are relevant to the content of this article.

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