Application of transfer path analysis technique to cruise ships

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Abstract. The transfer path analysis (TPA) method is considered to be an important and effective tool for identifying vibration and noise (VN) sources and main transfer paths. This technique is commonly developed and well-established in the automotive field. In contrast it has not been applied to in naval architecture yet, accounting for the complexity of the path, the higher number of the receivers' locations and the many sources on board (e.g. engine, propeller, generator, pumps…). In this paper, the Polytechnic School of the University of Genoa, together with Cetena, presents a preliminary approach for applying the TPA technique in the marine field to a cruise ship. After a comprehensive review of the method, the results of the TPA application are presented by analysing the measurements taken during a sea trial.

Keywords. cruise ship, sea trial, source contributions, transfer path analysis, vibration.

1. Introduction

Aspects related to a ship's vibrational behavior are significant both in terms of structures' possible fatigue failure and in terms of the safety, health and comfort of the people aboard. Undesirable vibrations and vibroacoustic noise level onboard can also be affect to the solution adopted for contain the hull weight, which leads to the design of increasingly lighter and inevitably less-rigid structures, which therefore are more prone to. The noise and vibration reduction in ships is often achieved using viscoelastic materials coupled with the main steel structure through various mechanical principles [1]. However, it is mandatory correctly identify vibration sources in order to improve their isolation acting on their interface with the hull and related energy transfer paths.

Normally vibration and structural borne-noise problems come from a source usually located in the lower part of the vessel. This source transfers energy via one or more transfer paths to the upper decks where the passenger areas are located. In structural paths, the energy is mechanically transferred from the source to the structure and propagated towards the receiver as vibrational energy. With the method based on Transfer Path Analysis (TPA) is possible to identify and evaluate the structural energy transfer paths from the various sources of excitation in an assembly to a given target location [2].

The TPA is test-based procedure widely used in the automotive noise, vibration, and harshness (NVH) industry. Many researchers from the 90s up to now have worked on it to find the root cause of a noise and vibration problem in a vehicle [3, 4, 5, 6, 7].

It is an experimental method which allows the identification of the preferential paths for the individual sources contributing to a level of vibrational response at a receiving point. In this way, it is possible to identify the most significant energy transmission paths on which it may be most appropriate to act to reduce the vibrational response [8].

Tang et al. [9] analyzed the transfer paths from the engine and suspension points to the cabin of an electric vehicle with the TPA method. Shin et al. [10] used the in-situ blocked force transfer path analysis to identify the structure-borne path of rumbling noise in the vehicle cabin. Ye et al. [11] analyzed the steering wheel vibration from different transfer paths employing the TPA method to reduce the low-frequency vibration of the steering wheel. If the TPA is an established method in automotive field, in the naval field it is not an usual application due to the complexity of the ship system.

The aim of this paper is investigated if the experimental TPA technique could be useful to evaluate the vibration propagation phenomena in a cruise ship. Not acoustic, but only structural sources and targets are considered in this preliminary activity and so hereafter only vibrational system behavior is considered and analyzed. The goal is to verify if this method can provide designers with useful information to solve vibration problems by identifying most critical area. This would be a huge step forward compared to traditional testing methods, which do not have as systematic approach as TPA and may not lead to an optimal solution.

2. The case study

The TPA application in the naval field is substantially innovative, therefore a mid-sized cruise ship is analyzed inthis study. By limiting the size and massive characteristics of the system, it is easier to generate excitations suitablefor measuring FRFs representative of the vibration energy path from source to receiver. The principal characteristics of the case study are shown in Table 1.

Table 1. Vessel Principal Characteristics of the case study

Principal Characteristics	
Displacement	40855 grt
Length between perpendiculars	181 m
Beam moulded	27 m
Design draught	6.5 m
Nominal propeller revolution speed	152 rpm
Service speed	17 Kn
Passenger cabins	298
Max persons on board	1040

The selected cruise ship is characterized by a transmission shaft for the connection between the propulsion electric engine and the propeller. The application of the TPA technique can highlight as the shaft line and the relative constraints are responsible for the vibratory response of the ship.

3. TPA model

The TPA technique is based on a source-path-receiver model to study the dynamic behavior of the system under analysis. The “framework” of the model consists of the list of selected targets, paths, indicators (the location for which the measured response is used to calculate the load at a path) and the operational data cases. A path is defined through an experimental FRF, that is a system characteristic, and represents the response at target t for a unit load at path p, if all other loads are 0. For this approach to be valid, all ‘source’ locations (paths) should be considered. If some paths are not taken into account, that the calculated contribution will differ from the total measured contribution.

Sources are defined as system excitation. Receivers or targets are the quantity to be determined, analyzed and generally reduced, such as a vibration level at a well-defined structural point. Energy transfer paths are all interconnecting paths between sources and receivers.

An experimental activity articulated in two test sections is required to evaluate the vibro-acoustic energy flow from the sources towards receivers. The first test section must be performed through dockside measurements aimed to identify the system in terms of frequency response function (FRF) between all paths and between active and passive side of the sources.

Then an experimental section during sea trials is needed to measure operational vibrational system response in correspondence of sources and receivers. The vibrational energy flow analysis from on-board sources to receiver locations is then obtained by defining a TPA model and processing the acquired data. TPA results can provide diagnostic information on the vibration system behavior by identifying the main transfer path contribute to specific vibrational and noise issues. Modifying the components on the main transfer path allows the vibration and radiated noise to be controlled within the expected target value. This will allow to find an optimized design solution for making the transmission of noise and vibration better.

Dockside measurements are performed with artificial excitation systems (shakers equipped with load cells and/or instrumented hammers) in order to evaluate FRFs for both reconstructing operational loads from vibrational response measurements and identifying the structural paths of the ship’s vibrational energy.

Once the loads generated by the sources are evaluated in their interface points with the vessel, paths are used to relate the force generated by the sources to the vibration level at the target

In this case operational forces applied to the system are evaluated adopting inverse force identification method. According this approach, loads are calculated from the knowledge of the system's operational responses and the characteristics of the structure under consideration, i.e. the FRF. Calculation involves solving a system such as the one below.

Tij is FRF measured between the response (e.g. acceleration) at location i and load (e.g. force) applied at transfer path j. Xj is the vector of operational data (e.g. acceleration) at the passive side (indicators) and Fi the loads (structural, e.g. forces). The matrix is then inverted and combined with operational measurements at the indicators, in order to obtain load estimates. In order to avoid numerical problems in the matrix inversion, singular value decomposition methods are used. The number of indicators should at least be equal to the number of loads to be estimated, in order to have a unique solution for the operational forces. Taking more indicator measurements at the target side, allows you to over-determine the set of equations. This allows you to obtain a more accurate least square estimate results, for the operational forces.

$$\begin{Bmatrix} y_1(f) \\ \vdots \\ y_n(f) \end{Bmatrix} = \begin{bmatrix} T_{11}(f) & \cdots & T_{1m}(f) \\ \vdots & \ddots & \vdots \\ T_{n1}(f) & \cdots & T_{nm}(f) \end{bmatrix} \begin{Bmatrix} x_1(f) \\ \vdots \\ x_m(f) \end{Bmatrix} \tag{1}$$

$$\begin{Bmatrix} x_1(f) \\ \vdots \\ x_m(f) \end{Bmatrix} = \begin{bmatrix} T_{11}(f) & \cdots & T_{1m}(f) \\ \vdots & \ddots & \vdots \\ T_{n1}(f) & \cdots & T_{nm}(f) \end{bmatrix}^{-1} \begin{Bmatrix} y_1(f) \\ \vdots \\ y_n(f) \end{Bmatrix} \tag{2}$$

The TPA is a relatively complex analysis technique. This aspect may become more critical in naval applications where the measurement aspects may not be simple due to the problems inherent in field measurements and the non-negligible size, massive characteristics and relevant inertia of the system to be investigated. For this reason, in this pioneering study (to date there are very few cases where the TPA technique has been applied in the naval field), where the objective is to verify the applicability and usefulness of this technique in the naval field, it has been decided to introduce appropriate simplifications so that the results obtained will always be significant. In particular, the behavior of the measured diesel engine (the right rear) was considered representative of all four engines on the vessel. Similarly, propeller and bearing measurements on the right-hand shaft line for the same components on the left were assumed to be representative. Furthermore, dynamic (and geometric) mirroring by the system under investigation was assumed when defining the FRFs of the paths for the vibration energy propagation. The sources considered in the present activity are:

- 4 diesel engines (each with a nominal rotational speed of 600 rpm);
- 2 propellers (right and left both equipped with 5 blades);
- 2 shaft line journal bearings (right and left).

4. System identification

Structural FRF experimental measurement are obtained from impact tests through instrumented hammer with a mass of 20 kg reported in Figure 1.

The exchanged impact load with the structure is assessed by measuring the instant variation in system translational momentum in correspondence of the impact. For this purpose, a specific accelerometer suitable for measuring shock phenomena was used. The adopted hammer is able to excite the structure with impulse forces with a maximum value of $2\cdot10^6$ N pk.

Figure 1. Impact hammer with inertial force estimation by shock accelerometer.

A viscoelastic rubber mat interposed between hammer and the structure is used to control impact surfaces and thus the excitation frequency content. It is placed on the excitation point and allows to modify the equivalent system stiffness where the force is applied. In this way it is possible properly to define the frequency range where the structure under examination is best excited and so it can be better identified. Low contact stiffness allows to concentrate impact energy in the range of lower frequencies. This improves the identification accuracy and definition of FRFs in this frequency range. On the other hand, if the high frequency range must be explored, it is necessary to maximize the stiffness of impact surfaces and so in this case no rubber is used in order to obtain a steel-steel contact force.

Figure 2 shows a comparison in terms of impact force AutoPower spectrum between ship deck with and without the viscoelastic rubber. In the absence of the viscoelastic material (green curve), under the highest stiffness condition, the hammer energy is significant up to high frequency values, showing that impact applied on the deck is suitable for characterizing the ship dynamics up to 10 kHz.

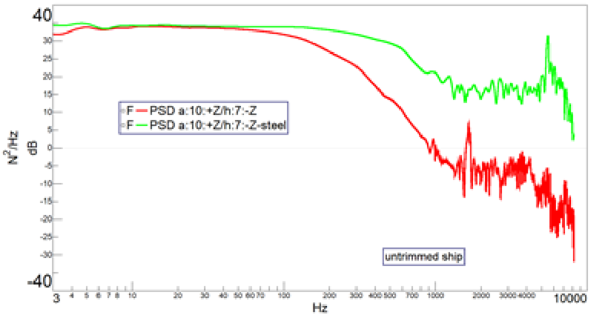

Figure 2. Impact force AutoPower spectrum comparison when impact on the viscoelastic rubber and directly on the deck (metal-to-metal contact).

For FRF measurement, the response was measured using accelerometers with appropriate high sensitivity.

The defined indicators, representing the coupling interface between the sources (active side) and the structure of the ship (passive side) were considered. In the dockside tests, the force generated by the artificial source (shaker or instrumented hammer) is applied to these points and the correspondent vibration generated by the aforementioned excitation is measured both on the indicators and on the receiver points.

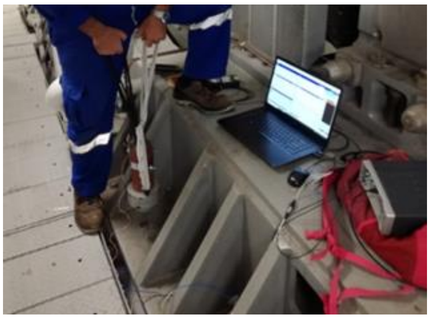

Figure 3. Application of artificial excitation generated by the inertial hammer on the diesel engine.

For diesel engine sources, indicators at the installation points on the ship's foundations are used to define FRFs. In the case of propellers, the related FRFs are defined with indicator points at the stern vault, while for shaft line journal bearings are considered to be the indicator points. The following Figure 4 shows the results in terms of time history of impact measurements conducted with excitation on the engine block and responses in decks 3 and 4. The accelerometer time history traces show that the adopted artificial excitation system used is capable of generating a measurable related response.

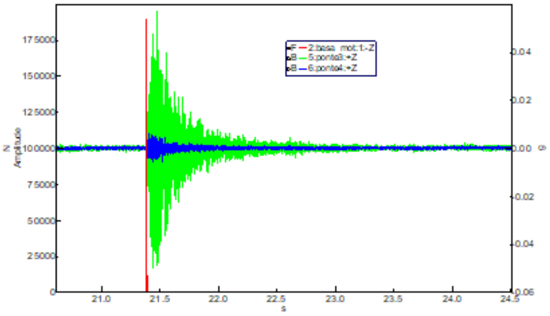

Figure 4. Acceleration time history response measured in decks 3 (green trace) and 4 (blue trace) obtained with an excitation applied on the motor baseplate on ship foundations (red trace).

The computation of the two FRFs and their comparison provide information on the attenuation characteristics of the ship's vibrational energy at the two response points (Figure 5).

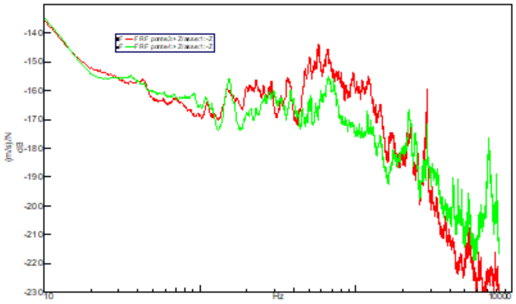

Figure 5. FRFs with excitation applied on the diesel engine motor baseplate and responses on decks 3 (red trace) and 4 (green trace).

5. TPA Results

The results are reported below for different ship operating conditions and for different receivers.

5.1. *Target deck 3 and frame 32*

The Target 3 frame 32, which is closest to the sources, was considered. In this case, the application of the method seems more robust as sources and receivers are closer enough and the adopted exitaion system is able to excite the system correctly providing well defined FRF. This is confirmed by the good levels of the coherence function in the frequency range of interest as shown in Figure 6.

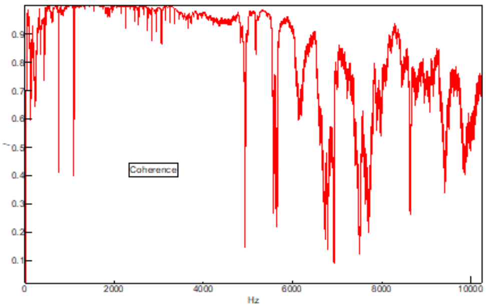

Figure 6. Coherence between target 3 deck and engine mount.

The measurement was carried out with an accelerometer placed directly on the ship's structure as there are no layers of insulation and no interface flange between the sensor and the deck to be measured as shown in Figure 7. Two operating conditions characterised by two different rotation speeds of the shaft line were considered.

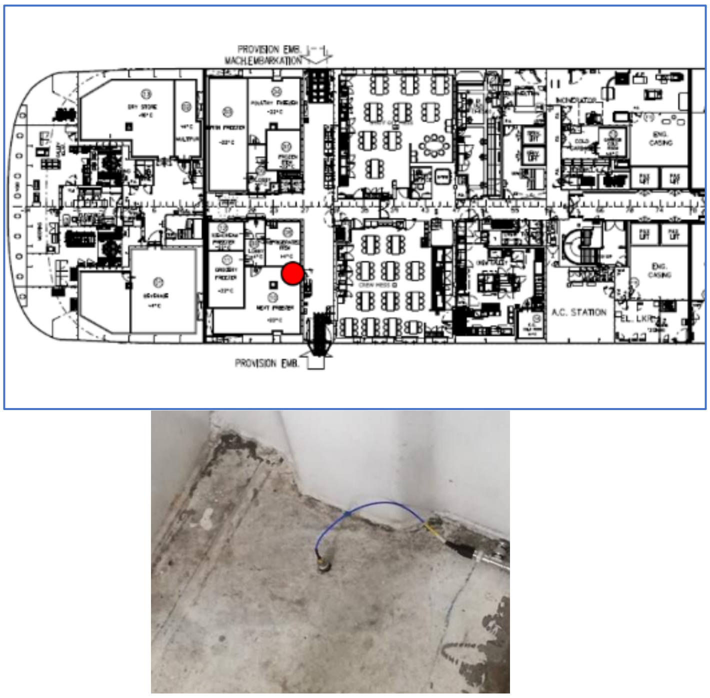

Figure 7. Target deck 3 and the accelerometer adopted for the measurement.

5.1.1. *n = 151 RPM*

The operating rotational frequency of the diesel engines is set to 10 Hz while the propeller blade frequency is 12.6 Hz. In the considered operating condition, it can be seen that the vibrational energy generated by diesel engines is comparable to that of propellers. This seems to be due to the position of the target near both the sources and the high rotation speed of the propeller (maximum operating speed). In this condition propeller sources seem to contribute substantially to the overall value of the measured vibration at the target. Analysing the frequency content of the individual contributions of each source, significant energy may be found at frequencies close to 3 kHz that can be attributed to the propellers. The shaft lines do not seem to contribute significantly to the target. Reconstruction of the target appears sufficiently correlated with the measured value and this seem to validate the obtained results. The TPA appears to underestimate the vibrational value at the target. This could be due to a limitation in the accuracy of the measured experimental FRFs due to the critical aspects discussed previously related to the complexity of the ship system. Comparing the results in terms of the vibration frequency measured and reconstructed, some discrepancies (clearly visible on the logarithmic scale of the colour bar in Figure 8) are evident in the high frequency range. These may be due to approximations and limitations in the accuracy of FRF identification and operational measures. However, the correlation appears acceptable indicating the significance of the performed TPA analysis.

Figure 8 and the next figure 10 show values in term of acceleration in g in the frequency spectrum. The first line reports the global measured value, the second line reports the total value calculated by TPA, the other line report value calculated by TPA in order for motors engine (lines 3-4-5-6), two propeller (lines 7-8) and two shafts (lines 9-10).

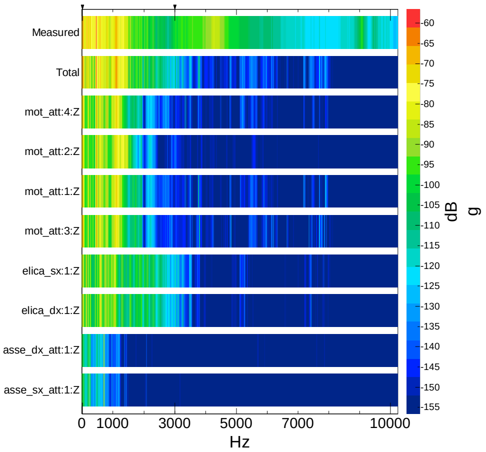

Figure 8. Frequency content contribution analysis at target 3 - n = 151 rpm (four active diesel engines).

Figure 9 and the next figure 11 show global values in term of acceleration in g. The first bar reports the global measured value, the second bar reports the total value calculated by TPA, the other bars report value calculated by TPA in order for motors engine (bars 3-4-5-6), two propeller (bars 7-8) and two shafts (bars 9-10).

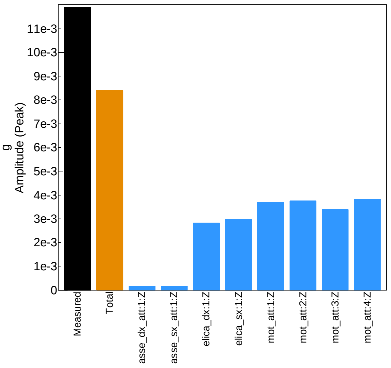

Figure 9. n = 151 rpm (four active diesel engines) - source contributions to the target (overall values).

5.1.2. n = 101 RPM

The operating frequency of the diesel engines is fixed at 10 Hz while the propeller blade frequency is lower with respect to the previous considered condition equal to 8.4 Hz. The following figure shows the frequency contents of the individual contributions for the considered sources. In this operating condition, the main contributions to the target appear to be from the diesel engines (all four running during the test). In addition, in this case the propeller seems to generate non-negligible energies at frequencies close to 3 kHz.

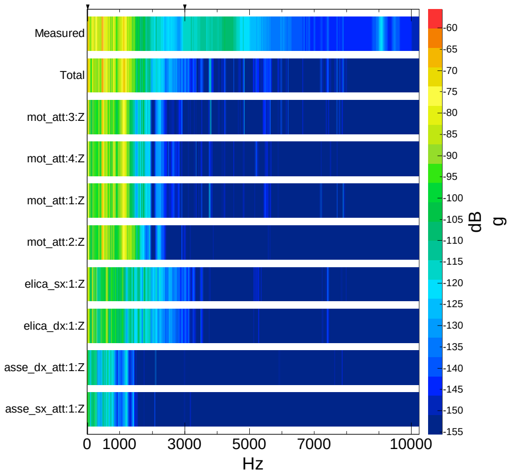

Figure 10. Frequency content contribution analysis at target 3 - n = 101 rpm.

The overall contributions to the source target show a lower propeller weight, while comparable values are slightly lower than in the 151 RPM case for diesel engines. The shaft line contribution is always negligible.

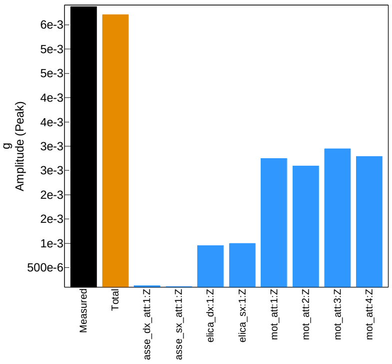

Figure 11. n = 101 RPM- source contributions to the target (overall values).

6. Conclusions

The TPA seems to allow to identify which sources are the most critical to improving system characteristics to achieve optimal vibration (and noise) requirements at the targets. The actions to be taken consist of design solutions to reduce the transfer of vibrations (or noise) from the most critical sources to the system's passive structure (the hull). It must be emphasised that TPA is a technique that relies solely on experimental measurements and the accuracy of the results is highly dependent on the quality of the system identification (FRF) and operational measurements.

In this work has been possible to verify the applicability of this technique (well established in the automotive field) in the naval field. For this purpose, a limited data set has been considered and processed.

The obtained result in this specific application seems to be encouraging and consistent. The presented TPA applied to a target close to the sources (deck 3 and frame 32) provided significant and reliable results. This indicates the robustness of the model defined by classical FRFs obtained from previous dockside measurements. It seems to be due to the fact that the energy transmission phenomena affect a limited portion of the ship that has been identified correctly with the artificial exciters, such as hammers and shakers. Moreover, it is believed that future applications involving more detailed identification steps will provide more detailed information on the vibrational dynamics of the ship.

On the contrary, the application of classic TPA for targets farther from the sources involving the whole ship has shown some limitations could be attributable to the not correct determination of the paths between source and receiver. It seems that the operational approach where the transmission paths are modelled by cross correlation functions calculated between appropriate response points near sources and targets might be the most suitable solution for the naval application. The identification of the system to be used for the TPA model takes place during the sea trial during particular manoeuvres (e.g. bump off test) where the operational forces (not measurable) appear to be most suitable and better than the artificial forces in correctly exciting the dynamics of the ship making it observable and therefore identifiable with response measurements.

The method is based on the identification of a transmissibility matrix between two sets of responses, one of them being representative of excitation forces generated by the sources (diesel engines, propellers, shaft bearings) and the other are placed on the receiving structure in the correspondence of the considered vibrational targets.

In future works, operational TPA techniques may be considered and applied to compare them with classical methods and to analyse the quality of their results.

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