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EXPERIMENTAL NOISE TRANSFER PATH ANALYSIS ON THE HELICOPTER A109

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Abstract: An experimental vibroacoustic Transfer Path Analysis is performed for the first time on the helicopter Agusta A109. The proposed approach considers the helicopter gearbox as the main source affecting cabin vibroacoustic comfort and focuses on the structural joints connecting the gearbox to the helicopter frame, which correspond to the main transmission paths.

Vibroacoutsic Frequency Response Functions are measured on a test mock-up consisting of a helicopter A109 grounded and with “body-in-white” boundary conditions. Operational data are measured in simulated operating conditions - on the grounded mock-up - and during flight. Matrix inversion method is used to compute dynamic loads. The experimental data are used to implement a TPA model of the helicopter that allows computing the operating loads acting on the gearbox joints during flight manoeuvres, pointing out a number of critical noise tonal components affecting cabin comfort, and identifying and ranking the main transmission paths.

Once operational loads, critical frequency components and critical transmission paths are known, the TPA model is used to simulate a number of noise reduction scenarios and to predict the effect of active control system in cabin or design modifications at source level.

The analysis focuses on the connecting points between the gearbox and the helicopters frame and shows that noise comfort improvement can be achieved with an active control systems acting on the anti-torque plate hosting the gearbox. In this respect, the model also provides an estimate for the value of the dynamic forces that are required to secure improvements in cabin comfort.

1 INTRODUCTION

Noise levels recorded in helicopters' cabin are severely affected by the strength and vicinity of noise sources. The jet engines, the gearbox and the rotors can be considered as separated sources - whose spectral content is strongly tonal and rpm dependant - exciting simultaneously the cabin's acoustic cavity. Under the hypothesis of linear behaviour, the total sound pressure level measurable in the cabin can be considered as the summation of a number of partial pressure contributions, each generated by one source acting separately. The mechanism responsible for transferring the mechanical energy from each sources to the target location can be either structure borne - via the mechanical joints connecting the gearbox to the helicopter's frame - or airborne - via the sound propagation in the air.

Analysis techniques such as Transfer Path Analysis have been largely applied in the automotive industry that allows identifying the main transmission paths and their relative contribution to the total sound pressure level at target location. From a theoretical standpoint there is not reason why TPA should be limited to cars. An helicopter is a more complex system then a car, but this actually implies that there may be more noise sources, hence more transfer paths, with a direct impact on the size and the completeness of the complex stiffness matrix and therefore on the reliability of the matrix inversion process (conditioning number).

An experimental TPA approach is hereby applied for the first time to the helicopter Agusta A109, to assess noise source contribution to the cabin noise and to simulate a number of realistic noise reduction scenarios. Issues related to the application of a standard automotive technique to a more complex system are discussed with special focus on test data completeness and model validation.

Data collected through a number of experimental tests carried out both on the ground and in-flying conditions on the helicopter Agusta A109 are used to implement a numerical TPA model. The model points out the most critical transfer paths and paves the way to a number of simulations that allows predicting the noise reduction achievable in the helicopter cabin for a given reduction of the source strength and as result of structural modifications. The analysis focuses on the connecting points between the gearbox and the helicopters frame and shows that noise comfort improvement can be achieved with active control systems acting on the anti-torque plate hosting the gearbox.

2 THE A109 HELICOPTER MOCK-UP

A full-scale mock-up of an Agusta A109 helicopter was made available for testing. The mock-up consists of a real helicopter A109, which was reduced to "body-in-white" conditions as for standard TPA testing in automotive. Body-in-white condition is obtained by removing the tail rotor, the turbines, the landing gear, all the cabin interior lining and any sound proofing treatment with the only exception of the ceiling panel, a honeycomb structure embedded into two aluminium sheets.

Two punched shell-shaped metal sheets are attached to the rotor shaft and replace the main rotor to simulate the drag effect of the rotor hence to reproduce actual loading on the gearbox without endangering safety-proof laboratory conditions. Two electrical motors drive the gearbox hence the small rotor providing a power level equivalent to about 20% of the actual power available with the two jet engines mounted on the flying helicopter. Figure 1 and 2 show the helicopter mock-up in laboratory conditions and the coordinates system used in the test campaign;

Figure 1: mock-up coordinate system

Figure 2: A109 helicopter mock-up

3 THE TRANSFER PATH ANALYSIS TECHNIQUE

TPA is an experimental analysis technique that allows identifying the most relevant transfer mechanisms of the vibroacoustic energy from the generating sources to a number of target locations. These transfer mechanisms are also referred to as energy paths and once identified, can be ranked and separately analyzed. The technique makes intensive use of measured test data in the view of experimentally modelling and reconstructing a number of sources, Transfer Functions and target levels. Dedicated test techniques are often required to provide not-easy-to-measure data such as operating loads. The general theory underlining the TPA and some of the most used dedicated testing techniques will be briefly reviewed in the following paragraphs.

3.1 TPA Theory in brief

A consolidated technical approach often encountered in literature ([1][2]) makes use of three basic elements to describe any vibroacoustic propagation phenomena: the source, the transmission path or vibroacoustic system and the receiver location or system response (Figure 3).
The source is the location where the generating mechanism for the vibroacoustic energy takes place. In cars this namely refers to the engine and the gearbox as sources of mechanical vibrations, tail pipe exhaust, tyres and vibrating trim panels as sources of acoustic loads.
The transmission path relates how the energy generated by the sources reaches the target locations. The transmission can be either structural – structure borne TPA – if a structural link between source and target locations allows transmitting vibrations, or acoustical – airborne TPA – if the transmission is realized by pure acoustic propagation.
Finally the target location or the receiver is the place where the effects of the vibroacoustic excitation are recorded (system response) and is the target location for any noise and or vibration reduction action. Such an action is ultimately meant to improve the vibroacoustic comfort for the users (e.g. vehicle's driver and passengers).

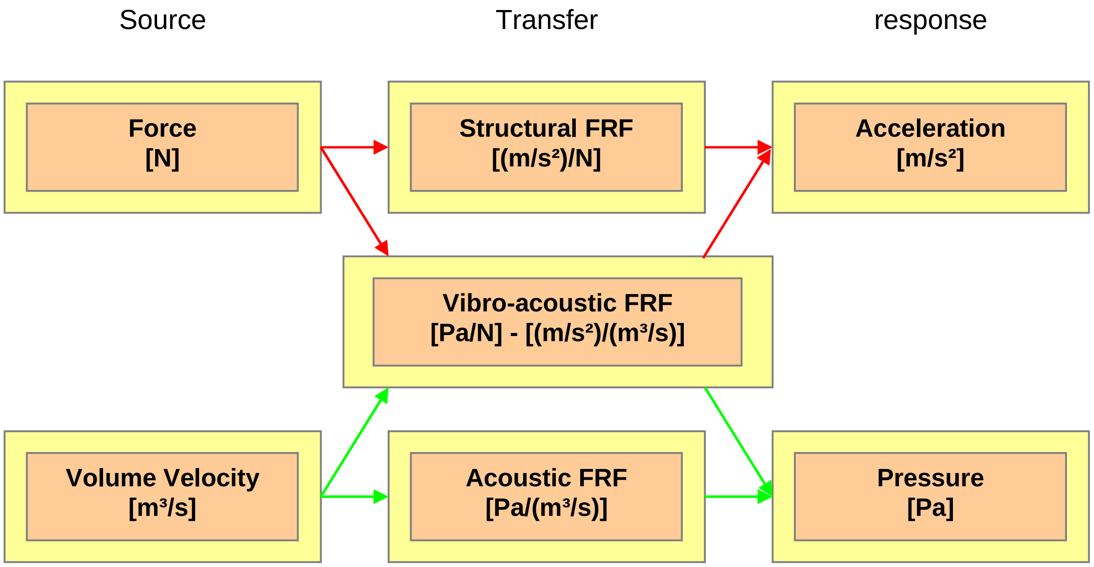

Figure 3: FRF-based model of vibroacoustic system

The basic methodology uses a Frequency Response Functions (FRF) model description of the vibro-acoustical system, which relates a loading or excitation vector $\{s(\omega)\}$ to the target response vector $\{t(\omega)\}$ by mean of an FRF matrix $[H(\omega)]$

$$\{t(\omega)\} = [H(\omega)] \; . \; \{s(\omega)\} \qquad (1)$$

where s (or the source) can be a force, $\{s(\omega)\} = \{f(\omega)\}$ or a volume velocity $\{s(\omega)\} = \{Q(\omega)\}$ depending on whether structural or airborne path are respectively considered. Likewise the sources, responses can be respectively either accelerations $\{t(\omega)\} = \{\ddot{x}(\omega)\}$ or pressures $\{t(\omega)\} = \{p(\omega)\}$.

In a real mechanical system, several sources and targets locations can be defined. TPA considers sources and targets as two different subsystems connected to each other by means of a number of more or less stiff connections (e.g. the engine mounts) forming the so-called transfer paths.

If the system is composed of N transfer paths, then the total target response can be written as the sum of the partial responses from the individual paths.

$$t(\omega) = \sum_{i=1}^{N} \frac{T(\omega)}{S_i(\omega)} \; . \; s_i(\omega) \qquad (2)$$

$\{t(\omega)\}$ is the target response which can be a function of frequency or rpm, $\dfrac{T(\omega)}{S_i(\omega)}$ is the frequency response function between the target and the applied source (force or volume velocity) for transfer path i, $s_i(\omega)$ is the operational force or volume velocity at transfer path i.

Operational forces have to be used for a structural path. Volume velocities are needed for airborne path analysis.

TPA technique requires FRFs for all transfer paths at the target locations. These are normally measured after disassembling the sources from the structure in order to eliminate source cou-

pling of the FRFs. Each direction at a given location constitutes a separate structural transfer path, hence FRFs have to be measured in all directions.
Hammer impact, or shaker excitation can be used as artificial source when measuring FRFs. The response can be acoustical or a mechanical. Airborne transfer paths are typically measured in a reciprocal way. The excitation is realized by a volume velocity source at the receiver location while the response is measured with a microphone at the source location.

3.2 Structure borne TPA of the Helicopter A109

In case of transmission of the vibroacoustic energy from mechanical sources to acoustic target, the terms of Eq. 1 are respectively forces and pressure, thus Eq.2 can be rewritten as

$$p(\omega) = \sum_{i=1}^{N} \frac{P(\omega)}{F_i(\omega)} \cdot f_i(\omega) \qquad (3)$$

or in matrix form

$$\{\ p\ \} = \left[H(\omega)\right] . \{\ f\ \} \qquad (4)$$

which indicates that the total pressure at target location is calculated as sum of the partial contributions of each single transfer paths.

$$\begin{Bmatrix} p_1 \\ \vdots \\ p_M \end{Bmatrix} = \begin{bmatrix} P_1/F_1 & \cdots & P_1/F_N \\ \vdots & \ddots & \vdots \\ P_M/F_1 & \cdots & P_M/F_N \end{bmatrix} \cdot \begin{Bmatrix} f_1 \\ \vdots \\ f_N \end{Bmatrix} \qquad (5)$$

In the case under study single reference TPA approach has been used. This consists of considering only one coherent excitation as the prevailing one. This was indeed the case for the Helicopter A109, where focus was on the evaluation of the impact of the gearbox on the vibroacoustic comfort in the cabin of the helicopter.

3.3 The vibroacoustic reciprocity

To measure the vibroacoustic FRF's $P(\omega)/F_i(\omega)$ in the A109 mock-up, the vibroacoustic reciprocity property was enforced. This states that the matrix $\left[H(\omega)\right]$ is symmetric and can be formulated as follows:

$$\left(\frac{P_j}{F_i}\right)_{\dot{Q}_j\ =\ 0} = -\left(\frac{\ddot{X}_i}{\dot{Q}_j}\right)_{F_i\ =\ 0} \qquad (6)$$

where
$\dot{Q}_j$ is the Volume Velocity of the acoustic source at the location j $\left(m^3/s^2\right)$, P_j is the acoustic pressure at the location j (Pa), F_i is the force acting at the location i (N), and $\ddot{X}_i$ is the measured acceleration at the location i $\left(m/s^2\right)$.

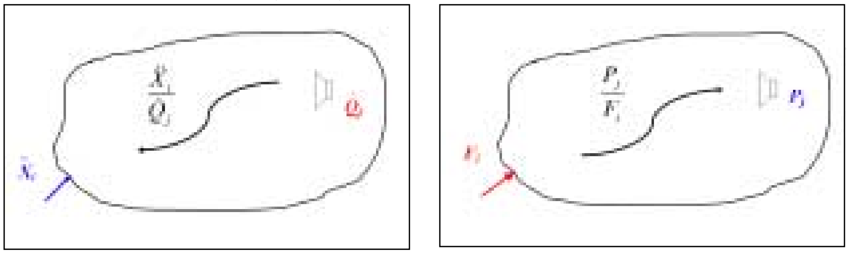

Figure 4: The reciprocity property

As a result, the reciprocity property makes it possible to excite at target location with a volume velocity source and measure acceleration at source location. The resulting FRFs are equal to the ones measured acquiring pressures at target locations and exciting with a force at source location (Figure 4).

3.4 Operating loads

Operating loads are the dynamic loads acting on the system under analysis in working conditions. These loads are required for a structural transfer path analysis. In case of an airborne source analysis, operating volume velocities and accelerations are required.

Operating forces can be directly measured from experiments or derived indirectly from other physical quantities using the following analytical procedures.

3.5 Complex dynamic stiffness vs. matrix inversion method.

In cases mounts are used to isolate the target from the source, operational forces can be determined indirectly using the complex dynamic stiffness of the mounts and the operational displacements at either side of the mount during operation. The method is based on the following equation:

$$f_i(\omega) = K(\omega)(X_s(\omega) - X_t(\omega)) \tag{7}$$

$f_i(\omega)$ is the operational force at transfer path $i, K(\omega)$ is the complex dynamic stiffness as function of frequency ω, $X_t(\omega)$ is the displacement at the mount connection at the target side $f_i(\omega)$, $X_s(\omega)$ is the displacement at the mount connection at the source side.

As no mounts are used to connect the gearbox the helicopter roof, this method is not applicable on the case under discussion and another technique must be applied to identify the operational forces.

In case subsystems are linked through rigid connections, the dynamic stiffness method yields inaccurate results. This also occurs for mounts whose stiffness is much larger than for the rest of the structure such as only minimal relative displacements are measurable under normal operating conditions.

In these cases a matrix of FRFs needs to be acquired. FRFs are measured between the structural (accelerations) or acoustical responses due to force excitation at all transfer paths. The resulting FRF matrix is then inverted and combined with operational measurements of the structural responses. This allows obtaining an estimate for the operating forces.

$$\{\ f\ \} = \left[G(\omega)\right]^{-1} \ .\ \{\ \ddot{x}\ \} \tag{8}$$

or in matrix form

$$\begin{Bmatrix} f_1 \\ \vdots \\ f_N \end{Bmatrix} = \begin{bmatrix} \ddot{X}_1/F_1 & \cdots & \ddot{X}_1/F_N \\ \vdots & \ddots & \vdots \\ \ddot{X}_M/F_1 & \cdots & \ddot{X}_M/F_N \end{bmatrix}^{-1} \cdot \begin{Bmatrix} \ddot{x}_1 \\ \vdots \\ \ddot{x}_M \end{Bmatrix} \tag{9}$$

In order to avoid numerical problems in the matrix inversion, singular value decomposition methods can be used. The number of responses *(M)* should at least be equal to the number of input forces to be estimated *(N)*, in order to have a unique solution for the operational forces.

However, the set of equations can be over determined by taking more response measurements at the target side *(M > N)*. This can be achieved adding extra measurements points (3 digit labels in Figure 5) at locations other than the main transfer path locations but very near to them (2 digit labels in Figure 5). This allows obtaining a better least square estimate and results in more accurate computation of the operating forces.

The matrix inversion was performed for the two cases of main paths only and main paths plus all the additional measurements points (secondary paths). The resulting FRF matrix showed a slightly better conditioning number in the second case. However, for both cases except for the very low frequency range, the FRF matrix is well invertible and the computed operational forces accurate.

In the application case under analysis, hammer test technique was applied to acquire a sufficient number of structural FRFs on the mock-up. The structure exhibits a linear behaviour responding with overlapping FRFs to different input strengths with a quite satisfactory fulfilment of the reciprocity property.

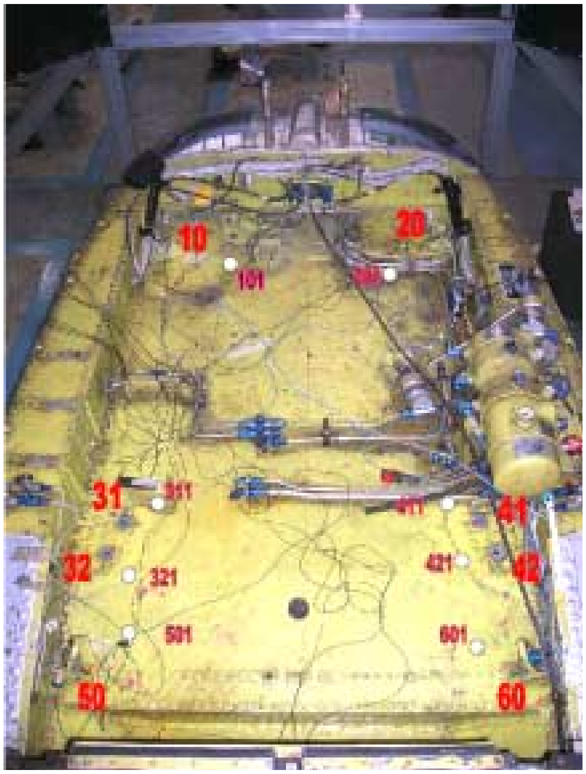

Figure 5: Transmission paths: main paths (2 digit labels), secondary paths (3-digit labels).

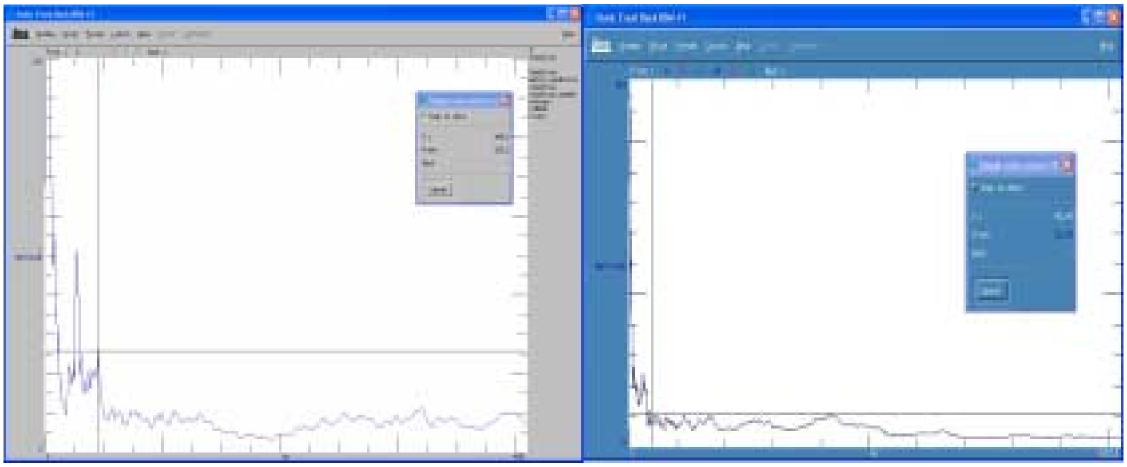

Figure 6: Matrix conditioning number vs. frequency. Main paths only (left) and with additional secondary paths (right).

4 EXPERIMENTAL TRANSFER PATH ANALYSIS

A structural transfer path analysis of the A109 mock-up is performed in the frequency band 15-4000 Hz. The main rotor and the gearbox are considered as the most relevant excitation sources. Eight connections points between the gearbox and the helicopter's frame (four struts and the four bolts on the anti-torque plate) are selected as transmission paths. Targets locations are in the helicopter cabin; one near the pilot's seat, the other one at the back seat.

Figure 2: local coordinate system on a strut

Figure 3: volume velocity sources at target location

The gearbox is disconnected from the frame and reciprocity property is applied to measure the vibro-acoustic transfer functions. To this goal, specially designed volume velocity sources are used that excite the cabin cavity with a random signal. Accelerations are correspondingly measured at the connecting points. In order to apply the matrix inversion method, also structural transfer functions are measured in a number of locations on the helicopters frame. Finally, operational accelerations in correspondence of the transmission paths are measured with the gearbox mounted on the mock-up and rotated by the two electrical motors, up to the gearbox nominal rotational speed.

4.1 Noise Transmission Paths on the A109 mock-up

The spectral analysis of the computed operational loads combined with a spectral analysis of the sound pressure levels measured in the helicopter mock-up cabin during simulated operating conditions leads to the identification of a number of critical frequency tones that show a very efficient noise transmission mechanism in the helicopter cabin.
Out of a list of critical frequencies, 3 main tones are hereby identified that are responsible for generating the largest contribution to the cabin noise spectrum (Figure 7). These tones correspond to the rotor shaft rotation and two of the gearbox meshing frequencies (one being related to the Gleason gear). The noise path analysis will then focus on those frequencies only.

Looking at the different paths, the operational load spectra shows that path 60 (corresponding to the rear right strut) in the Z directions exhibits the highest levels and provides the major contribution to the cabin noise at the identified critical frequencies. Sorting out all path contributions, it appears that the paths 42 (boomerang), 50 and 60 (respectively rear left and rear right struts) all in the Z direction, are the main contributing transmission paths for the rotor shaft tone (Figure 8).
Paths 31, 32, 41 and 42, all in the X direction are the main contributors to the main gearbox meshing frequency (Figure 9). Those paths corresponds the gearbox anti-torque plate and the X direction corresponds to the boomerang plane.

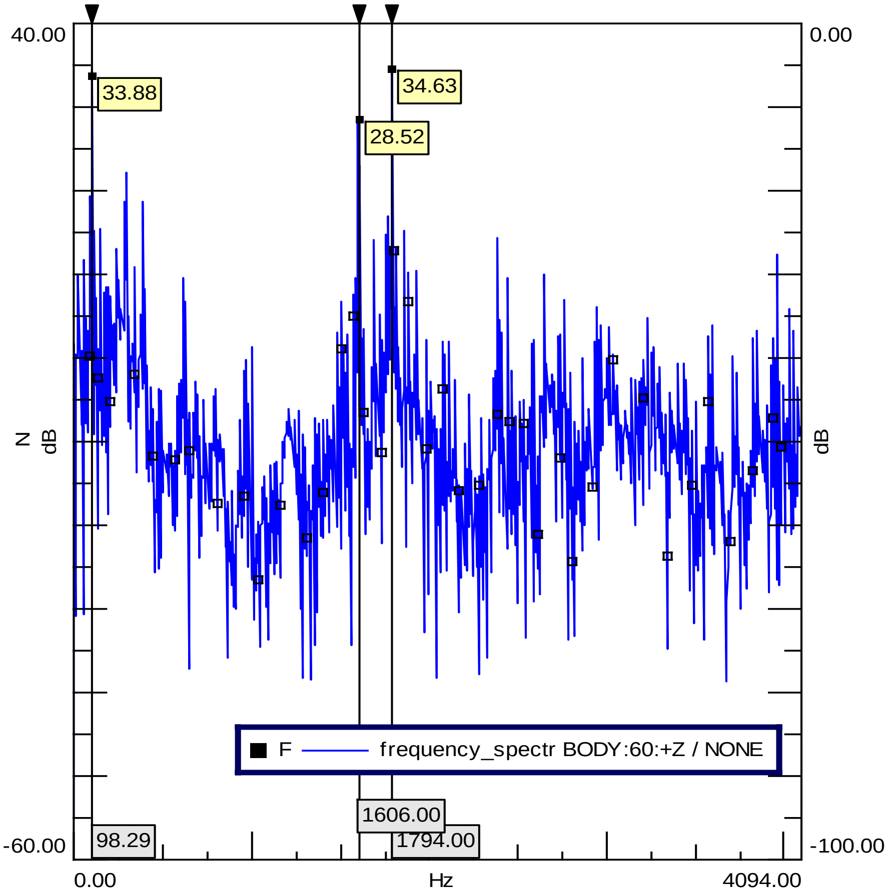

Figure 7: Operational force. Path 60 direction Z

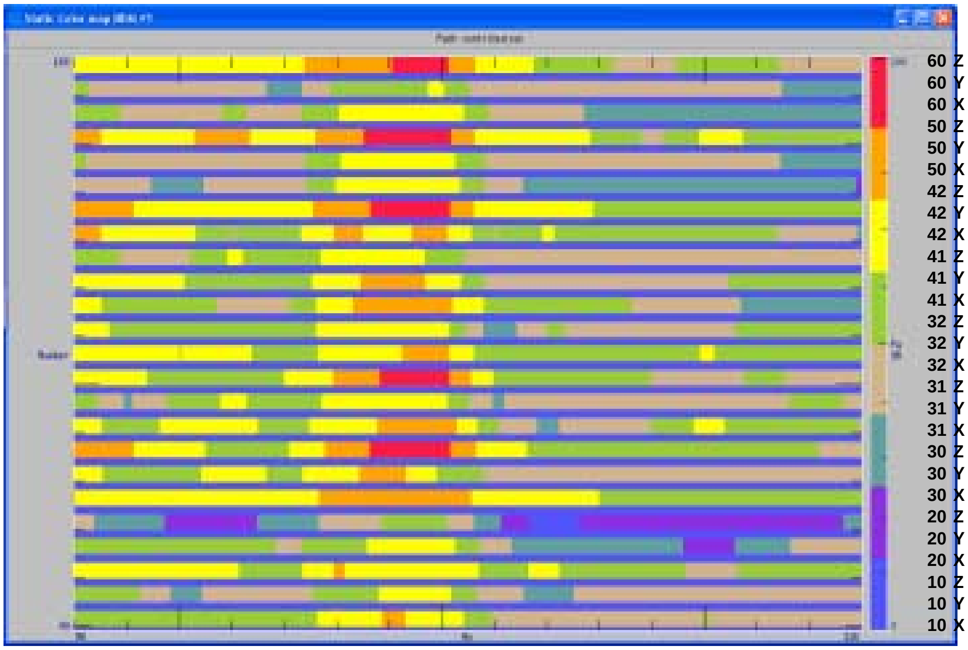

Figure 8: transmission path, rotor shaft frequency

Figure 9: transmission path, gearbox meshing frequency

Similarly to main gearbox meshing frequency, also for the meshing tone related to the Gleason gear, the paths which contribute the most to the cabin noise are path 42 X and 42 Y. These transmission paths correspond also to the boomerang.
This means that the any action aiming at reducing cabin noise recorded at those frequencies should focus on the anti-torque plate; more specifically the in-plane forces must be suitably controlled to achieve any relevant noise reduction result.

5 SIMULATION OF ACHIEVABLE CABIN NOISE REDUCTIONS.

Once the main noise transmission paths contributing to the cabin noise are identified for the most critical noise frequency, the TPA model can be used to simulate the noise reduction that can be achieved if structural modifications would be implemented on the helicopter structure or on the gearbox.

Two simulation scenarios are thus presented. One consists of introducing a modification in the TPA models; this can be easily done by editing the FRF of a selected transmission path and, e.g., zeroing the FRF amplitude in correspondence of the selected frequency. This is equivalent to simulating an active noise control system that induces a modification in the FRF of a specific transmission path. A second one consists of simulating a source modification that results into a frequency shift of q selected critical frequency. This corresponds to simulating a design modification in the gearbox resulting into q shift of the meshing frequency. The TPA model is then run again to compute a new set of partial pressure contributions to the interior cabin noise.

In order to select the best target frequency to be treated by the noise reduction simulation, a simple spectral analysis is carried out that shows the effect of zeroing the cumulatively the previously identified critical tones and compute the rms noise reduction that results from that action.

Figure 10 shows that suppressing the main gearbox meshing frequency tone results into 5 dB(A) SPL reduction (Figure 10, left) as the SPL decreases form 111 dB(A) (dark green bar) to 106 dB(A) (light green bar).

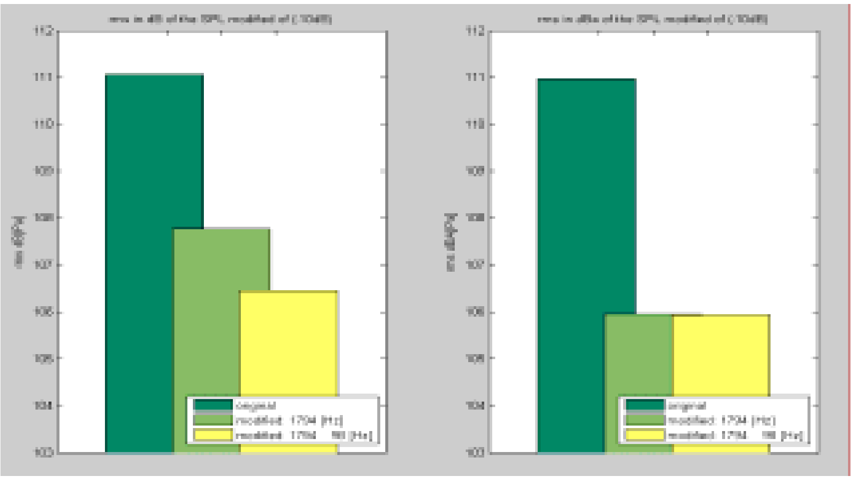

Figure 10: Noise reduction cumulative effect after suppression of 2 noise tonal critical components.

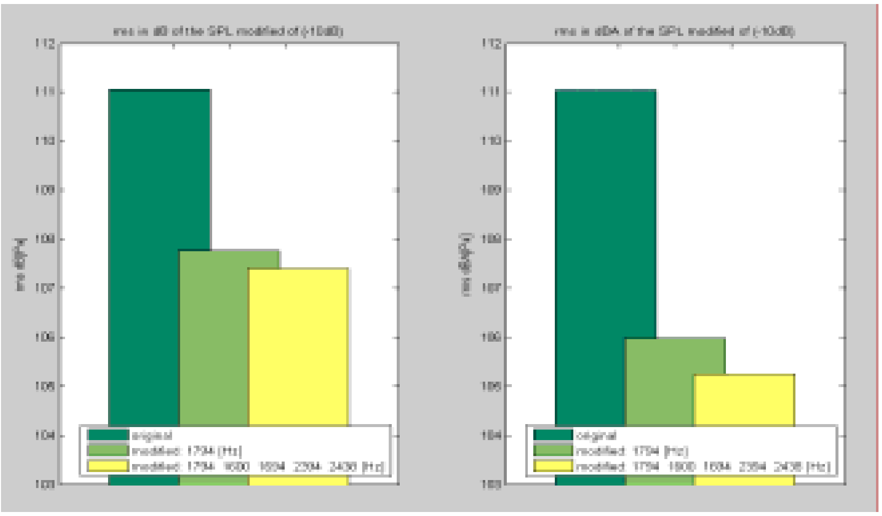

Figure 11: Noise reduction cumulative effect after suppression of 5 noise tonal critical components.

The suppression of the rotor shaft frequency does not give much more reduction (yellow bar), yet suppressing the 5 highest tones results into 1dB(A) more noise reduction (Figure 11).

The first simulation scenario is implemented by zeroing the gearbox meshing frequency tone for the most relevant transmission paths. Figure 12 (left side) shows the editing of the FRF and the resulting SPL reduction (right side). In Figure 13 the vector representation of SPL in cabin is reported corresponding to the modification of the FRF relatively to the most critical transfer paths.

Figure 14, shows that controlling the main 4 critical path a reduction of more than 5 dB(A) can be reached.

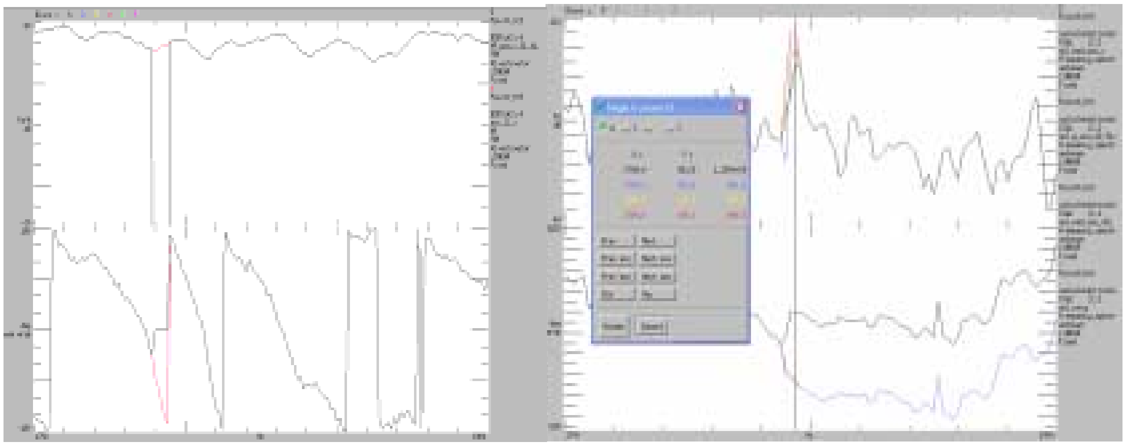

Figure 12: FRF modification at the meshing frequency: original (red) vs. modified (blue).

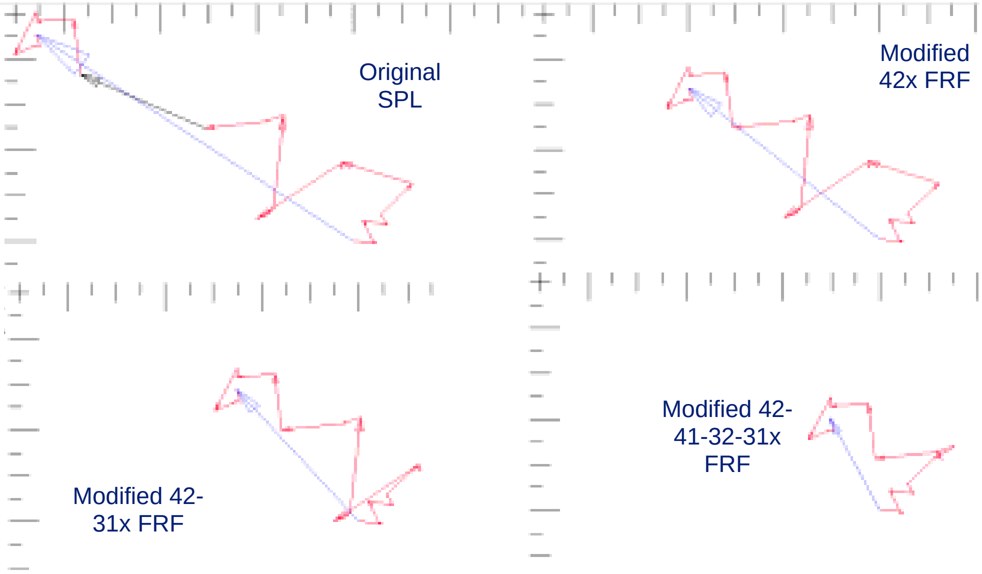

Figure 13: SPL vector representation for FRF modifications at different path.

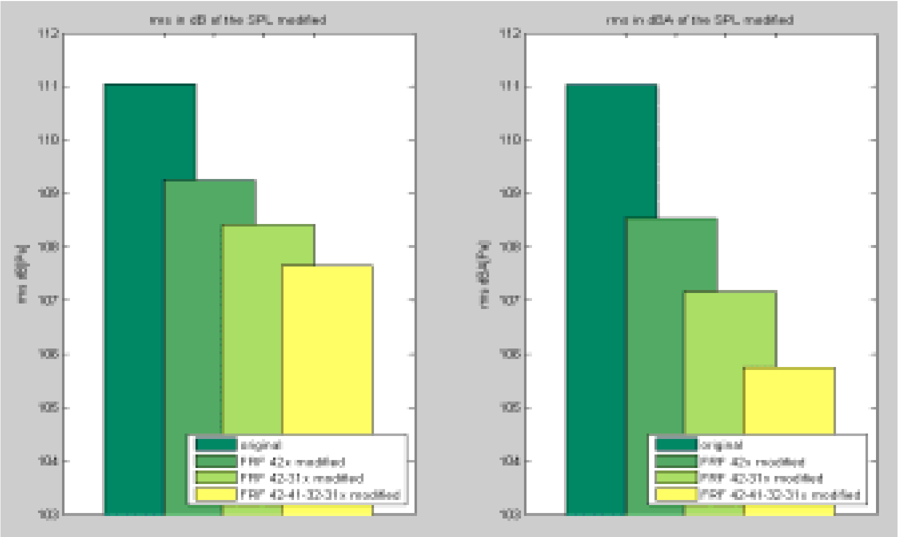

Figure 14: SPL reductions corresponding to the FRF modifications at different path.

The second scenario consists of simulating a modification at source level. The source is the gearbox; the target frequency is again the meshing tone. The objective is to simulate the effects of a design modification of the gearbox that would results into a frequency shift for the Gleason gear meshing tone and for the correlated shaft rotation frequency of the hydraulic pump mounted on the gearbox casing. Any variation in the Gleason gear design parameters (gear diameter, number of teethes, RPM, etc.) will result in a change of the meshing frequency. This implies that all the operational accelerations will be reduced at that frequency.
10 dB reduction in all the operational accelerations results into a remarkably lower SPL. The results of the simulation are shown in Figure 15 in vector form and in Figure 13, where a reduction of 5 dB(A) can be observed (yellow bar).

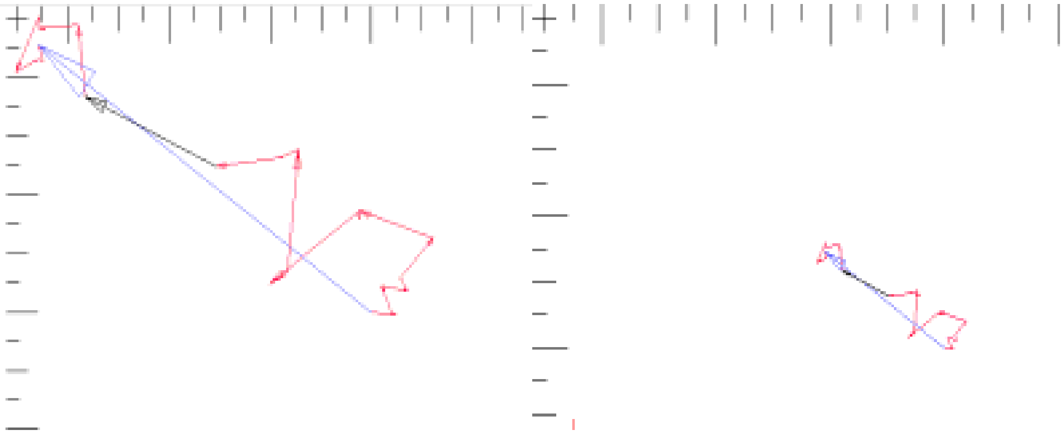

Figure 15: SPL vector representation for source modifications at meshing frequency

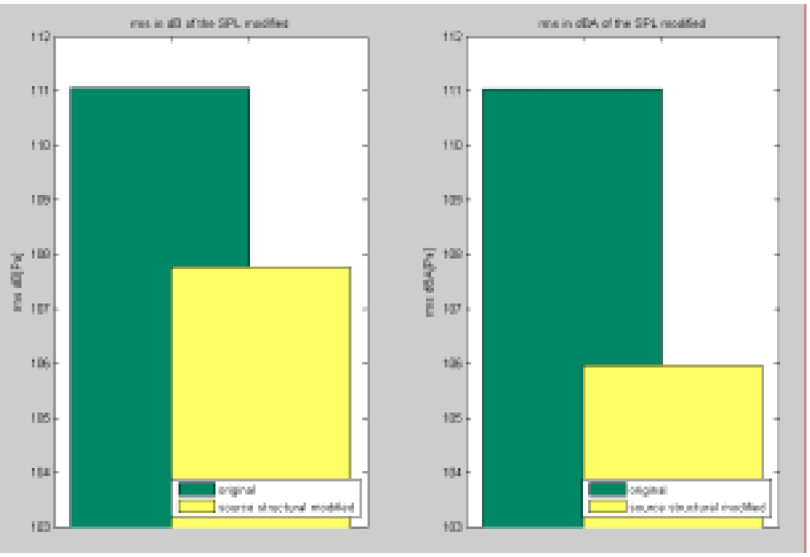

Figure 16: SPL reductions corresponding to a source modification at meshing frequency.

6 CONCLUSIONS

An experimental Transfer Path Analysis is performed on the helicopter Agusta A109, under the assumption that the gearbox is the main source affecting vibroacoustic comfort in cabin. Experiential data are collected on a helicopter mock-up that makes it easier to access and modify the experimental set-up. The mock up is a “body in white” helicopter and can reproduce real operating conditions both in terms of RPM regimes and NVH operational loads.

The experimental TPA model consists of structural-acoustical FRFs measured on the mock-up in reciprocal way, structural FRFs on 8 joints connecting the gearbox to the helicopters frame and 2 sets of operational accelerations measured respectively on the ground and in flight conditions. Matrix inversion method is applied to compute operational loads.

Paths contribution analysis allows pointing out a subset of critical frequency tones that are transmitted into the helicopter cabin and a sub-set of transmission paths contributing the most to the cabin noise.

Two simulation scenarios are finally presented that allow predicting the noise reduction achievable in the helicopter cabin for a given reduction of the source strength and as result of structural modifications in the transmission paths. The results show that noise comfort improvement can be achieved with active control systems acting on the anti-torque plate hosting the gearbox.

7 ACKNOWLEDGEMENTS

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