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Operating Transfer Path Analysis (OTPA). Can this novel technology be applied successfully outside the automotive sector?

Juha Plunt

Müller-BBM Scandinavia AB, Box 1054, SE-405 22 Göteborg, Sweden, juha.plunt@muellerbbm.se

Transfer Path Analysis (TPA) is used when quantitative ranking of contributions from different sources and transfer paths to sound or vibration response need to be known and is a common method used for development of road vehicles. "Classic" TPA relies on estimating the interface forces (or volume velocities if airborne sound sources) acting at different attachment points (radiating surfaces) of the sources and frequency response functions between these forces (volume velocities) and the response of the transmitting system. The FRFs are measured using artificial excitation (hammer, shaker or loudspeaker), in addition to operational sound and vibration needed to derive the operating excitations. The force estimation methods use additional data; either extensive FRF measurements (inverse matrix method) or measurements of resilient element dynamic stiffness (mount method). The Operating Transfer Path Analysis (OTPA) method is now available as an alternative. It can separate source and path contributions using operational measurement data only. All data are measured simultaneously, and the method allows accurate synthesis in the time domain of the individual path contributions as well as the calculated total response. The benefits are significantly reduced measurement time and no modifications to the measurement object. The large test effort when using "classic" TPA has been the main obstacle for use in buildings, off-shore platforms, ships, construction equipment, heavy machinery, industrial plants, appliances etc. OTPA can be applied much more efficiently and without the need to turn off the operating equipment, which makes it clearly attractive for analysis of noise and vibration transmission in those applications

1 Introduction

Transfer Path Analysis (TPA) is used when quantitative ranking of contributions from different sources and transfer paths to sound or vibration response need to be known. This is typical for NVH development of road vehicles and TPA is routinely used in the automotive industry. Better diagnosis and ranking of significant source and path contributions is also needed for other products when noise or vibration issues occur, in order to find optimal solutions.

"Classic", force-based TPA has not been much used for other products, due to the large effort needed to perform all necessary operational and non-operational (FRFs) measurements. Also, acquiring high-quality, noise free frequency response functions in large structures using e.g. impact or shaker excitation has been a considerable challenge, requiring very large excitation forces to generate sufficient response levels at distant points of interest (e.g. from the engine foundations and the hull at the propellers to the bridge in large ships). It has also been practically impossible to apply TPA to industrial process plants or other machinery running continuously.

Operational TPA (OTPA) [1], [2], [3] has been developed and tested (mainly in vehicles) during the last 4-5 years. It is a fast and efficient method of identifying critical sound and vibration paths and source contributions since only measurement of operational data is needed to perform the analysis. It has also been demonstrated that similar or improved results are obtained with OTPA, when compared to the "classic" FRF matrix-inversion method [2].

As many operating conditions as possible should be used to excite all vibrational modes of the system for the derivation of the characteristics of the different transfer paths. Usually this is obtained by measuring during a slow run-up of the major source(s). This may also be obtained approximately for a continuous industrial process, without the need to shut-down, by varying process parameters that influence sound and vibration during a relatively short measurement time.

2 Theory overview

OTPA, as implemented in the PAK® software from Müller-BBM VibroAkustik Systeme GmbH, uses a method to find linearized transfer functions (TF) between a set of chosen input and output channels from a multichannel measurement. The input-output relations are determined as independent quantities. The resulting TFs are used in a transfer path analysis to determine the contributions of a source path to the response of interest.

The relation between simultaneously measured data of sources and receivers is derived by statistical methods. Principal Component Analysis (PCA) is used to separate the total signal into individual path contributions (crosstalk cancellation, CTC), while operating on airborne and structure-borne contributions simultaneously. Since the CTC is based on principal component analysis (PCA) it can also be applied to operational data. The OTPA module in PAK® (AMM) is used to normalize the airborne and structure borne parts during cross-talk cancellation.

The main difference of the CTC is that it skips the normalization to the excitation forces. Thus this method is not based on FRFs but uses PCA to statistically find the relation H_i between observed signals on the source side and simultaneously observed signals on the receiver side. The main advantage is that this method is not limited to the use of synthetic point excitation forces but can also be applied directly to operational data. This makes it also possible to investigate the transfer behavior for different load conditions like e.g. a run-up and a run-down.

Consider an arbitrary, linear system with a number of input and output degrees of freedom (DOFs), represented by a “black box” of transfer functions. The relationship in matrix form is

$$\left[H(\omega)\right]\left\{x(\omega)\right\} = \left\{y(\omega)\right\} \tag{1}$$

$\left[H(\omega)\right]$ is the transfer function matrix connecting the vector of output (response) DOFs $\left\{y(\omega)\right\}$ to the input (source) DOFs $\left\{x(\omega)\right\}$. The signals are usually accelerations $a(\omega)$, sound pressures $p(\omega)$ or forces $f(\omega)$. The input and output vectors can thus be assembled from those quantities

$$\left\{x\right\} = \begin{Bmatrix} a_x \\ p_x \\ f_x \end{Bmatrix} \quad ; \quad \left\{y\right\} = \begin{Bmatrix} a_y \\ p_y \\ f_y \end{Bmatrix} \tag{2}$$

It is up to the engineer to define input and output sets from the measured data. He is not restricted to use forces as excitations. Accelerations or sound pressures can also be used, although they are responses from a physical point of view. Not all physical quantities have to be present in the vectors defined in (2), neither do they have to have the same dimensions. Usually, the number of input (source) DOFs will be larger than the number of output (response) DOFs.

The elements of the TF matrix ***H*** have the form

$$H_{ij} = \frac{y_i}{x_j}\Big|_{x_k=0} \quad k \neq j \tag{3}$$

The OTPA method determines all elements of the TF matrix from measurements where all excitations are present at once. Take the transpose of Equation (1) and write it on entry level:

$$\begin{bmatrix} x^{(1)} & \dots & x^{(m)} \end{bmatrix} \begin{pmatrix} H_{11} & \dots & H_{n1} \\ \vdots & \ddots & \vdots \\ H_{1m} & \cdots & H_{nm} \end{pmatrix} = \begin{bmatrix} y^{(1)} & \dots & y^{(n)} \end{bmatrix} \tag{4}$$

Here *m* and *n* denote the number of source and response DOF. Taking this transpose does not allow the determination of the TF elements. However, during an operational measurement with varying running conditions, a number of synchronized multichannel measurement steps will be collected. These measurement steps will not be the same as the excitation by sources change during the measurement. If the TFs are by definition to be linear(ized) and constant during the entire measurement, Equation (4) is valid for each individual step. Then Equation (4) can be extended to all measurement steps *r*, as:

$$\begin{pmatrix} x_1^{(1)} & \cdots & x_1^{(m)} \\ \vdots & \ddots & \vdots \\ x_r^{(1)} & \cdots & x_r^{(m)} \end{pmatrix} \begin{pmatrix} H_{11} & \cdots & H_{n1} \\ \vdots & \ddots & \vdots \\ H_{1m} & \cdots & H_{nm} \end{pmatrix} = \begin{pmatrix} y_1^{(1)} & \cdots & y_1^{(n)} \\ \vdots & \ddots & \vdots \\ y_r^{(1)} & \cdots & y_r^{(n)} \end{pmatrix} \quad (5)$$

The explicit determination of the TF matrix ***H*** will cause numerical problems in the inversion of the matrix ***X***. The matrix is heavily overdetermined and singular value decomposition (SVD) is used to overcome these problems. It was found that the smaller singular values are caused by noise or other external disturbances, and they should be rejected to obtain useful TF estimates.

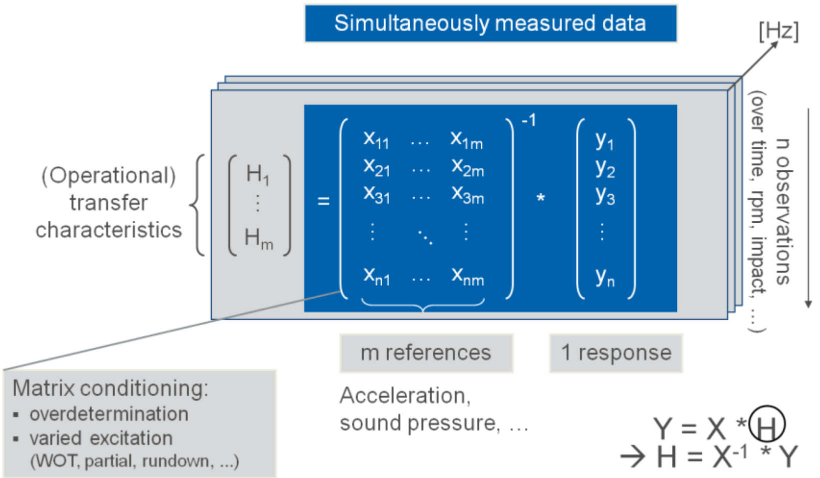

Figure 1. Illustration of the matrix equation solution for operating transfer path analysis in PAK®.

Generally, the following benefits are obtained compared to "classic" TPA:

- Crosstalk is automatically included since only reactions to any kind of excitation are measured (source side and receiver side)
- Correct separation of airborne and structure borne components
- No artificial excitation is needed (typical problems like bad coherence due to a vibrating plate nearby the hammer do not occur)
- Fast results
- The operating state is described rather than the idle structure (the result is not distorted by wrong temperatures, progressivity of mounts etc.)
- Correct positioning of sensors is not as crucial as for impact TPA

3 An automotive application example

To illustrate the practical use of OTPA, a typical automotive example is discussed briefly. An OTPA including both structure-borne and airborne sources has been conducted, for demonstration purposes. Numerous other OTPA applications have also been performed but those are client confidential. Figures 2 and 3 illustrate the positions for tri-axial accelerometers and microphones respectively.

The total number of simultaneous channels to record is 39 when a tacho channel for the engine speed is included. No sensors to pick up wind noise have been included, neither are there any sensors on the wheel suspension that allow path separation of the contribution from the four wheels. Further, airborne sound contributions from the tyres are not included. Obviously, a full-fledged OTPA on a car, including path separations for powertrain-, road- and wind noise, would require at least 10-12 more microphones and roughly 15-20 tri-axial accelerometers, bringing the typical channel count to approximately 90-100. This requires a respectable investment in hardware, but will pay off after just a few OTPAs due to much shorter measurement time and analysis and actually better total quality of the source and path separation. Of course, the sensors and frontend (may be several synchronized units) will also be available for any other kind of measurements.

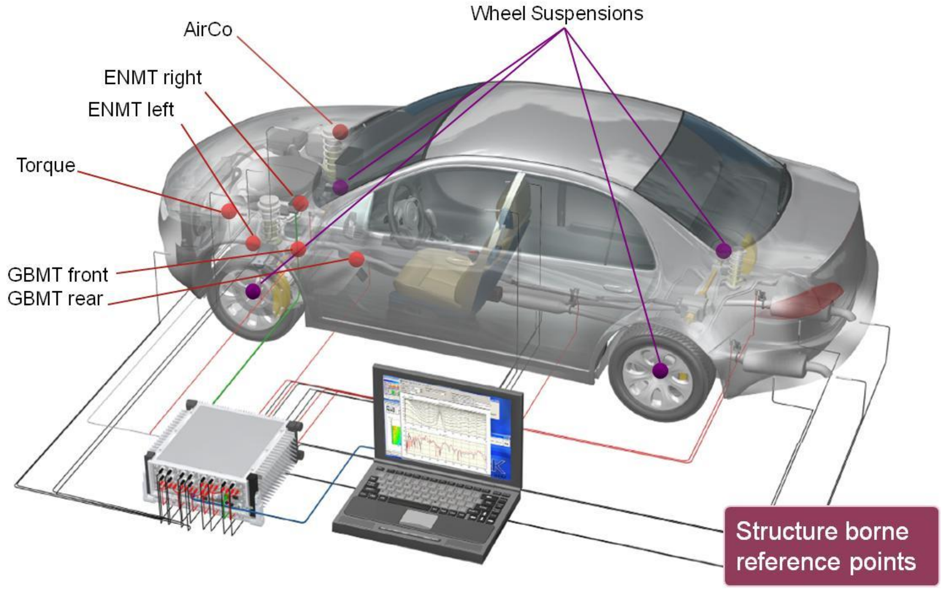

Figure 2. The positions of the source accelerometers for structure borne sound contributions. Number of channels: 30 from 10 tri-axial accelerometers.

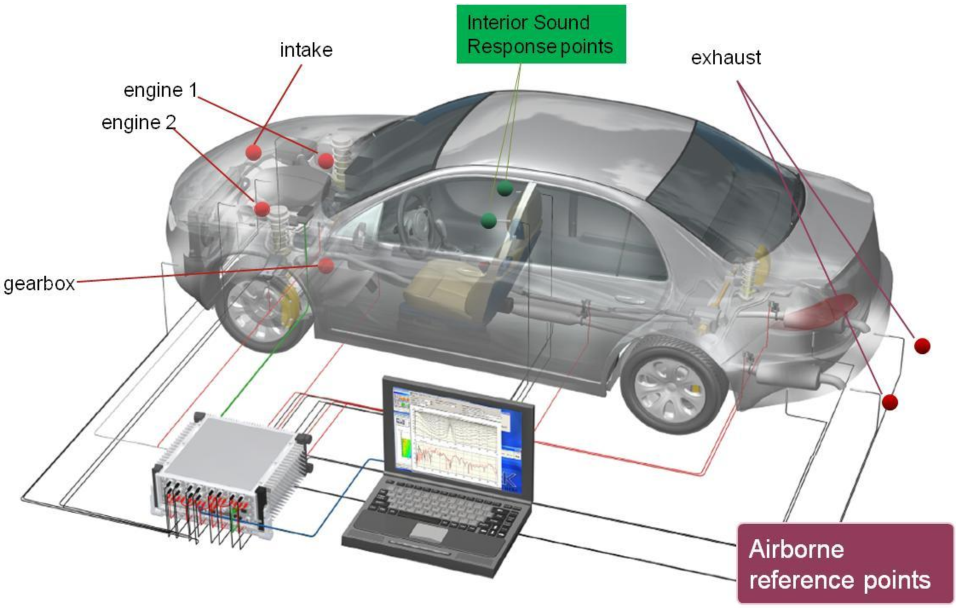

Figure 3. The positions of the microphones for airborne sound contributions. Number of channels: 8.

The near to perfect match in Figure 4, when all sources are equipped with sensors is typical for OTPA. It is not necessarily an indication of the total quality of the test setup and analysis, as the right-hand side diagram shows. In this demonstration case, we are however not interested in the wind noise or the high frequency airborne contribution from the tyres.

Placing source sensors is vital for the success of an OTPA, illustrated in figure 5. Relevant source contribution is obtained by using one sensor on the source or the body side at some point close to the source. However, a relevant path separation is only obtained if sensors are used at the body side of all relevant mounts or links from the source.

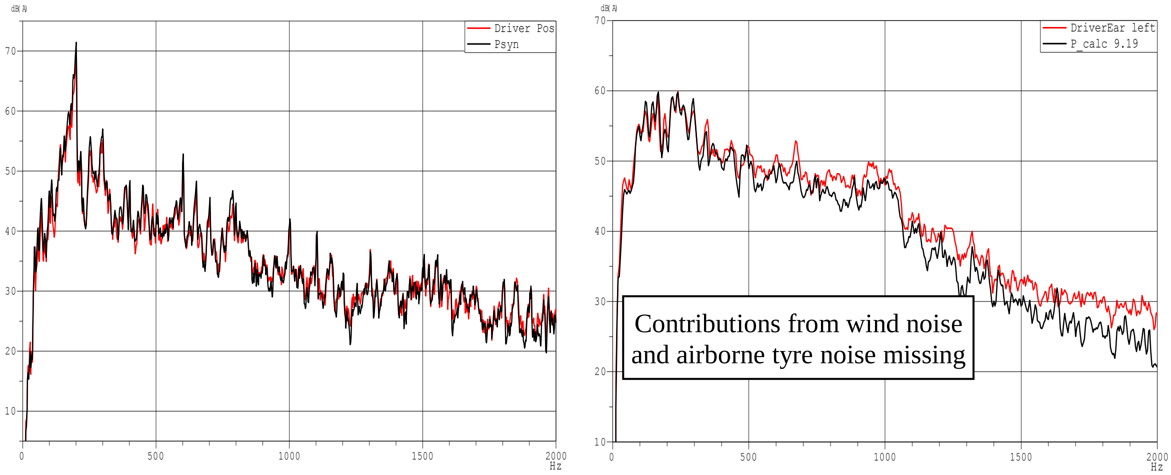

Figure 4. Comparison between measured and calculated averaged SPL spectra at drivers ear. Left) Idle condition. Right) WOT measurement in 3rd gear, top speed 140 km/h.

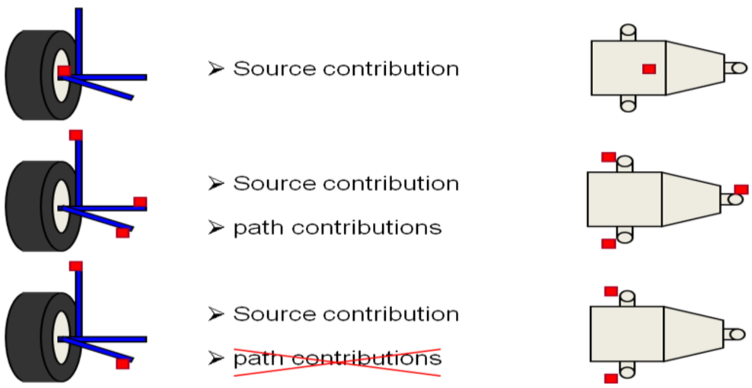

Figure 5. Sensor strategies to get relevant source and path contributions respectively.

Due to the inherent property of the path calculations, the total source contribution will always become relevant as long as there is at least one sensor close to the source. If there are fewer sensors than paths, the calculations will distribute the total source contribution between those measured paths, including any contributions from paths not measured. This will not show up as an error in the analysis results, but may result in wrong estimates of the contributions through individual paths. This is a very important practical property of this method that the engineer has to master in order to avoid errors. It is further illustrated in Figure 6. The left diagram shows the contribution of a single sensor at the gearbox mount car body side. In the right diagram two sensors have been placed at different positions near this mount. The green curve shows the sum of both sensors.

As seen, the powertrain source contribution via the gearbox mount is correct in both cases, also with the two sensors representing separate “faked” paths.

The source and path contributions can be shown in many ways, and since the synthesis is done in the time domain, it is also possible to listen to all source and path contributions especially if binaural recordings are used for the response. Figure 7 illustrates one way to plot source contributions in real time for an “area” selected in a Campbell colour plot for the response SPL, utilizing PAK® graphics features. When moving the double cross cursor, the contribution diagram immediately shows the contributions for the new selection.

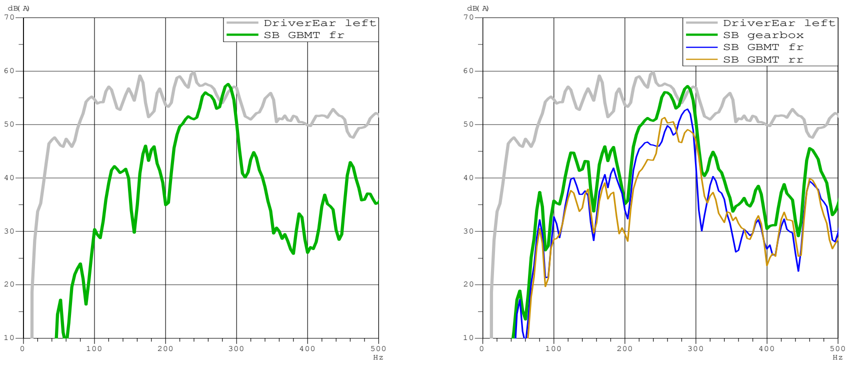

Figure 6. Example of influence of sensor placement.

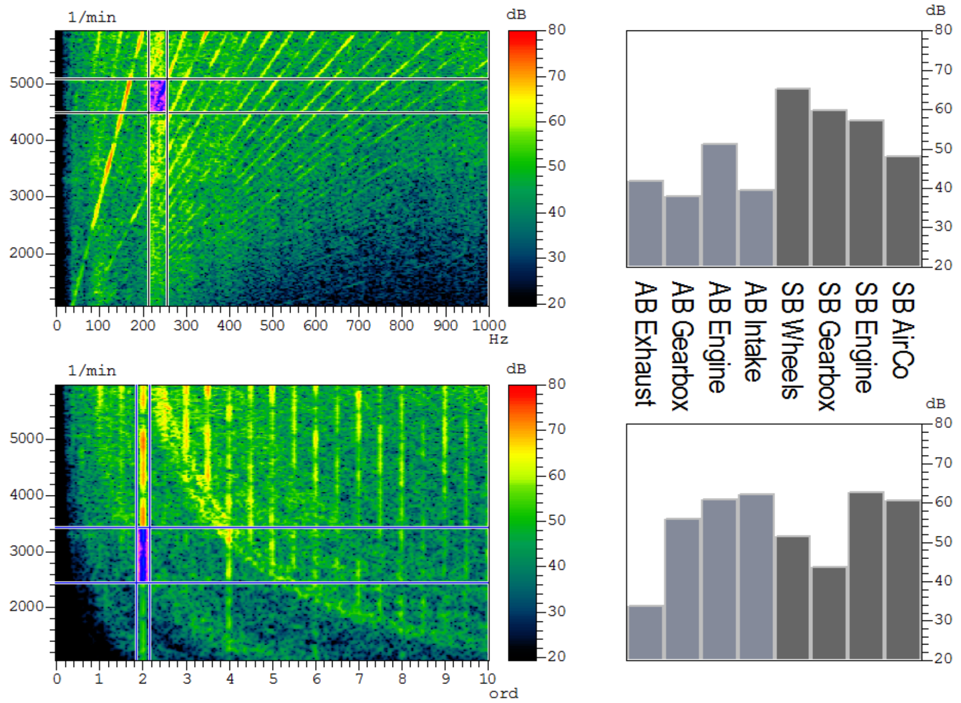

Figure 7. Example of an "active" source contribution presentation in PAK®. The contributions are shown for the marked area in the color plots. This can be moved around with the cursors.

4 Possible applications for other products or machinery

Since only operational data needs to be measured, a number of interesting areas of application for the OTPA as a new engineering tool can be envisaged. The most obvious examples are:

- Rail bound vehicles, like locomotives, train cabs, or tram cabs
- Aircraft
- Ships and submarines
- Household appliances, e.g. dishwashers, washing machines.
- HVAC, heat pump or heating installations in buildings
- Complex machinery installations

The distances between measurement points may be large in the first three cases, and since all data must be measured simultaneously, use of relatively long multichannel cables with break-out boxes is a rational solution. Otherwise, the application of OTPA is rather straightforward. An example of equipment with a suitable multichannel cable system is shown in figure 8.

Figure 8. Example of special cables and the PAK® MKII systems used by Müller-BBM Scandinavia.

The operational TPA allows fast test setup and preparation, consisting of installing a number of accelerometers and microphones. No modification of the test object or to shut-down the process is needed. Many of the obstacles that made the use of “classic” TPA unpractical and too expensive for many of these applications are thus overcome. Also the total cost will be much lower, allowing the technology to be used for e.g. developing and troubleshooting products that are manufactured in small series and even for unique installations industrial plants, ships and buildings.

A generic industrial example is illustrated in Figure 9. It shows a vibration isolated refrigerator unit with a number of possible structure-borne and airborne sound paths to a sound insulated control room. There may be a number of such units and also other machinery installed in the vicinity. If the noise level obtained in the adjacent control room is still too high, one need to know in detail which source and which paths that are most responsible for the issue, before selecting countermeasures. The red spots represent tri-axial accelerometers and the blue spots represent microphone positions, in order to separate airborne and structure-borne sound contributions.

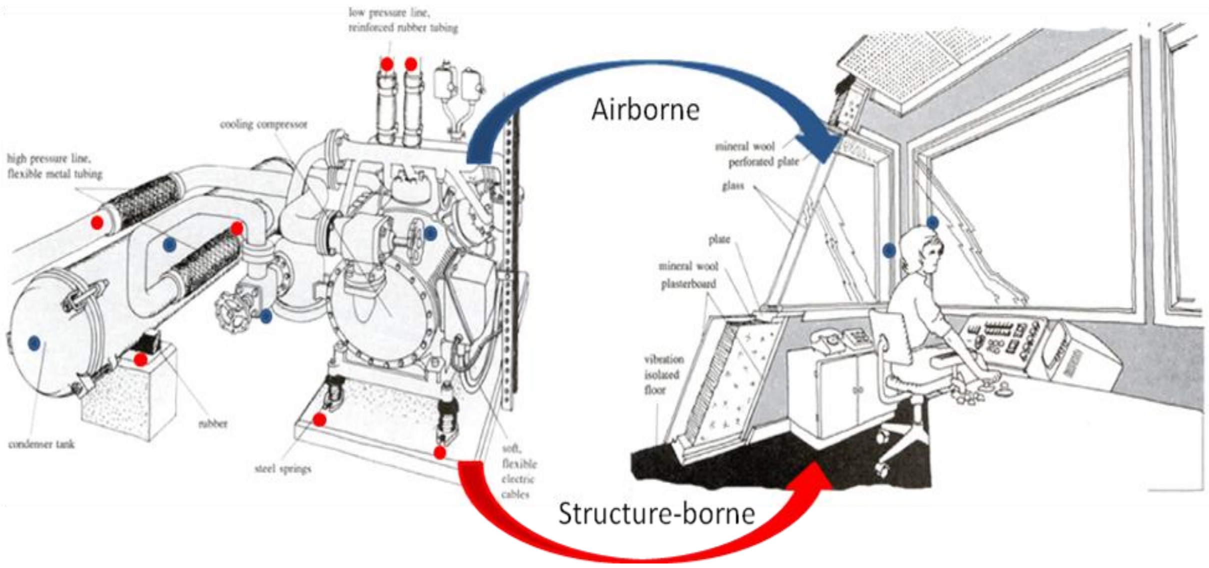

Figure 9. Generic example of an industrial machinery installation (based on pictures from [4]).

More challenging and large scale applications may be

- Offshore platforms
- Petrochemical plants
- Paper mills

The main additional challenge in these cases is to manage to measure all inputs and outputs simultaneously in spite of the very large geometrical scale of those installations. Using operational TPA is of course quite possible in principle, but may need either the use of several well synchronized frontends at different locations or special, very long multichannel cable systems in order to reach all necessary measurement points. PAK® MKII frontends may be synchronized with minimum phase deviation between channels by using fibre-optic links for broad frequency range data or by using wired or wireless Ethernet LAN if only low frequency data is of interest.

5 Summary

TPA has been used a long time and has evolved into a complex method relying on multichannel testing systems and advanced analysis software. Cheaper transducers and frontends have had a significant impact on the availability of the method. Experimental TPA is a powerful tool for diagnosing transmission of vibration or air-borne sound via multiple paths in complex systems. It is used as a routine method in the automotive industry. It is well proven and can be used in other branches as well to find rapid solutions to complex issues.

Operational TPA using crosstalk cancellation has proven to be more accurate for sound synthesis under actual load conditions than “classic” force-based TPA. Furthermore CTC is capable to produce accurate results from coherent structure borne and airborne sound contributions. By completely avoiding separate FRF testing using hammer, shaker or volume velocity calibrated loudspeakers, operational TPA will reduce testing time significantly while improving simulation accuracy. It also allows transfer path analysis to be applied when modification of the tested object is prohibited or a shut-down of operation will lead to high stand-still costs.

OTPA thus makes the transfer path analysis technology much more affordable and practical to use on numerous non-automotive, applications, such as buildings, industry and a diversity of manufactured products.

6 References

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