

# An Overview of Experimental Techniques for Noise and Vibration Analysis on Ships

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*Measurements and Analysis of Noise, Vibration in a ship structure is of prime importance not only from comfort of the crew/passengers and durability of the structure/components but also due to the fact that higher radiated noise/vibrations make ships particularly warships vulnerable for enemies to detect. There are various techniques available to measure and analyze the noise/vibration to quantify the response at the receiver location for example noise inside the cabin, localize the source and to quantify the contribution of various paths to identify the root cause of the problem. This paper describes some of the advanced experimental techniques available for analysis of noise and vibration in a ship structure for fault diagnosis.*

## KEY WORDS

Noise; Vibration; Signature; Spectrogram; Operational Deflection Shapes; Transfer Path Analysis; Acoustic Holography; Beamforming.

## NOMENCLATURE

Air Borne Noise	ABN
Angular Frequency	$\omega$
Frequency Response Function	FRF
Irregular Nearfield Acoustic Holography	iNAH
Nearfield Acoustic Holography	NAH
Near Field Focalization	NFF
Operational Deflection Shapes	ODS
Structure Borne Noise	SBN
Transfer Path Analysis	TPA
Wavelength	$\lambda$

## INTRODUCTION

Systematic noise and vibration trouble shooting involves study and understanding of Source-Path-Receiver model. Generally, the “Receiver” is considered only to quantify the noise or vibration levels to assess the effect or damage potential. These quantification methods and procedures are mostly governed by Standards/Regulations (for example Acceptance Tests for ABN and SBN from engines as per MIL-STD-740-1 / 740-2) and does not call for a detailed root cause analysis. For an engineering insight into the system and for refined system with lesser noise and vibrations, it is very important to understand the root cause of the problem. Few important experimental techniques available that helps to achieve this at an accelerated time frame are briefed in this paper.

Techniques like Signature testing and Operational deflection shapes provide valuable information on the possible dynamic behavior of the system (forcing or resonant frequencies etc) from the data measured on the receiver side only. Sound Source Localization techniques discussed here are for the airborne noise

quantifications that gives acoustic hot spots on the source in a shorter testing time. Advanced techniques like Transfer Path Analysis involve detailed measurements on the complete Source-Path-Receiver of the system to determine the Forces (from the Source), Transfer Functions (characterization of various Paths) and Operational responses (Receiver). The exhaustive data sets measured are processed for Contribution plot which illustrates the dominant path responsible for a higher noise/vibration measured at receiver location. All these techniques are briefed with an application case in the subsequent sections of this paper.

## SIGNATURE TESTING AND ANALYSIS

Signature Testing involves processing of frequency spectra of noise or vibration of any equipment at stationary speed or during run up or rundown. The frequency spectrum measured at constant rotational speed indicates the predominant frequency components and the amplitude levels which can be correlated with the kinematics of the system to predict the source for higher noise or vibration. Further, processing of run-up or run-down data helps in characterizing the noise/vibration for the whole operating speed range of the system. The frequency spectra processed during run-up or run-down is represented as a 3D map (Amplitude vs. Frequency vs. Speed) referred as Spectrogram or Colour map. Such a plot is an effective tool not only in identifying the predominant frequency components (high amplitude components) but also in distinguishing whether the frequency of interest is speed dependant (seen as diagonal lines in the colour map attributed to rotating equipments or rotational phenomenon) or speed independent (seen as straight lines in the colour map attributed to structural resonances).

Fig 1.1 shows the spectrogram measured on a large diesel engine during run-up. The colour map clearly shows higher amplitude of vibrations at around 450 and 870 Hz, further these predominant frequency components appear to be independent of speed (seen as straight lines). Thus from the spectrogram it can

be inferred that, structural resonances dominate the vibrations at higher speeds.

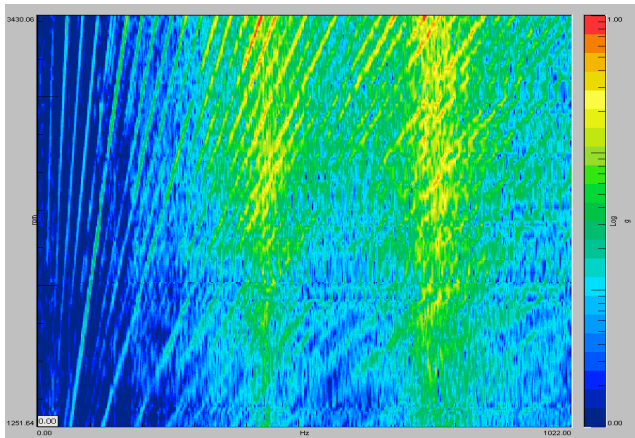


Fig. 1.1 Colour Map of Diesel Engine Vibration

### OPERATIONAL DEFLECTION SHAPES

ODS (Operational Deflection Shapes) is defined as the deflection or deformation of a structure at a particular frequency. The ODS helps to visualize the motion or vibration of the system during its operation, thus by performing ODS measurements one can visualize how much the structure is moving at a particular frequency (both at resonant and forcing frequencies). This readily helps in identifying the component/parts which vibrate more at a frequency of interest and thus accelerate the process of fault diagnosis to do corrective actions to reduce vibration levels.

In general, an ODS is defined with a magnitude and phase value at each point on a machine or structure. To define an ODS vector properly, at least the relative magnitude and relative phase are needed at all response points. This requires that either all of the responses have to be measured simultaneously, or they have to be measured under conditions which guarantee their correct magnitudes and phases relative to one another (this is ensured by fixing one accelerometer location as reference and with respect to the reference point the phase/magnitude of all other response points are defined).

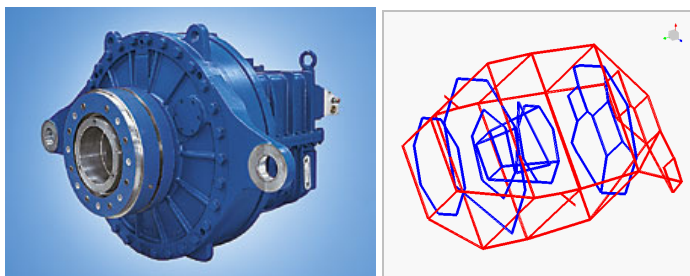


Fig. 1.2 ODS Analysis of a planetary gearbox

Fig.1.2 illustrates the ODS measurements made on a planetary gearbox, the ODS plot clearly indicates higher response attributed to flexibility (lower stiffness) at the 3rd stage planetary gear internal support.

### SOUND SOURCE LOCALIZATION

The ultimate goal of sound source localization technique is to accurately project the sound origin on an image of the test object. The sound source is represented as a red spot

It is a complex and cumbersome task that most acoustic engineers face on a daily basis. Today, a number of rather standard methods help accelerate this task. But there is no one-size-fits-all solution. In general, the methods being used fall into two categories based on the distance of the measurement plane from the source or test object (as illustrated in the fig.1.3 below): Near-field Acoustic Holography (NAH – Near field technique) and Beamforming (Far field technique)

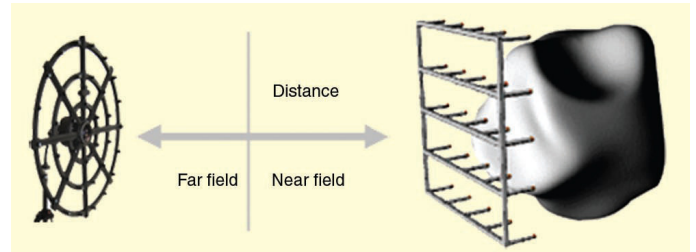


Fig.1.3 Sound Source Localization Techniques

**Near-field Acoustic Holography (NAH)** is a technique where the microphone array is placed relatively close to the sound source - in the near field (The near field can be described as the area that is closer to the sound source than one or two wavelengths of the highest frequency).

NAH measures sound pressure by arranging several microphones in a rectangular planar array. Microphones are regularly spaced both horizontally and vertically. The sound pressure in the plane is then back-propagated to the actual surface of the object. The NAH method is a very precise engineering tool for source localization. However, it has some disadvantages:

1. NAH can only propagate sound pressure to a surface that is parallel to the measured surface. The size of the propagation plane has to be identical to the measured plane.
2. The higher the required maximum frequency, the closer the microphone spacing. Practically speaking, NAH can be inconvenient for higher frequencies due to the large amount of data required to achieve a good analysis.

**Beamforming** is a technique where the microphone array is placed in the far field (as a rule of thumb, the far field is defined as being further away from the source than the array dimensions or diameter). In the near field, sound waves behave like circular or spherical waves, while in the far field, they become planar waves. Numerous microphone configurations are possible in Beamforming arrays and most commonly a circular array with a pseudo-random microphone distribution is used.

The Beamforming technique was first developed for submarines and environmental applications. In the far field, sound waves hitting the array are planar waves. Under these conditions, it is possible to propagate the measured sound field directly to the test object. All microphone signals measured by the Beamforming array are added together, taking into account the delay corresponding to the propagation distance. The pressure can be calculated at any point in front of the array, allowing propagation to any kind of surface. Beamforming requires that all data be measured simultaneously. Beamforming has the following advantages:

1. Propagation does not relate to the size of the measurement array.
2. The test object can be larger than the array. With an array of 0.5 m in diameter, it is possible to propagate pressure to an entire car. Since all data are measured simultaneously, results can be viewed only minutes after data acquisition.
3. Because of the relatively fast acquisition and analysis speed, Beamforming lets engineers evaluate several configurations in a limited amount of time.

The major limitation of the Beamforming technique is that it is only usable at frequencies above 1000 Hz. Further Beamforming cannot be used to calculate sound power and proper source ranking cannot be done with this technique. However these limitations are being resolved with recent advances in Sound Source Localization, important of them is Focalization and Irregular Nearfield Acoustic Holography (iNAH).

**Focalization:** Near-field focalization (NFF) is a beamforming technique based on near-field measurements. It allows the beamforming array to be moved closer to the sound source. In the near field, the sound waves no longer arrive at the microphone as planar waves but as spherical waves. The original beamforming back-propagation is reformulated to deal with these waves. NFF improves the spatial resolution to  $0.44 \lambda$ . In practice, this implies that, compared to beamforming, spatial resolution is improved by a factor of two over the entire frequency range. This technique is very useful for wide-angle beamforming acoustic cameras that can zoom into a sound hot spot, providing high-definition source localization. It also lowers the threshold of the minimum frequency at which beamforming can be employed.

**Irregular Near-Field Acoustic Holography:** NAH requires a rectangular array with evenly spaced microphones, both horizontally and vertically. Horizontal and vertical spacing can be different. However, NAH cannot be performed with a Beamforming array, because it is not rectangular and it has a pseudo-random microphone distribution. To overcome this, the problem is rewritten as an inverse method. The transfer function in this formulation includes both propagated and evanescent wave functions, and needs an optimal and stable PCA-based

regularization, which includes evanescent wave filtering. This provides a very low frequency analysis band of 60-70 Hz.

Example below (Fig.1.4) illustrates the Sound Source Localization of a compressor using Beamforming for higher frequencies and Focalization for the lower frequency of interest.

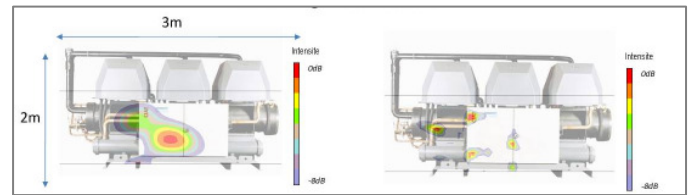


Fig.1.4 Sound Source Localization on a Compressor unit

## TRANSFER PATH ANALYSIS

Transfer Path Analysis is a test-based procedure which allows you to trace the flow of vibro-acoustic energy from a source, through a set of known structure- and air-borne pathways, to a given receiver location. The goal is: to evaluate the vector contribution of each path of energy from the source to the receiver, so that you can identify the components along that path that need to be modified to solve a specific problem - and perhaps to optimize the design by choosing desirable characteristics for these components.

In simple words, Transfer Path Analysis is used to assess the structure and air-borne energy paths between excitation source(s) and receiver location(s). Although simple in concept, the measurements are invariably time-consuming (several hundred FRFs need to be acquired) difficult to perform (because of the limited space available for transducers) and generate huge volumes of data - requiring careful data management to ensure important details are not overlooked. Nevertheless, performing a Transfer Path Analysis is a worthwhile exercise, because the insights it gives lead directly to faster troubleshooting, better product refinement and a more methodical approach to vibro-acoustic design.

A Transfer Path Analysis takes the frequency response functions between the receiver and the inputs (forces) applied at the different possible energy source locations, and combine them with inputs (forces) that are active at these locations during operational conditions. The receiver sound pressure level (or vibration acceleration level, if appropriate) during operational conditions is then explained as a superposition of partial results, each describing the contribution of the individual transfer paths:

$$r(\omega) = \sum_{i=1}^{nrpaths} \frac{R(\omega)}{S_i(\omega)} \times S_i(\omega) \quad (1)$$

$r(\omega)$  = receiver spectrum (Sound Pressure or Vibration Acceleration Level) as a function of frequency or rpm

$R(\omega)/S_i(\omega)$  = FRF between the receiver and the input applied at transfer path i

$S_i(\omega)$  = Operational force at transfer path i

Vibro-acoustic transfer functions can be measured using the most practical approach - either using hammer or shaker excitation techniques. The acoustic transfer functions (from volume-velocity to pressure) are measured by volume velocity source excitation techniques. The operational inputs (forces or volume velocities) are either available as experimental data (measured directly using Load cells) or from analytical simulations, or, more commonly, have to be determined indirectly (as in most of the practical cases fixing load cells is difficult).

For transfer paths where the source side is connected to the receiver via mounts, the operational forces can be determined from knowing the complex dynamic stiffness of the mounts  $K(\omega)$  and of the differential displacement over the mount during operation. The displacements are usually derived from acceleration measurements.

$$f_i(\omega) = K(\omega) \times [X_s(\omega) - X_r(\omega)] \quad (2)$$

$F_i(\omega)$  is the operational force at transfer path  $i$   
 $K(\omega)$  is the Complex dynamic stiffness as a function of frequency  
 $X_s(\omega)$  is the operational displacement at the mount connection point on the source side  
 $X_r(\omega)$  is the operational displacement at the mount connection point on the receiver side

The example detailed below illustrates a practical case of TPA carried out on a ship.

The objective of the TPA exercise on the ship is to breakdown and rank the Structure borne noise measured on the floor (vibration level) and inside the cabin (Sound Pressure Level).

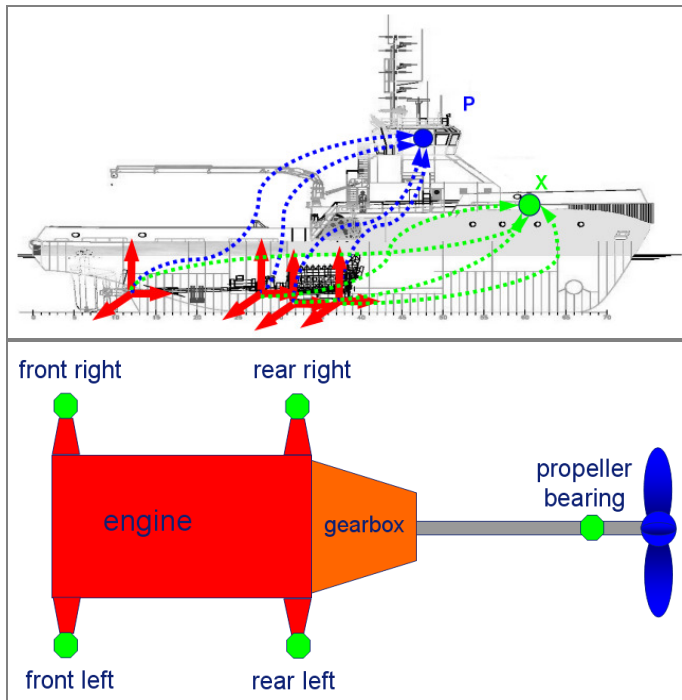


Fig.1.5 Path Definitions for TPA

The system under consideration is a six cylinder engine connected to gearbox powering the propeller of the vessel. Five transfer paths are defined and measurements/analysis is made to quantify the contribution of these five transfer paths on the bridge noise/vibrations and further to identify the dominant path which needs to be considered for noise/vibration mitigation. Fig.1.5 illustrates the path definition for TPA.

Operational measurements are made to quantify the bridge noise. The result shown in figure 1.6 indicates higher noise level around 4800 rpm. The Vibro-acoustic Transfer functions are measured using Impact Hammer excitation method. The transfer function measured at Propeller bearing is illustrated in figure 1.8 as an example. The forces determined by Mount Stiffness method using the Dynamic stiffness of the mounts. The dynamic stiffness is measured using Hammer excitation method as illustrated in figure 1.9 along with the dynamic stiffness result.

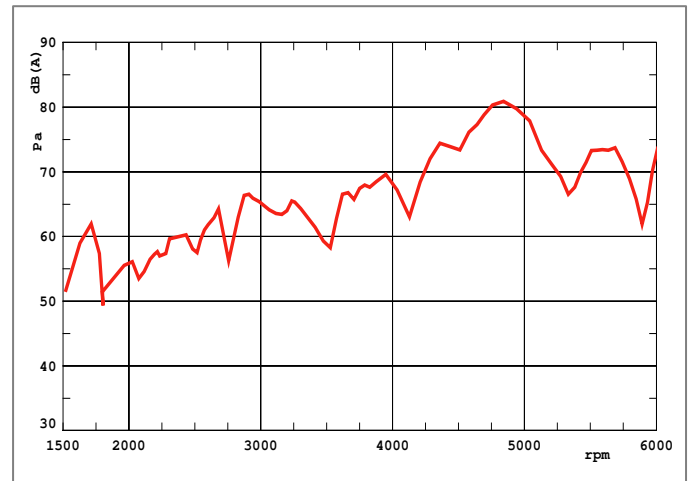


Fig.1.6 Bridge Noise Level in dB (A) vs. RPM



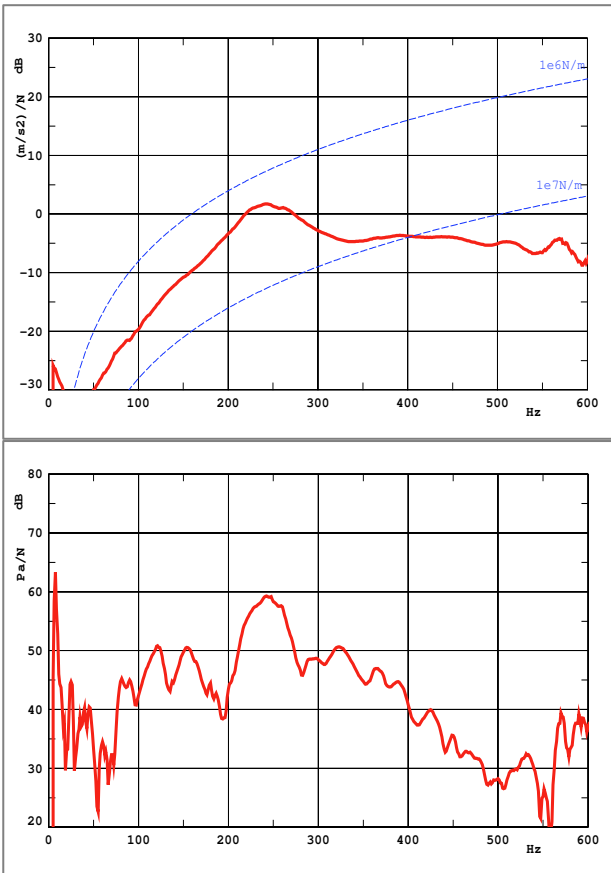


Fig.1.7 Vibro-Acoustic Transfer Function measured across Propeller bearing

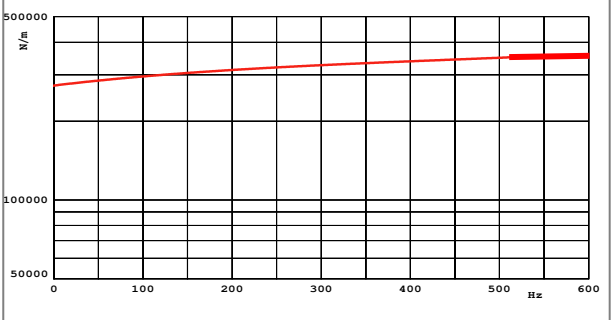


Fig.1.8 Dynamic Stiffness Testing of Mounts

The data measured are processed using LMS Test.Lab Transfer Path Analysis software suite to quantify the contribution of various selected paths to the measured bridge noise. The result of the transfer path analysis is shown in fig.1.9. From the TPA result it is evident that propeller bearing path is the dominant path which contributes more to the higher bridge noise observed at around 4800 rpm.

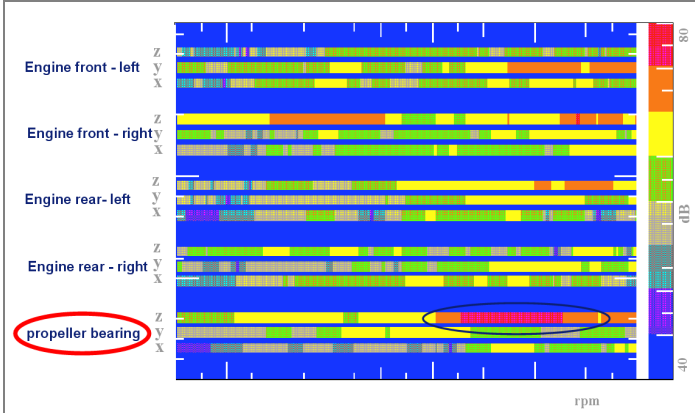


Fig.1.9 TPA result – Path Contribution Analysis plot

**CONCLUSIONS**

The experimental techniques described in this paper; Signature Testing and Analysis, Operational Deflection Shapes, Beamforming Technique with Focalization and iNAH and the Transfer Path Analysis can be highly effective. When used, they can help in trouble shooting noise and vibration issues accurately but also at an accelerated test/analysis time. Further, TPA gives lead directly not only to faster troubleshooting but for a better product refinement and a more methodical approach to vibro-acoustic design.

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