# Experimental transfer path analysis on helicopters

E. Mucchi[1], A. Vecchio[2]

[1] *Engineering Department, University of Ferrara, Ferrara, Italy, Email: emiliano.mucchi@unife.it*
[2] *LMS International, Leuven, Belgium, Email: antonio.vecchio@lmsintl.be*

## Introduction

In complicated structures involving many sub-assemblies (such as helicopters) the vibro-acoustic sensations that are experienced by an observer at any location (e.g. on the passenger cabin) may easily have been caused by vibration sources some way off. For example the energy from a source in a helicopter is transmitted into the passenger cabin by a number of different routes: from the gearbox connection points, rotor bearings, engine mounts or even via the tail rotors or main blade shafts. Airborne contributions from the main and tail blades, for instance, may be important as well. Some of these paths are important, some are negligible. Some transfer paths may cause interference at certain frequency such that the observer does not notice anything significant- until he moves position.

Transfer Path Analysis (TPA) is used to assess the structure and air-borne energy paths among excitation source(s) and receiver location(s) [1].

Hereafter a vibro-acoustic TPA is performed on a Agusta Westland AW-109 helicopter. Usually vibro-acoustic TPA involves measurements of accelerations in operational conditions and of vibration and/or vibro-acoustic transfer functions (TFs). The transfer functions can be measured using the most practical approaches – either using hammer or shaker or volume acceleration source excitation techniques. Due to the complex testing conditions that always happen in transfer function measurements of cumbersome systems [5], it is frequent to find corrupted data in a few sets of measurements.

In this scenario an attempt to perform the TPA using synthesized transfer functions, computed after a modal analysis, has been brought to completion with the aim of verifying at first the reliability of such an approach and then to assess whether this approach could be employed to substitute corrupted data with synthesized ones when the database occurred to be unreliable. It will be proved that using synthesized transfer functions yield significantly similar results to those obtained with the not-corrupted measured data. That being so, it could be thought that such an approach could solve poor quality transfer function issues that otherwise would cause to be compelled to repeat the measurements, which is costly and time consuming.

The structure of this paper is as follows. In the first Section a brief overview of the vibro-acoustic TPA performed on the AW-109 helicopter is presented giving a few details on the corrupted transfer functions acquired during tests. In the second Section the synthesized transfer functions that will substitute the measured transfer functions in the TPA model will be calculated by means of a modal analysis. The third Section is devoted to the verification of the proposed method: the results obtained with the synthesized TFs in terms of operational forces, path contributions and acoustic pressure will be compared with those obtained with the measured TFs. Eventually, some concluding remarks are given.

## The vibro-acoustic TPA on the AW-109 helicopter

The vibro-acoustic TPA is an analysis fully described by means of two sets of equations (1-2):

$$\begin{Bmatrix} F_1 \\ \vdots \\ F_n \end{Bmatrix} = \begin{bmatrix} \frac{\ddot{X}_1}{F_1} & \frac{\ddot{X}_1}{F_2} & \cdots & \frac{\ddot{X}_1}{F_n} \\ \vdots & & & \\ \frac{\ddot{X}_m}{F_1} & & & \end{bmatrix}^{-1} \begin{Bmatrix} \ddot{X}_1 \\ \vdots \\ \ddot{X}_m \end{Bmatrix} \quad [\mathrm{N}] \qquad (1)$$

$$\begin{Bmatrix} p_1 \\ \vdots \\ p_q \end{Bmatrix} = \begin{bmatrix} \frac{p_1}{F_1} & \frac{p_1}{F_2} & \cdots & \frac{p_1}{F_n} \\ \vdots & & & \\ \frac{p_q}{F_1} & & & \end{bmatrix} \begin{Bmatrix} F_1 \\ \vdots \\ F_n \end{Bmatrix} \quad [\mathrm{Pa}] \qquad (2)$$

where $\left\{\ddot{X}_1 \cdots \ddot{X}_m\right\}^t, \left\{F_1 \cdots F_n\right\}^t$ and $\left\{p_1 \cdots p_q\right\}^t$ are the acceleration, the operating force and acoustic response vectors, respectively.

Equation (1) brings into play the relation between the operating forces transmitted along the paths and the structural accelerations caused by these forces, while the second set of equations relates the acoustic responses, e.g. the noise inside a cabin, and the operating forces. Hence, it is pretty clear that by exploiting the information that the first set of equations carries it is possible to compute the acoustic responses from the second one. Indeed, it is much easier to measure the accelerations of a structure rather than the forces; these accelerations can then be employed in order to compute the operational forces which substituted in the second set of equations will lead to the final result. On the left hand side of equation (1), there are the operating forces. As it can be seen, it is necessary to invert the matrix linking the accelerations and the forces. This constitutes the biggest computational effort of the TPA. On the other hand, the matrix in equation (2) will be much smaller, and since it has not to be inverted, the computational cost of this second step is negligible compared to the first one. In the helicopter under study the vibro-acoustic TPA is performed considering the gearbox as the source and the cabin cavity as the receiver location.

The gearbox is connected to the cabin roof by means of two front struts, two rear struts and the anti-torque plate through four bolts leading to have eight structural paths. 24

accelerometers, one along each of the three orthogonal directions, have been placed on these eight paths. The transfer function matrix (equation (1)) has been obtained by exciting the structure with an impact hammer and measuring the acceleration responses. In the present work, this matrix has dimension of 48×24 and each TF is composed of 4096 spectral lines. Indeed the analysis has been pushed up to 4096 Hz (thus frequency resolution equal to 1 Hz) despite being hardly reliable at such a high frequency. But being the most important resonance peak situated far before, the analysis retains its interest. In order to have an over-determined matrix (hence 48×24) for matrix inversion purpose [3] another point close to each of the path points has been placed. In these extra positions, 24 accelerometers were placed thus building up the necessary database. The fact that the matrix is rectangular means that theoretically it is not possible to invert it. Nevertheless it is still possible to apply the singular value decomposition (SVD) and then to pseudo invert the diagonal matrix that this mathematical tool yields. Finally the acceleration vector of equation (1) (i.e. $\left\{\ddot{X}_1 \cdots \ddot{X}_m\right\}^t$) has been calculated in flight operational conditions in the 48 acceleration responses, so the operational forces can be calculated.

Concerning equation (2), the vibro-acoustic transfer functions have been obtained taking advantage of the vibro-acoustic reciprocity (i.e. $p_i / F_j = -\ddot{X}_j / \dot{q}_i$, where $\dot{q}_i$ is the volume velocity at location *j*). Therefore the TFs have been calculated exciting by means of two volume acceleration sources (LMS Q-sources) working at different frequencies, 0 - 400 Hz and 400 - 4000 Hz, and measuring the responses using the 24 accelerometers located in the eight structural paths. The sources were placed in the helicopter cabin, close to the pilot seat.

In the structural transfer functions matrix two full columns of data concerning two structural paths were completely unreliable. The coherence functions concerning these two transfer functions are particularly poor (Figure 1). In fact it has been discovered that in the transfer functions sharp peaks located between 200 and 700 Hz due to some electrical ground loops are present (Figure 2). Their magnitude could spoil the further analysis because it could make appear unjustified peaks.

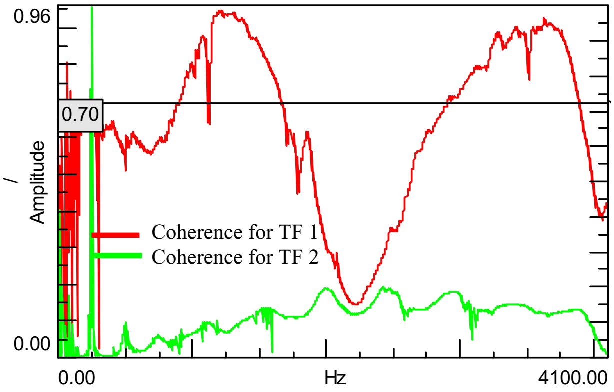

**Figure 1**: Coherence functions concerning two corrupted transfer functions (TF 1 and TF 2) in the frequency range till 4 kHz.

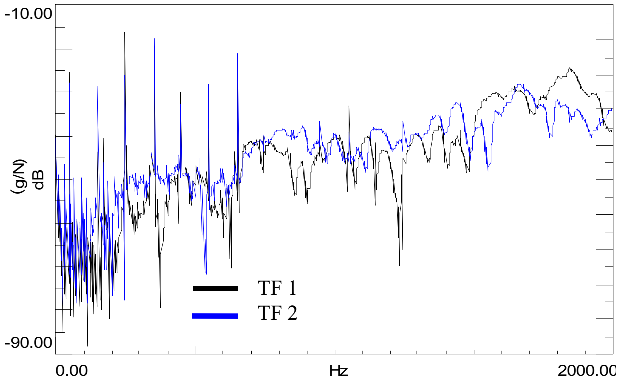

**Figure 2:** Corrupted transfer functions (TF 1 and TF 2) due to ground loops during measurements in the frequency range till 2kHz.

## Synthesis of the transfer functions

The entire structural transfer function matrix of equation (1) has been reconstructed by means of the modal parameter extraction algorithm PolyMAX [3]. The modal analysis of the cabin roof has been performed exclusively with the aim of obtaining the synthesized transfer functions. PolyMAX works properly when the modal synthesis is applied considering the full set of responses but only one reference at a time, as if the system were single input. Then, in order to have a good set of transfer functions the modal synthesis has been repeated for each of the eight paths and for all the directions, thus building the full matrix constituted by 24 references and 48 responses. More details about this modal analysis can be found in [2].

In Figure 3, an example of the application of the PolyMAX algorithm is shown. As it can be seen, the number of selected poles in the frequency range of analysis (0-4kHz) is limited to 26. Notice no poles have been selected in the range 0-100 Hz. In fact PolyMAX begins to find stable poles only at high model rank and furthermore no stable poles occur in the range 0-100Hz.

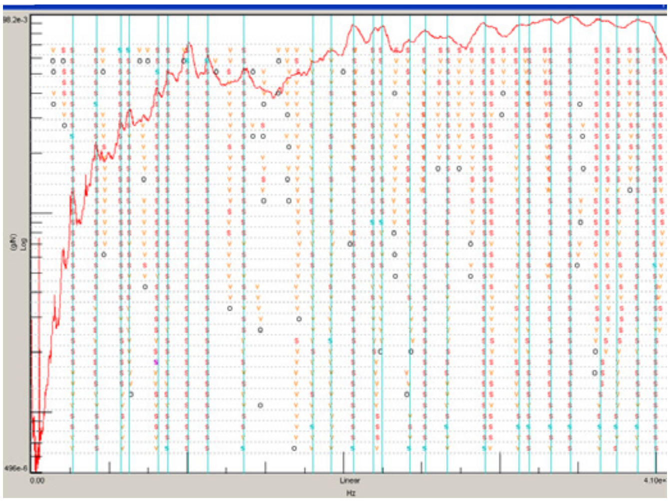

**Figure 3**: Stabilization diagram used for the modal analysis and for the further synthesis of transfer functions in the frequency range till 4 kHz. The PolyMAX algorithm has been used to estimate the system poles. The red curve is the *FRF-sum,* i.e. the complex sum of the TFs of all the measured structural points.

## Method assessment

In order to verify the proposed method, the two corrupted columns of transfer functions has been measured again obtaining good quality data (called hereafter *measured TFs*). Four different comparisons will be presented in order to assess the method.

First the *measured TFs* are compared with the synthesized one. In particular, Figure 4 depicts a *measured TF* and the relative synthesized one in the frequency range 1000-2500Hz. As it can be seen the general trend is quite respected.

Secondly, the operating forces which are calculated once the matrix inversion is computed are compared in Figure 5 and Figure 6. In particular the spectra in Figure 6 are referred to the range 800 - 2200 Hz in which most of the resonances takes place. The match between the two curves is quite impressive and gives a strong confirmation about the quality of the analysis that can be obtained using synthesized transfer functions. The fact that this bandwidth is the one which contains the most of the resonance peaks means also that this is where PolyMAX was able to find the largest number of stable poles. Hence it was expected to find a certain match between the two TPA models (i.e. the one obtained by using synthesized transfer functions and the one by *measured TFs*). It is at low frequency (Figure 5) where the models differ the most: this is due to the fact, already underlined, that at low frequency only a limited number of poles were selectable, therefore the description of the system is not complete and the synthesizes TFs can not properly represent the real behavior.

The third comparison is made considering the path contributions in terms of acoustical pressure at the receiver locations (cabin cavity), see Figure 7. The absolute values have been neglected for confidential reasons, nevertheless the color-scale is the same for both the maps. Considering both the amplitude of the path contributions and the location of the main paths, it can be stated that the models are providing the same result. Both in fact highlight the present of the resonances at the frequencies of 1793 and 1825 Hz.

Finally, the comparison between the acoustical responses calculated in the cabin cavity by using the *measured TFs* and the synthesized ones is shown. Looking at the RMS values (Table 1) the dB level is the same for both the TFs, furthermore the maximum peak level in the spectrum has similar value for both the models and occurs at the same frequency.

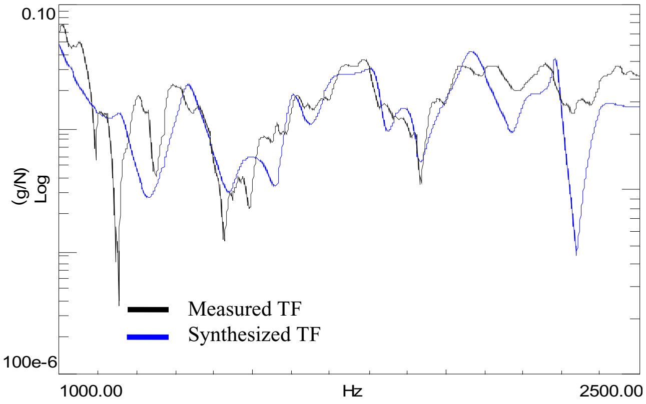

**Figure 4**: Synthesized (blue) and measured (black) TF in the frequency range 1000-2500Hz.

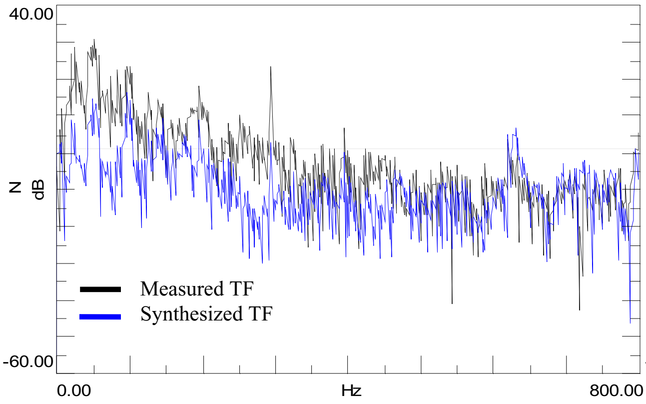

**Figure 5**: Operational forces calculated by the TPA model by using the synthesized and measured TFs in the frequency range till 800Hz.

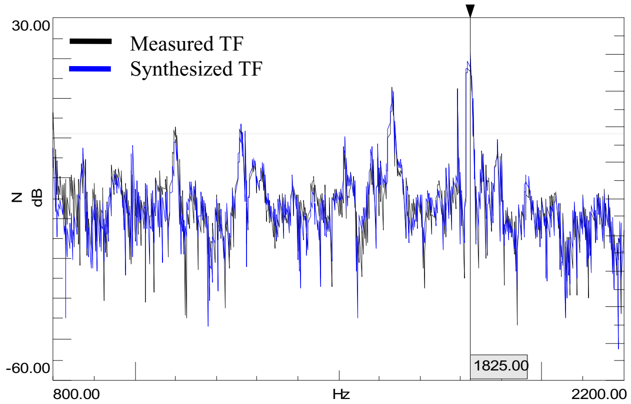

**Figure 6**: Operational forces calculated by the TPA model by using the synthesized and measured TFs in the frequency range 800-2200Hz.

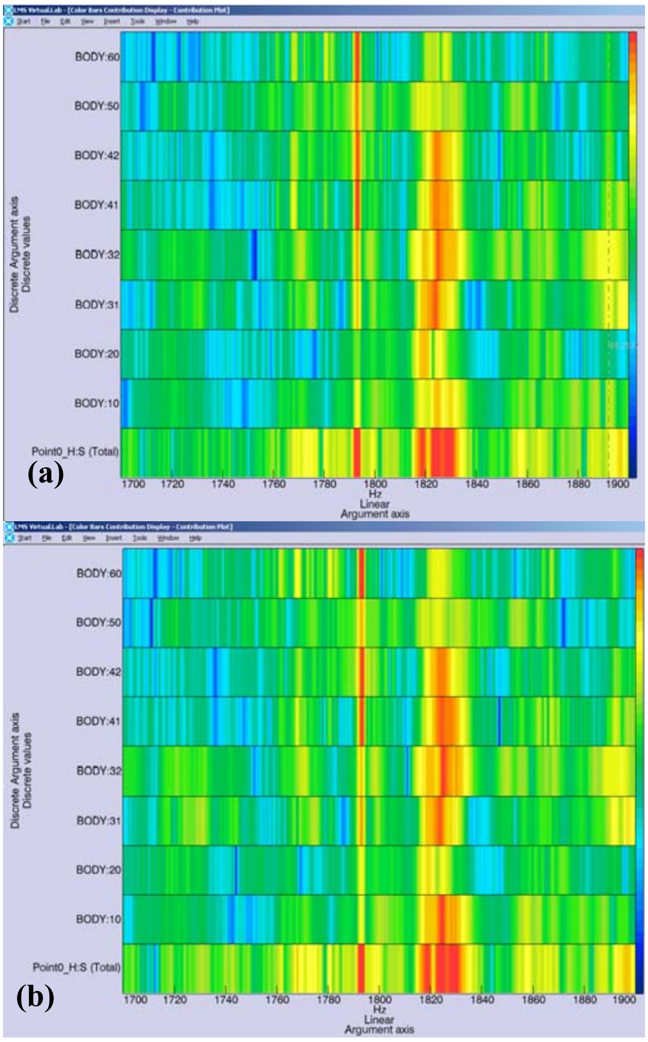

**Figure 7**: Path contribution comparisons in the frequency range 1700-1900Hz, (a) obtained with the measured TFs and (b) with the synthesized ones.

| Acoustic response curve | RMS (in 1500 – 2200 Hz) | Maximum peak [dB @ Hz] |
|---|---|---|
| Calculated with measured TF | 111.36 dB | 104.45 dB @ 1824 Hz |
| Calculated with synthesized TF | 111.81 dB | 105.32 dB @ 1824 Hz |

**Table 1:** Acoustic response comparisons in terms of RMS values (second column) and maximum peak amplitude (third column).

## Concluding remarks

A vibro-acoustic TPA performed on the AW-109 helicopter is presented. Since corrupted structural TFs were present in the database an attempt to perform the TPA using synthesized transfer functions, computed after a modal analysis, has been done. The proposed method has been verifying comparing the results of the TPA using both the measured TFs and the synthesized ones. The comparisons has been made in terms of TFs, operating forces, path contribution and acoustic response at the receiver locations.

It has been proved that using synthesized transfer functions yields significantly similar results to those obtained with the not-corrupted measured data. That being so, it could be thought that such an approach could solve poor quality transfer function issues that otherwise would cause to be compelled to repeat the measurements, which is costly and time consuming.

## References

[1] J.W. Verheij, *Multi-path sound transfer from resiliently mounted shipboard machinery*, PhD thesis, 1982.

[2] L. Testa, A. Vecchio, L. Bregant, *Transfer path analysis of the Agusta Westland AW-109 performed by means of in-flight data and PolyMAX synthesized FRFs*, Proceedings of ISMA2008, Leuven, Belgium, 2008, September 15-17.

[3] P. Mas, P. Sas, K. Wyckaert, *Indirect force identification based upon impendance matrix inversion: a study on statistical and deterministical accuracy*, Proceedings of ISMA19, Leuven, Belgium, 1994.

[4] B. Peeters, H. Van der Auweraer, P. Guillaume, J. Leuridan, *The PolyMAX frequency-domain method: a new standard for modal parametrs estimation?*, Shock and Vibration 11 (2004) 395-410.

[5] E. Pierro, E. Mucchi, L. Soria, A. Vecchio, *On the vibro-acoustic operational modal analysis of a helicopter cabin,* Mechanical Systems and Signal Processing 23 (2009) 1205-1217.