Operational Transfer Path Analysis applied to a Ship with Multiple Engines, Gearboxes and Propellers

Tjakko Keizer
Research Department, Damen Shipyards Gorinchem, The Netherlands. tjakko.keizer@damen.com
Dennis de Klerk
Müller-BBM VAS bv, Hattem, The Netherlands. ddeklerk@muellerbbm-vas.nl

Summary
The Operational Transfer Path Analysis (OTPA) method is the subject of research in this paper. After a brief review of its theory, the methodology is applied to a ship with a double engined, directly driven, power train. With the additional presence of a generator set, this test candidate makes a good example for the OTPA's simultaneous identification of multiple excitation sources in the perceived cabin's sound level. The ship is measured in two conditions to illustrate how this influences the ship's sound levels.

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1. Introduction

In this paper a ship is analysed with the Operational Transfer Path Analysis (OTPA) method. Both air-borne (AB) and structure-borne (SB) paths are included in the analysis. Vessel gradual run ups are used to excite the structure.
The analysis predicts the individual contributions of engines, gears and propellers and shows which frequency ranges are dominated by structure borne or air-borne noise.
The paper starts with a discussion on the OTPA method's theory, followed by the application on the 2 engined ship and a conclusion.

2. Theory of OTPA

Consider an arbitrary linear(ized) system described by a set of input and output Degrees of Freedom (DoF), represented as

$$H(j\omega)x(j\omega) = y(j\omega) \tag{1}$$

Here $H(j\omega)$ is the transfer function matrix linking the vector of input DoF $x(j\omega)$ to the vector of output DoF $y(j\omega)$. The dependency on frequency is denoted by $(j\omega)$.

In NVH problems, the measured signals are typically accelerations, denoted $a(j\omega)$, forces $f(j\omega)$ and sound pressures $p(j\omega)$. The input and output vectors may contain any of these or other quantities as long as they are sampled with the a synchronized sampling frequency.

Notice that it is up to the engineer to define the input and output sets from the measured data. He is not restricted to choose forces as excitations only, but acceleration and sound pressure, which are responses from a physical point of view, may also be chosen. This makes the OTPA method an engineering tool, requiring appropriate setup of the experiment. Done well, OTPA has shown to be very fast and accurate, enabling cost efficient product development [1].

By the construction of (1), the elements of the H matrix have the form

$$H_{ij} = \left.\frac{y_i}{x_j}\right|_{x_k=0} ; k \neq j \tag{2}$$

Strictly, one could thus determine a column of the transfer function matrix in OTPA also by exciting the system with only the input DoF x_j, while suppressing all other input excitations. In practice this is very hard to achieve as inputs are not only forces, but also motions, sound pressures or any kind of quantities. The determination of the transfer functions in this way will therefore often lead to very difficult, impractical and sometimes even impossible experimental setups. Analysis as

such will therefore require a big expense in time and resources.
To overcome this disadvantage, the OTPA method determines all elements of the transfer function matrix from one measurement only where all excitations are present at once. This determination is discussed next by first taking the transpose of equation (1) and writing the equation on entry level:

$$[x_1 \cdots x_m]\begin{bmatrix} H_{11} & \cdots & H_{n1} \\ \vdots & \ddots & \vdots \\ H_{1m} & \cdots & H_{nm} \end{bmatrix} = [y_1 \cdots y_n] \qquad (3)$$

Here *m* and *n* denote the number of input and output DoF. Taking the transpose does not allow the determination of the FRF elements though. In order to do so, notice that during an operational measurement of, for example, a ship run up, a set of synchronized measurement blocks will be collected. In general these sets will not have the same content, as the excitations change continuously during the measurement. If one requires, or defines, the relation between the input and output DoF as being linear(ized) and constant during the total measurement, equation (3) should however hold for each individual measurement block. One could thus extend equation (3) writing the equation for all measurement blocks *r*, yielding:

$$\begin{bmatrix} x_1^{(1)} & \cdots & x_m^{(1)} \\ \vdots & \ddots & \vdots \\ x_1^{(r)} & \cdots & x_m^{(r)} \end{bmatrix} H = \begin{bmatrix} y_1^{(1)} & \cdots & y_n^{(1)} \\ \vdots & \ddots & \vdots \\ y_1^{(r)} & \cdots & y_n^{(r)} \end{bmatrix} \qquad (4)$$

Or:

$$XH = Y \qquad (5)$$

The explicit determination of the transfer function matrix *H* by (5) may cause numerical problems in the inversion of the term *X* though. Use is therefore made of the Singular Value Decomposition (SVD) technique, to overcome this kind of problems.

Notes:

- OTPA is able to extract source contributions from measurements only. As excitation sources might be coherent among each other, run up/down is needed for transfer function calculation to de-correlate individual source excitations.
- Using the calculated transfer functions as FIR filters, one can resynthesize the defined response positions, based on individual contributions. The sum of all calculated contributions combined should be close to the originally measured response signal. Deficiencies indicate “forgotten” paths / sources, non-linearity or sensor noise.
- The contribution of missing sources are assigned to other sources on basis of coherence.
- Frequency resolution of the transfer function determines the block length taken from the time stream. The frequency resolution therefore determines the amount of equations available to solve for the transfer functions (too low over-determination may cause rank deficiency)
- As the method assumes linearity, non-linear behaviour will cause erroneous results. Reverberation that takes much longer than the chosen measurement block will also cause errors in the synthesis.

3. Application of OTPA

OTPA has been applied to a Damen Stan Tug 2208 (STu 2208). A picture of this STu 2208 is given in figure 1.

Figure 1. The Stan Tug 2208 in free sailing condition.

The main dimensions are given in table I.

Table I. Main dimensions of the Stan Tug 2208

Length	22.64 m
Width	7.87 m
Draft	2.75 m

This ship is designed to be used for towing operations. To deliver the required towing force, the ship is equipped with two Caterpillar 3512C main propulsion engines each capable of delivering 1014 kW at a rotational speed of 1600 rpm. Each propulsion engine is connected to a Reintjes WAF 665L gearbox with a reduction of 5.95. Each gearbox drives a fixed pitch propeller with a diameter of 2.2 m in an Optima nozzle. This way the vessel is able to deliver a maximum towing force (bollard pull) of 38 tonnes and achieve a maximum ship speed of 12 knots.

1.1. Measurements

The ship has been instrumented with accelerometers on the port and starboard main engine, the port and starboard gearbox, the generator set, the shell plating above port and starboard propeller and microphones in the engine room and outside near the engine room ventilation openings. Also microphones has been placed in the cabins on board.

The transfer functions have been derived for two operating conditions: free sailing and bollard pull.

For the free sailing condition, the transfer functions are derived using a run up and run down in free sailing conditions. At the start of the run up the ship is at zero speed, the engines are running idle (600 rpm) and the propeller are clutched out. Subsequently the propellers are clutched in and the engine speed is slowly increased to full rpm. This way the ship accelerates from zero knots to full speed in approximately 2 minutes. The run down is done in the opposite way.

After the free sailing measurements, the ship was connected to the shore with a towing line. This way the ship is brought in bollard pull condition.

For the bollard pull condition, the transfer functions are derived from a run up and down in the bollard pull condition.

At the start of the run the ship is at zero speed, with zero pull, the engines are running idle (600 rpm) and the propellers are clutched out. The propellers are clutched in and the speed of the engines is slowly increased to full speed. This way the pull of the ship increased from zero tons to full pull in approximately 1 minute. The run down is done in the opposite way.

1.2. Analysis

The transfer functions derived for both operating conditions are applied to two conditions: free sailing at 100% rpm, and bollard pull at 100% rpm.

Several analysis have been done in which the dependence is investigated of varying the number of sources taken into account. Also the influence of the frequency resolution in which the transfer functions are derived is investigated.

In this paper several analyses have been done for the mess room, as summarized in table II.

Table II. Source taken into account

Source	I	II	III
Main engine top (SB)	X	X	X
Main engine feet (SB)	-	-	X
Gearbox top (SB)	X	X	X
Shell plating above propeller (SB)	X	X	X
Generator set top (SB)	X	X	X
Engine room (AB)	-	X	X
ER Ventilation ducts (AB)	-	X	X

In analysis I, only structure borne sources are taken into account. The choice of the sources are based on the sources that are normally taken into account when predicting the sound levels on board.

In the figure 2 the contributions of the selected sources to the total A-weighted sound level in the mess room is shown.

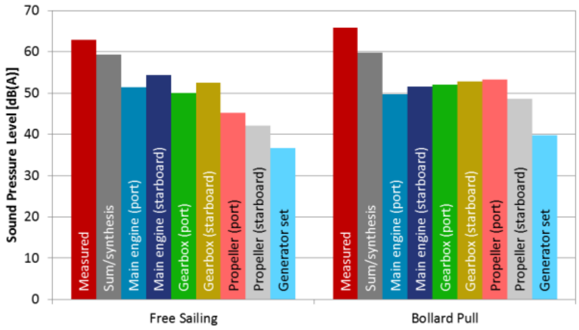

Figure 2. Contributions of the selected sources to the sound pressure level in the mess room for free sailing and bollard pull condition for OTPA analysis I.

It is seen that the difference between the measured levels and the synthesis is larger for bollard pull than for free sailing conditions.

It is noticed that the contributions of the starboard machinery and portside machinery are not equal. The contributions of the starboard main engine and starboard gearbox are approximately 2 dB more than the contribution of the portside main engine. For the propellers the portside propeller has a 4 dB higher contribution than the starboard propeller.

Also clear differences can be seen between the free sailing condition and the bollard pull condition. In the free sailing mode, the main engines have a 2 dB higher contribution than in bollard pull mode. In bollard pull, the propellers have a 6 dB higher contribution. This is in accordance with the expectation, since more cavitation will be present on the propeller in bollard pull condition than in free sailing condition.

In figure 3 the contributions of the selected sources are shown in one third octave bands for the free sailing condition.

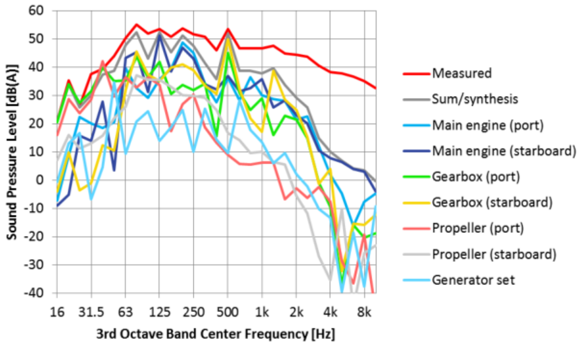

Figure 3. Contributions of the selected sources to the sound pressure spectrum in the mess room for free sailing condition for OTPA analysis I.

At frequencies below 500 Hz a good match is found between the synthesis and the measured sound level.

It can be seen that the portside propeller dominates the sound level in the mess room at the frequency bands below 40 Hz. These frequency bands contain the 2 first harmonics of the blade passing frequency.

In the frequency bands between 63 Hz and 160 Hz, the starboard main engine is dominant. These bands contain the 1st and 2nd harmonic of the engine ignition frequency.

In the bands between 160 Hz and 315 Hz both main engines are dominant.

The frequency band of 500 Hz is dominated by the gearboxes. This band contains the gear meshing frequency.

In analysis II, air borne sources are added that could potentially be important.

The contributions of the selected sources to the total A-weighted sound level in the mess room are given in figure 4.

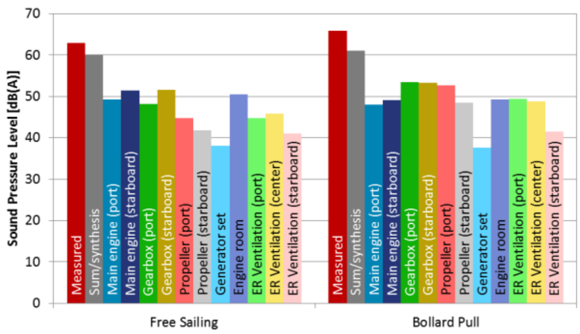

Figure 4. Contributions of the selected sources to the sound pressure level in the mess room for free sailing and bollard pull condition for OTPA analysis II.

The synthesis of analysis II is 1 dB closer to the measured levels than analysis I.

For the structure borne sources the same trends can be seen as in the previous analysis.

The contributions of the main engines is reduced by 3 dB by adding the engine room sound as an airborne source. This is shown in figure 5, where the spectra are shown of the contributions of the main engines compared to the previous analysis.

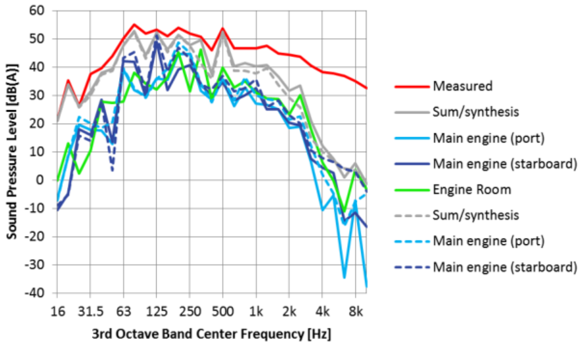

Figure 5. Contributions of the main engines to the sound pressure spectrum in the mess room for free sailing condition for OTPA analysis I (dashed) and analysis II (solid).

The most reduction of the structure borne contribution of the main engine sound is seen at frequencies above 3.15 kHz

In the analysis III two extra indicator sensors on the feet of the main engines are added in the analysis.

In figure 6 the contributions to the total A-weighted sound level in the mess room are given.

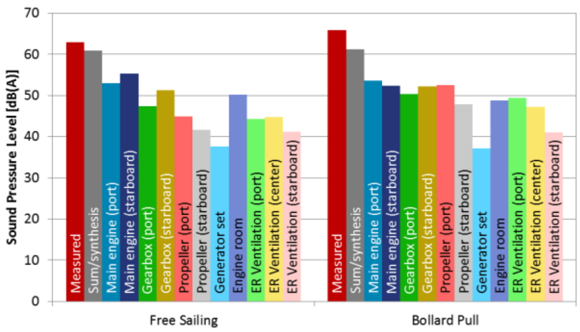

Figure 6. Contributions of the selected sources to the sound pressure level in the mess room for free sailing and bollard pull condition for OTPA III.

The synthesis of analysis III is 1 dB closer to the measured levels than analysis II.

For the structure borne sources the same trends can be seen as in the previous analysis.

The contributions of the air borne sources are the same as the previous analysis.

The contributions of the main engines is increased by 4 dB by adding these additional sensors. This is illustrated in one third octave bands in figure 7. The contribution is increased over almost all frequency bands.

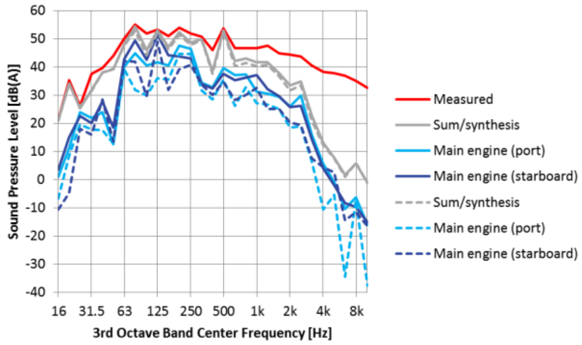

Figure 7. Contributions of the main engines to the sound pressure spectrum in the mess room for free sailing condition for OTPA analysis II (dashed) and analysis III (solid).

For the third analysis the influence of using 4 times longer measurement blocks to determine the transfer functions is investigated. This way the transfer functions are determined with a 4 times higher resolution, but also the number of measurement sets is reduced by a factor of 4.

Using these higher resolution transfer functions, again the contributions of the selected equipment is calculated.

The contributions to the total A-weighted sound pressure level in the mess room are given in figure 8.

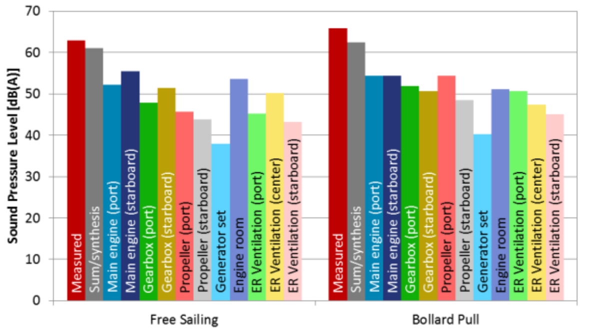

Figure 8. Contributions of the selected sources to the sound pressure level in the mess room for free sailing and bollard pull condition for analysis III using high resolution transfer functions.

The synthesis of the analysis with high resolution transfer functions is as close to the measured levels as the synthesis of the low resolution transfer functions.

For the structure borne sources the same trends can be seen as in the previous analysis.

The contributions of air borne sources is increased by 3 dB on average. This effect is given in one third octave bands in figure 9.

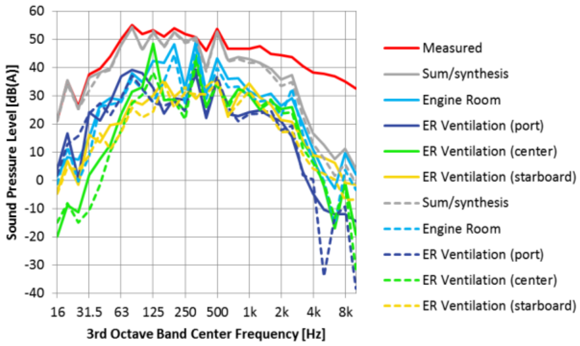

Figure 9. Contributions of the air borne sources to the sound pressure level in the mess room for free sailing condition for analysis III using high resolution transfer functions.

1.3. Conclusions

Three different OTPA analyses have been done in which a different selection of sources are taken into account. The third analysis is done with two different frequency resolutions.

In figure 10 all analyses are compared.

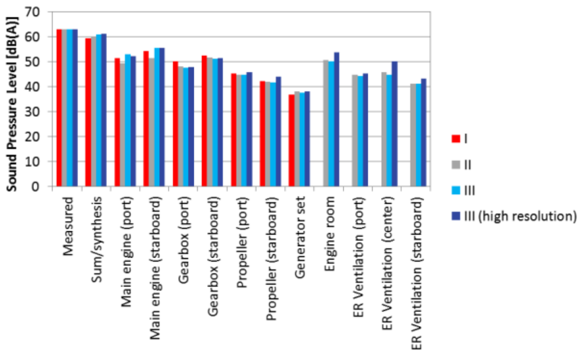

Figure 10. Comparison of the calculated contributions to the sound pressure level in the mess room for free sailing condition for all four OTPA analyses.

Adding air borne sources decreases the gap between measurement and synthesis. The air borne sound of the engine room takes part of the contribution that was first assigned to the structure borne sound of the main engines. The contributions of the other structure borne sources is not influenced.

Adding more sensors on the main engines increases the structure borne contribution, the other contributions are not changed and therefore this decreases the gap between measurement and synthesis.

Using high resolution transfer functions increases the contribution of the air borne sources, the contribution of the structure borne sources is not influenced. This way a synthesis is obtained that is closer to the measured sound levels.

The differences between the analyses illustrate that OTPA is indeed sensitive to choices that the user makes. There is no change in source ranking though.

Despite the differences between the analyses, it should be noted that these differences are less than the commonly experienced deviations between measurements on sister vessels under the same conditions [2][3][4].

References

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