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HYBRID MODELLING OF A HELICOPTER GEARBOX

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Abstract
A hybrid modelling technique is presented that uses test data measured on an industrial test-bench to characterize the acoustic behaviour of a helicopter's gearbox in operating conditions. The proposed approach uses inverse technique to compute the gearbox surface velocities leading to the identification of hot spots on the gearbox surface and paving the way to noise source localization. Direct boundary element techniques are then used to propagate back the pressures and compute the gearbox acoustic power for different operating conditions.

INTRODUCTION

In the quest for quieter, faster and more efficient transportation means, the helicopter industry is currently investing in research and development programs aimed at improving NVH performances of helicopters. The development of a quieter helicopter requires a systematic study of its vibroacoustic behaviour, with special attention to the operating conditions. Dedicated experimental techniques such as Transfer Path Analysis are in use in the automotive industry that can help identify relevant noise sources and provide hints for design improvements. TPA is a hybrid modelling technique based on experimental data that allows identifying the energy transmission paths from sources to target locations. The availability of a reliable TPA model paves the way to the prediction of achievable comfort improvements induced by design modifications at sources level or on the transmission paths.
An important requirement of TPA modelling is to quantify the vibroacoustic sources and rank them by relative strength. In this respect, the applicability of TPA on a complex test article such as a helicopter requires special attention to localize the most

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critical noise sources. A common opinion amongst helicopter manufacturers states that the main noise sources active on helicopters are the jet engines the rotors and the gearbox. The latter is usually recognised as the most important source affecting cabin comfort. In order to experimentally prove this assumption, testing techniques such as Acoustic Intensity measurements could be used to characterize the helicopter gearbox, but this would require testing under controlled conditions, ideally in anechoic rooms. Unfortunately test-benches capable of operating a helicopter gearbox are not always compatible with noise testing requirements, therefore sub-optimal test conditions apply that may endanger data quality. In such case, hybrid modelling can help improve reliability and accuracy in the estimation of source locations and strengths.
This paper presents the results of a numerical simulation of the acoustic behaviour of a helicopter gearbox in operating conditions. The model uses experimental data acquired on a dedicated test-bench and allows computing surface velocities leading to the identification of vibrations hot spots that are responsible for noise radiation. Furthermore, the model allows using computed velocities to predict sound pressure levels measured over a virtual microphone grid positioned around the gearbox and thus to compute the gearbox sound power in different operating conditions. The analysis focuses on some selected frequencies that are considered the most critical for interior acoustic comfort in the helicopter cabin.

EXPERIMENTAL CAMPAIGN

A test campaign is carried out on a dedicated gearbox test-bench. The test-bench is able to run the helicopter gearbox under simulated running conditions. This includes the possibility to rotate the gearbox at the nominal RPM, while variable loading conditions are applied through a dynamic braking system acting on the rotor mast.

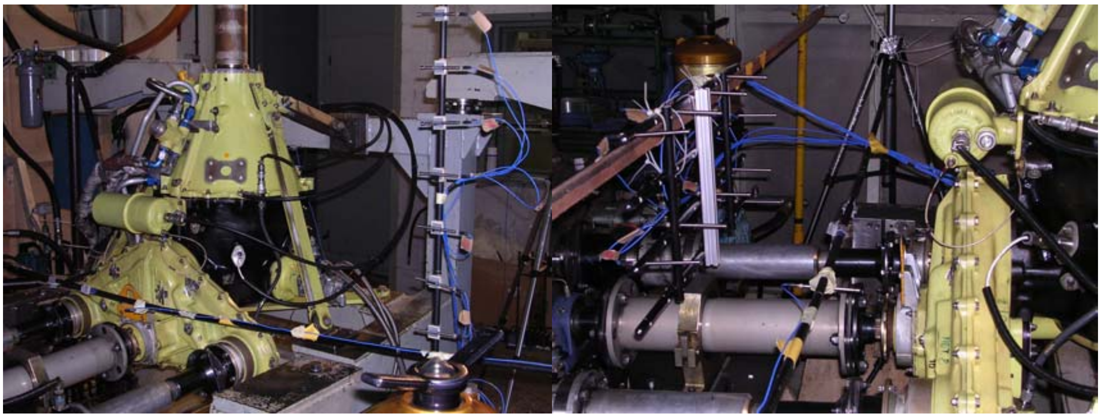

Figure 1 – Test set-up (left) and a particular of the backside mixing system (right)

The test article is a complete helicopter gearbox in a dynamic configuration that reproduces exactly a real helicopter's assembly. This consists of four rods connecting the gearbox casing to the helicopter's frame, and one anti-torque plate hosting the gearbox case. Two electrical engines located outside the test room and able to provide up to 110% of the full jet engine power, rotate the gearbox. A specially designed mixing system, located on the backside of the gearbox, is in charge of merging the input power of the two engines, and transmitting it to the gearbox gearings and the tail rotor. A cinematic chain starting form the mixing system activates the tail rotor and completes the test-bench, which perfectly reproduces real operating conditions.

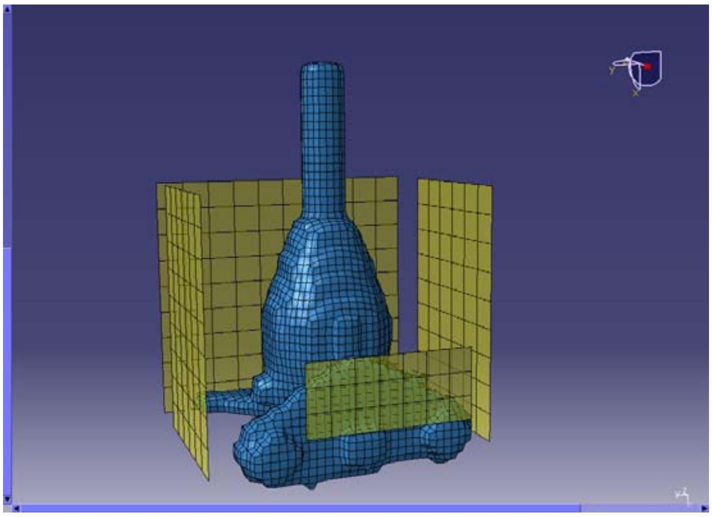

Figure 2: the microphone measurement grids

The tests consisted of rotating the gearbox at nominal speed and measure sound pressure levels over four microphone grids placed at 70 cm distance of form the gearbox surface (Figure 2). Given the large number of measurement locations, a multi-patch testing technique is used that allows roving a 10 microphone line-array over several locations and running the test-bench at the same testing conditions, until the measuring grid is covered. Three reference microphones, located respectively in front of the test-bench, on the left side and on the backside, are left at a fixed position during the whole acquisition process. Finally a number of accelerometers are mounted on the gearbox surface in correspondence of the gearbox satellite carrier, the anti-torque bar, and the mixing system.
The test bench is driven according to a numerically controlled program that consists of running-up the gearbox from 0 RPM up to nominal speed (about 10 seconds) than holding on at nominal speed for about 20 seconds, finally running-down the gearbox until the rotational speed is again zero. The program is repeated for tree different load conditions, namely 50%, 75 % and 100% of the maximum engine power. Time data are acquired and cross-power spectra are computed for all grid points with respect to a reference sensor.

ANALYSIS OF THE TEST DATA

A simple spectral analysis allows identifying the most relevant noise components. A dedicated labelling exercise is carried out that consists of the identification of all relevant tonal frequencies in the spectrum and the correlation of each tone with the gearing parameters (teeth numbers, rpm, gearing ratios, etc). This is done in order to identify the gearbox component that is responsible for the noise generation at a given frequency. Such analysis is beyond the scope of the present paper and will not be reported in detail. However, it is significant to refer that the spectral analysis and a TPA model combining gearbox noise with operating measurements taken in the helicopter cabin, show that one of the most critical frequencies is the so-called meshing frequency. The inverse BEM model will therefore focus on this frequency to the aim of identifying the source location originating such a noise component.

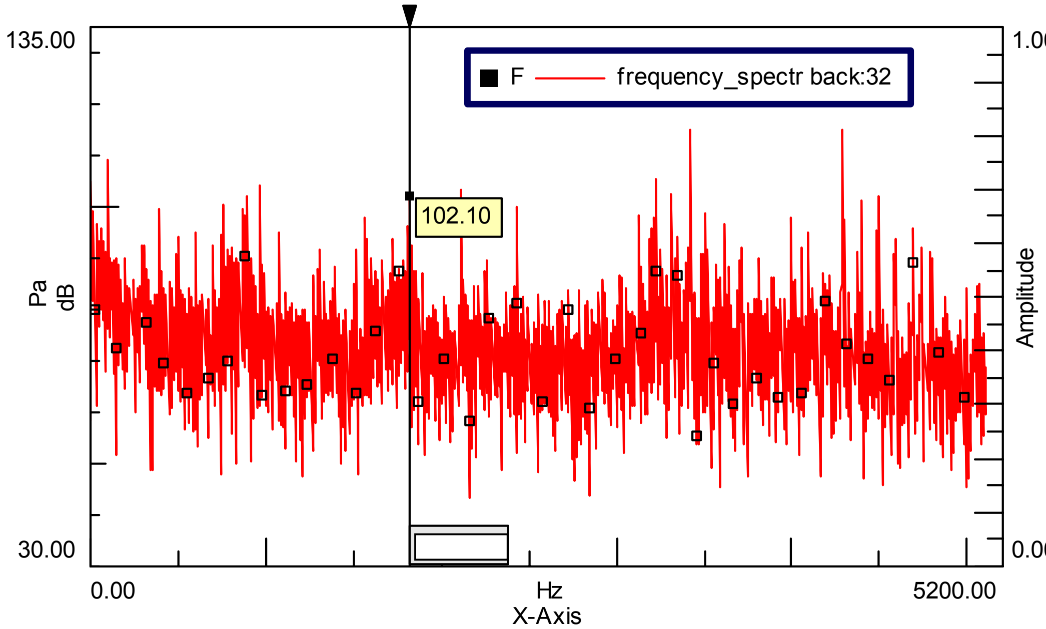

Figure 3: Noise spectrum, microphone on the backside (mixing system)

LINEAR ACOUSTICS AND INVERSE NUMERICAL ACOUSTICS

An exhaustive formulation of inverse numerical acoustic can be found in literature [1-3], however in the following a succinct description is provided of the most relevant concepts such as the Acoustic Transfer Matrix (ATM) relating the field pressure p_f and surface normal velocities v_n .

The general equations describing the acoustic propagation in an elastic means are the equation stating the principle of conservation of mass and momentum. In the hypothesis of linear behavior and for small pressure perturbations regimes, these equations can be simplified in a “linearized” form: the wave equation, governing time domain acoustics and the Helmholtz equation, governing frequency domain acoustics.

An acoustic system can be represented by three elements: a source, a transmission path and a target location. If such a system is linear, a linear input output relationship can be established between the mechanical surface vibrations generating sound waves (input) and the sound pressure at a number of locations in space (output). These locations are discrete and are generated by "discretization" of the continuous domain, which is an engineering process consisting of the subdivision of the vibrating surfaces into a finite number of patches or vibration panels. The input-output relationship can then be formulated as:

$$\{Sound\ \mathrm{Pr}essure\} = [Acoustic\ Transfer\ Matrix] \bullet \{Surface\ Velocities\} \tag{1}$$

where $\{Sound\ Pressure\}$ is a column vector containing the sound pressures at the different locations, $\{Surface\ Velocities\}$ is a column vector containing the structural velocities of the vibrating panels and [*Acoustic Transfer Matri*x] is the system matrix relating input and outputs. In particular, the surface velocities of the vibrating panels are the normal component of the structural velocities, since only the normal component concurs to the generation of sound waves. If $\{v_{ns}\}$ is the surface velocities column vector (where index *ns* denotes the normal components of structural velocities) and *p* is the sound pressure level at a single microphone location, the matrix relationship becomes:

$$p = \{ATV(\omega)\} \cdot T - \{v_{ns}(\omega)\} \tag{2}$$

where ω denotes the frequency dependence.

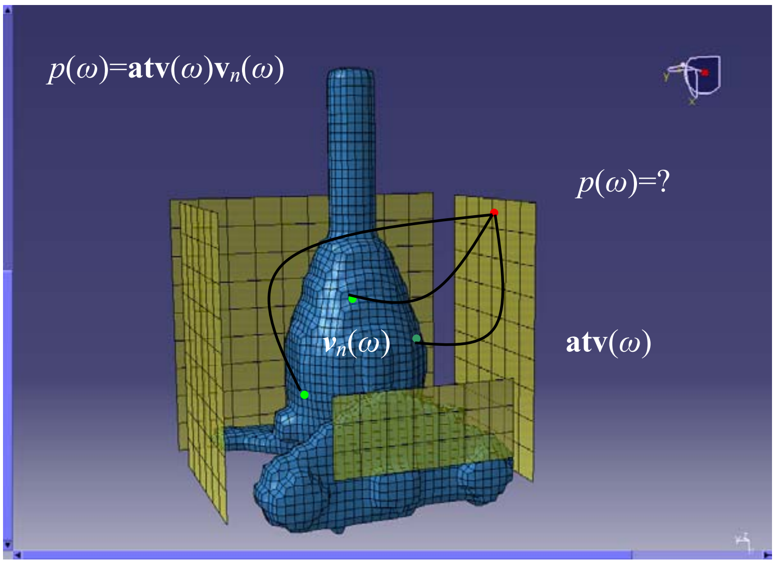

Figure 4: the ATV Matrix concept

The Acoustic Transfer Vector concept (ATV) also referred to as acoustic contribution vectors or acoustic sensitivity, is an set of Acoustic Transfer Functions relating the normal vibration velocities of a number of discrete panels, to the sound pressure at a single microphone location (Figure 4). The matrix ATM depends only on system parameters such as geometry of the vibrating surfaces, microphones positions, etc.
Inverse Numerical Acoustics is a computation techniques based on the Acoustic Transfer Vector concept that allows inverting the direct propagation problem (from source to target) and solve the inverse problem (from target to source).

In Inverse Numerical Acoustics, the input output relationship between field point pressure and normal structural velocity is given by:

$$p(\omega) = \{ATV(\omega)\}^T - \{v_{ns}(\omega)\} \tag{3}$$

or, in matrix form and for multiple field points:

$$\{p(\omega) = [ATV(\omega)^T]\bullet\{v_{ns}(\omega)\} \tag{4}$$

This relation can be inverted and used to back calculate the normal structural velocity on the radiating surface from the measured acoustic pressure levels measured in a grid of field points:

$$\{v_{ns}(\omega)\} = \{[ATV(\omega)^T]\}^{-1}\bullet\{p(\omega)\} \tag{5}$$

This formulation allows using the ATV principle for acoustic source localization and quantification and it is of particular interest when the source is not accessible for physical testing (rotating or moving machineries, weight or temperature limitations). The inversion of the input output relationship is obtained computing the inverse of the Acoustic Transfer Matrix. This is done using Singular Value Decomposition and the L-shape regularization curve to select tolerance and accuracy for the inversion. The boundary conditions for a boundary element model are hence obtained thought the inversion of the ATM matrix, using experimental pressure values. As the number of nodes of a BE model is usually much higher than the dimension of the vector p this leads typically to an ill-posed and ill-conditioned problem [3]. The solution is optimized through a procedure based on Truncated Singular Value Decomposition (minimal norm solution).

INVERSE BEM OF THE GEARBOX

The above-described method is applied to the helicopter gearbox. First the ATVs are calculated (Figure 5). Then the boundary conditions are applied to the model. This step consists of imposing the surface velocities in correspondence of the mesh points where the accelerometers were placed together with the sound pressure values measured on the microphone grids surrounding the gearbox.

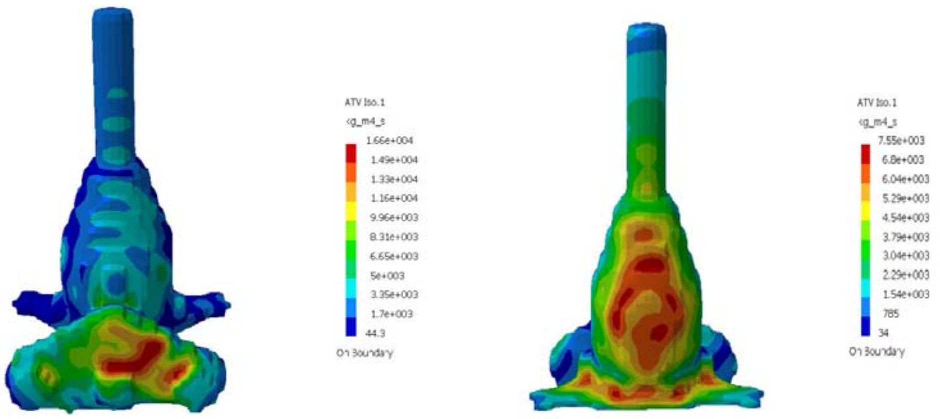

Figure 5: the ATVs on the gearbox surface. Right: back side; left: front side

Before inverting the ATV matrix the L-shape stabilization curve is computed and a tolerance of 0.01 is selected that determines the max number of singular values to be used for the inversion (Figure 6). Usually a number of iterations is required to find the optimal value of tolerance.

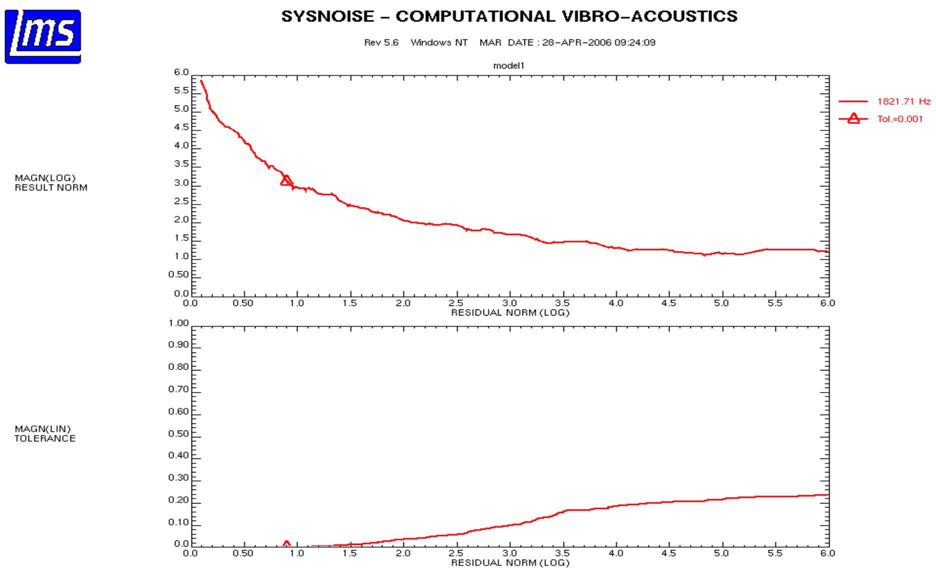

Figure 6: the L-shape regularization curve for the inverse model

Finally, the surface velocities are calculated according to eq. 5. The result is that the surface velocities (Figure 7) show two clear hot spots in correspondence of the mixing system and the connections of the anti-torque bar.

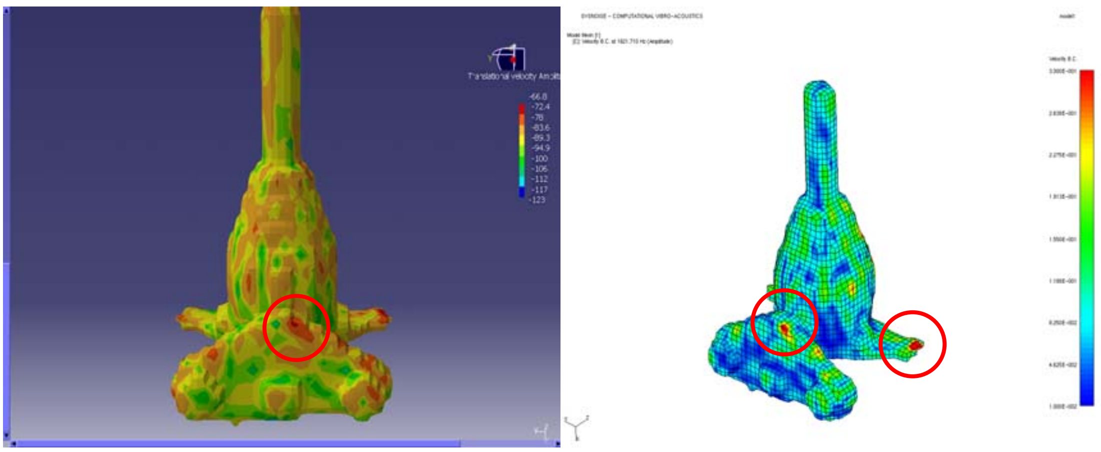

Figure 7: gearbox surface velocities at meshing frequency (back view and side view)

This correlates very well with the pressure measurements. Figure 8 shows that the pressure maps plotted on the measuring grids confirms that the high noise level recorded on the back panel is generated by the mixing system. Surface velocities allow computing the gearbox sound power emitted at different operating conditions.

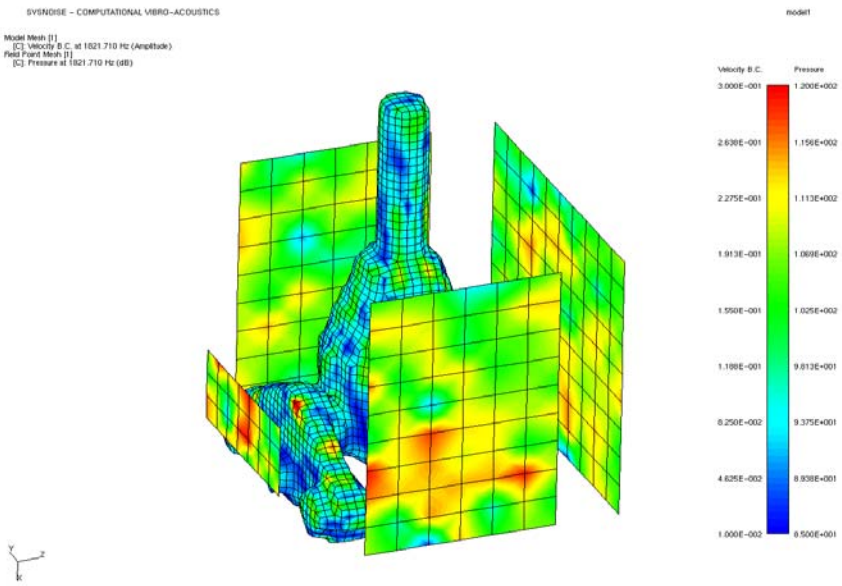

Figure 8: gearbox surface velocities and grid pressures (meshing frequency)

CONCLUSIONS

A boundary element model is developed to characterize the vibroacoustic behavior of a helicopter gearbox. Experimental sound pressure data are used as the input of an inverse problem aimed at computing surface normal velocities. The computed velocities allow identifying hot spots on the gearbox surface that are potential targets for design improvements. In particular, at the gearbox meshing frequency, noise sources are clearly localized on the gearbox mixing system that are responsible for a highly effective noise propagation. The sound pressure levels measured on the back microphone grid correlates very well with the surface velocities for that frequency.

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