COMPREHENSIVE APPROACH FOR NOISE REDUCTION IN HELICOPTER CABINS

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Abstract

The work presented here settles down in the general framework of a “Comfortable Helicopter” Research program, and particularly focuses on acoustical comfort improvement in helicopters’ cabins. To optimize internal noise levels at given added sound-proofing weight, space and cost constraints, one needs both to have a good knowledge of noise sources and path contributions to the interior noise and to develop some efficient and innovative sound-proofing concepts adapted to the sources frequency content and localization in the helicopter. This paper presents the comprehensive approach chosen by Eurocopter including a diagnosis and modelling methodology based upon the coupling of Nearfield Acoustical Holography measurements and geometrical acoustics simulations. Innovative noise reductions concepts such as optimized sound-proofing panels and windows and Main GearBox suspension devices have been developed. All these solutions have been tested in flight. Finally, the achieved overall performances obtained on the demonstrator are highlighted, insisting on the significant comfort improvement obtained in flight and on Eurocopter expectations for further noise reductions.

NOMENCLATURE

NAH	Nearfield Acoustical Holography
MGB	Main Gear Box
GRIM	Green Ray Integral Method
S_{vi}	Vibrating Surface *i*
Pvi(M)	Acoustical Pressure generated by a vibrating surface S_{vi} at a Point M in cabin
R_{ai}	Transmission Loss of panel *i* before modification
R_{bi}	Transmission Loss of panel *i* after modification
Gv	Green function (for a panel V)
dB SIL4	Speech Interference Level, 4-octave average
H/C	Helicopter
MCP	Maximum Continuous Power

1. INTRODUCTION

The demanding increase of comfort by the helicopter customers requires continuous efforts on various fields such as vibrations, thermal, ergonomics, aesthetic and acoustics. The work presented here settles down in the general framework of a “Comfortable Helicopter” Research program, and particularly focuses on acoustical comfort improvement in helicopters’ cabins. The targets of this research program were to fly a demonstrator exhibiting significant internal noise comfort improvement based upon an EC155 helicopter in offshore configuration.

The noise levels measured in helicopters are severely affected by the strength and the vicinity of noise sources, and reducing these levels implies acting on all noise sources (gearboxes, engines, rotors and turbulent boundary layer) and transfer path (airborne and structure borne). Several challenges are to be tackled, as the optimization of the sound proofing requires taking into account the weight, space and cost constraints. To comply with these objectives, one needs both to have a good knowledge of noise sources and path contributions to the interior noise and to develop some efficient and innovative sound-proofing concepts adapted to the sources frequency content and localization in the helicopter.

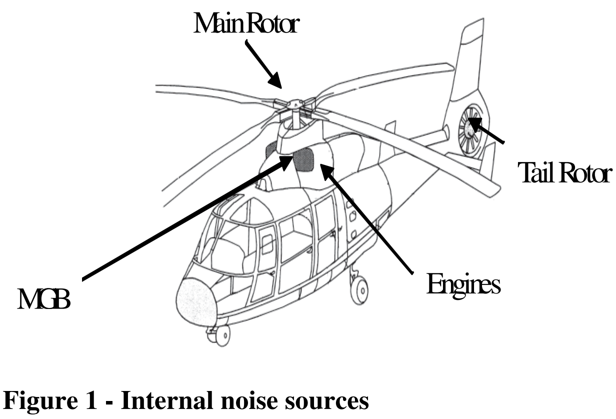

Figure 1 - Internal noise sources

The diagnosis and modelling approach chosen by Eurocopter relies on both in-flight Nearfield Acoustical Holography measurements inside the cabin, coupled with geometrical acoustics simulations. This methodology is validated on a full aircraft case and proves to be suitable for the targeted mid and high frequency range.

From this modelling approach and from innovative noise reduction concepts, the choices of the most suitable technologies, adapted to the internal noise sources frequency content and localization in the helicopter cabin, have then been made considering all the other internal constraints. These technologies have been validated through laboratory tests and simulations, and implemented on a demonstrator.

This paper presents this comprehensive approach. In a first part, the chosen methodology for the diagnosis and modelling approach of noise sources contributions is discussed and validated on a full helicopter case. Then, the main noise reduction technologies implemented on the demonstrator are presented. Finally, the achieved overall performances obtained on the demonstrator are highlighted, insisting on the significant comfort improvement obtained in flight and on Eurocopter expectations for further noise reductions. In the end, some perspectives of applications of these technologies to the retrofit of existing aircrafts and to the future Eurocopter helicopters are drawn.

2. DIAGNOSIS AND MODELLING APPROACH

2.1. Diagnosis

The goal of this diagnosis phase is to locate the main radiating zones and the leaks in the cabin, so as to apply efficient noise reductions techniques. Because of the numerous reflexions of the acoustical waves in the cabin and of the complexity of the cabin interiors, the diagnosis cannot be performed with a single microphone measurement technique. The idea developed during the PhD study [10] was to benefit from recent evolutions in antenna techniques enabling to complete the spectral analysis of the sources by their spatial structure analysis. Based on practical and theoretical comparisons, the chosen technique was Nearfield Acoustical Holography. The latter is widely described in the literature ([1], [2]). Validation tests, for internal applications in reverberant environments similar to a helicopter cabin, have been performed. They are presented in [7], [9], and [10]. Finally, the implementation of such a measurement in a helicopter cabin in flight has been described in [3] and [10]. An example of such sound pressure cartography is presented on Figure 2.

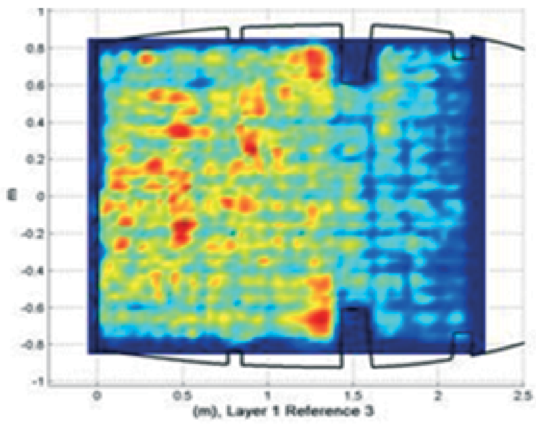

Figure 2 – Example of NAH measurement result – EC155 cabin roof panel.

The analysis of the in-flight measurements results obtained on several measured surfaces for a wide frequency band enabled to assess globally the weak points of the serial sound-proofing definition. These results confirmed previously known information, but also enabled to quantify the effect of these phenomena and to detect additional noise sources. This analysis was of critical importance for the development of adequate noise reductions devices presented in section 3.

2.2. Modelling

The modelling approach chosen is based on the coupling of NAH normal velocity output results on all the measured surfaces of the cabin, with the geometrical acoustics software ICARE ([6], see example on Figure 3 below). This approach is presented in [8].

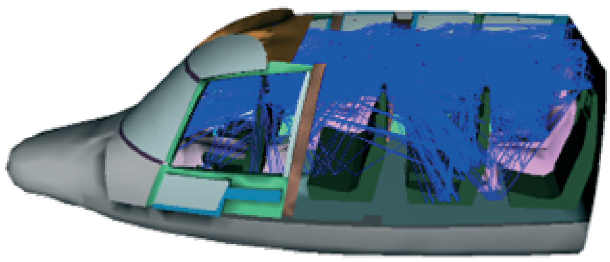

Figure 3 - Example of beam tracing calculation results with ICARE.

The so-called GRIM methodology described in [4] and [5] allows to calculate the sound pressure $P_{Vi}(M,\omega)$ at any point M in the cabin, generated by the different panels S_{vi} of the helicopter cabin, from the knowledge of the panel vibration velocity field V derived from the NAH measurement and of the Green functions Gv computed with a beam tracing algorithm:

(1) $P_{Vi}(M,\omega) = \int_{S_V} j\omega\rho V(Q,\omega) G_V(M,Q,\omega) dS(Q)$

The complex summation of the contribution for all the measured vibrating surfaces enables to rebuild the total sound pressure at any point M in the cabin.

(2) $P(M,\omega) = \sum_i P_{V_i}(M,\omega)$

Noise measurements performed at passenger's ears on the same helicopter used for the NAH measurement campaign were used to assess the quality of the reconstruction. The average measured and calculated third octave spectra are presented on Figure 4. It can be seen from this figure that the quality of the calculation results is very good for frequencies higher than 800Hz, while they overestimate the noise levels at lower frequencies. This is mainly due to the fact that both NAH and geometrical acoustics techniques are well adapted to high frequencies domain, but present some limitations at low frequencies. Nevertheless, the overall assessment is that the results give a good approximation of noise levels expressed in dB SIL4 (Speech Interference Level, 4-octave average), which is the frequency band at stake here.

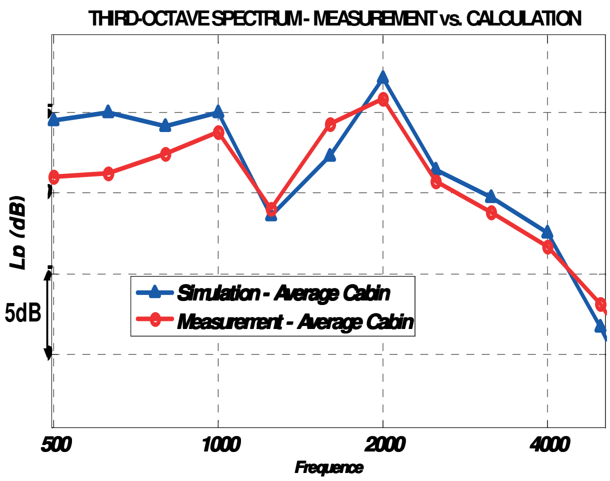

Figure 4 - Measured vs. calculated Noise Spectra

The proposed methodology, which, in addition, has been widely validated through several tests presented in [9], allows thus to rank the contribution of each measured panels in the cabin with good confidence.
An example of the global contributions obtained for one particular measurement condition is given on Figure 5.

More detailed analyses have been performed to identify the contributions of each panels and windows, for all frequency bands. These results are not presented here.

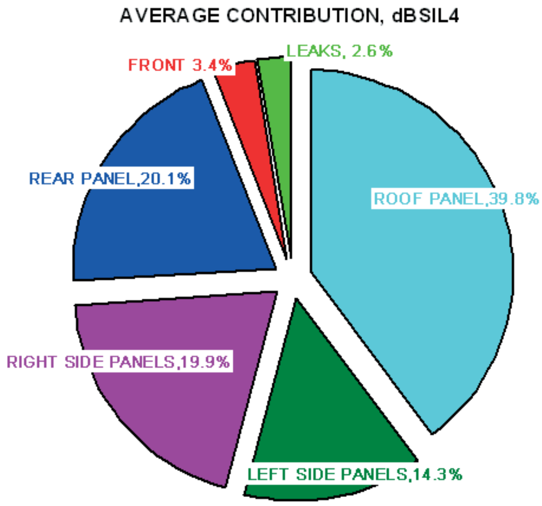

Figure 5 - Average Contribution in the cabin dB SIL4

2.3. Comprehensive approach for noise reduction simulations

On the one hand, the approach coupling measurements and simulations is consequently used to identify the zones that should be particularly sound-proofed, and the frequency bands for which these treatments should be efficient.

On the other hand, the simulation results are used to roughly assess the noise reductions to be achieved when applying sound-proofing modifications on the panels S_V of the cabin.
The methodology chosen here relies on the knowledge of the transmission losses of the initial a_i (measurement configuration) and modified b_i panels on the surface *i*:

(3) $P_{V_i}(M,\omega) = \iint_{Sv} j\omega\rho \sqrt{\frac{\tau_{bi}(\omega)}{\tau_{ai}(\omega)}} V_i(Q,\omega) G_V(Q,M,\omega) dS_V(Q)$

Where,

(4) $R_{ai} = 10.\log(\frac{1}{\tau_{ai}})$ and $R_{bi} = 10.\log(\frac{1}{\tau_{bi}})$

, are the transmission losses of panel a_i and b_i.

The latter can be obtained, either from measurements performed in EC coupled reverberant and anechoic chambers, either from calculations with the in-house code PIAMCO developed with ONERA ([11], [12]). Examples of the results given by this code are given in paragraph 3.3.
The total noise levels in the cabin with the new set of sound-proofing panels {bi} at any position M in the cabin is then calculated with the formula (2), as the summation of all internal panels and windows contributions.

Several sets of sound-proofing configurations can be calculated, and the internal noise levels can thus be optimized based on weight, cost, and space constraints.
The chosen approach is quite simplistic because it does not take into account the phase shifts that are introduced by the modifications of the panels. Nevertheless, the results prove to be acceptable. An assessment of this global approach is given in section 4 of this paper.

This optimization phase depends obviously on the performances of the noise reduction techniques that can be implemented. Several concepts have been developed and tested in the frame of this research program. They are presented in the next section.

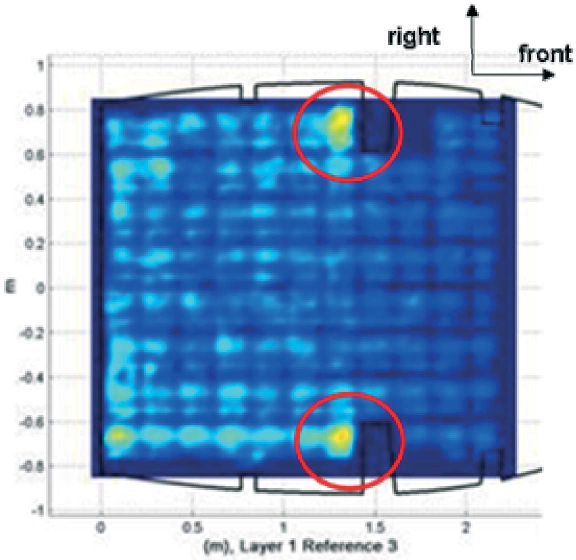

Figure 6 - Leaks detections in the structure

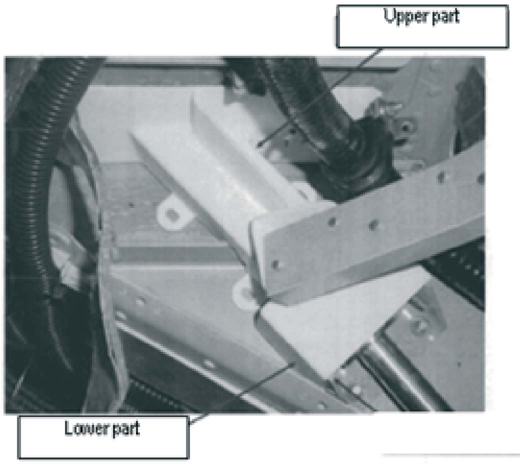

Figure 7 - Example of Cover on structure leaks

3. INNOVATIVE NOISE REDUCTION CONCEPTS

The optimization of the internal noise levels in the cabin requires working on any contributing noise source and path. Several issues have then be treated during this research program, among them the sound-proofing panels, the window panes, the structure damping layer and the leaks. The choice and selection of appropriate technologies have been made according to the results obtained in the diagnosis and modelling phase, with the goal to act on all noise sources, on both airborne and structure borne path.
One of the main constraints for the demonstrator was that these technologies had to be implemented with a limited weight increase, acceptable for an offshore helicopter. Moreover, these technologies had to reconcile with thermal, vibratory, ergonomics and aesthetic effects.

Some examples of the developments made during this program are presented in this section.

3.1. Leaks

Among the weaknesses that were highlighted on the serial H/C NAH measurement, several holes in the cabin structure or between existing panels were identified. Depending on their positions in the cabin, these leaks produce some disturbing noise sources in their near field. The example of leaks generated for flight controls feedthroughs behind a main frame are presented on Figure 6.

Some appropriate parts were designed to treat the leaks presented on the above picture. An example of dedicated cover is presented on Figure 7.

Several other leaks detected on acoustical imaging results were treated with lightweight materials. In the same idea, new doors seals have been developed in order to reduce the leaks.

3.2. Structure damping

One of the concepts used to decrease internal noise levels relies on the addition of patches of constrained visco-elastic materials that are bonded to the structure. These patches enable to decrease the noise radiated from the structure by a mass and damping effect. However, even if this concept is very efficient for internal noise reduction, the associated added weight is an issue. One of the targets here was to optimize the ratio performance versus added weight on the helicopter.
On the one hand, this was achieved thanks to the application of a new damping material with some characteristics adapted to the temperature and frequency range of the helicopter. On the other hand, this ratio was improved through the optimization of

the locations at which the patches are bonded to the structure, thanks to a detailed analysis of NAH measurement results.

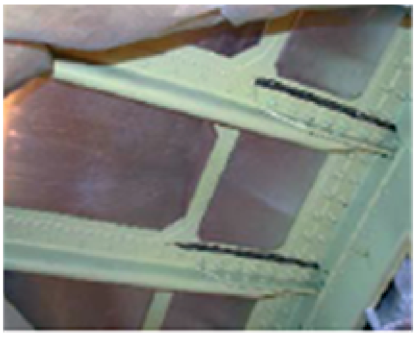

Figure 8 – Damping patches bonded on the demonstrator

A substantial weight saving was achieved with this modification.

3.3. Sound-Proofing Panels and windows

A critical point for the reduction of internal noise levels in helicopter cabins concerns sound proofing panels optimization. As shown in the previous section 2, there is a need to optimize panels' transmission losses depending on their location in the cabin and thus depending on the frequency content of the noise sources they should attenuate.
Some performance objectives were defined for each location based on the identified contributions to internal noise levels on a serial H/C (example of Figure 5).

In the frame of this research program, an in-house code named PIAMCO ([11], [12]) was developed, to simulate the transmission losses of infinite composite panels. This code was validated using extensive measurement campaigns that were carried out in a coupled reverberant/anechoic room on a set of panels (900x900mm) and glazings (400x400mm) defined from PIAMCO simulations (example on Figure 9).

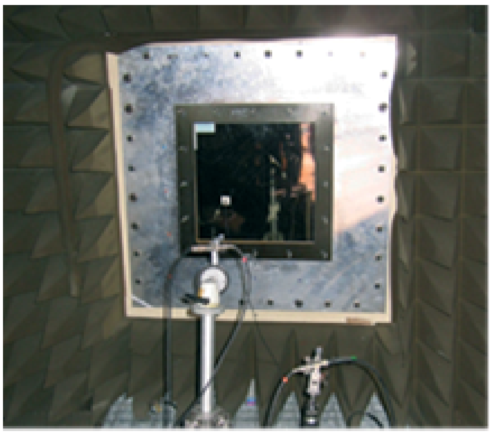

Figure 9 – Glazing tests in an anechoic room

The good correlations (Figure 10) that are obtained between Transmission Loss measurements and calculations, on a wide range of panels definitions using several distinct materials, enabled to be confident on the code results. It was thus possible optimize the panels for given weight and space constraints, for each location in the cabin.

The innovative idea here was based on the definition of sandwich panels with "soft core", with a dilatation frequency low enough to benefit from a high acoustical attenuation above this frequency ([14]).
Some additional criteria linked for example to the required rigidity of the panel and to the complexity of the manufacturing process were implemented in the analysis to converge on the final panels definitions.

The example on Figure 10 below shows the measured and calculated transmissions losses of a sound-proofing panel before (serial definition) and after this optimization process (demonstrator configuration).

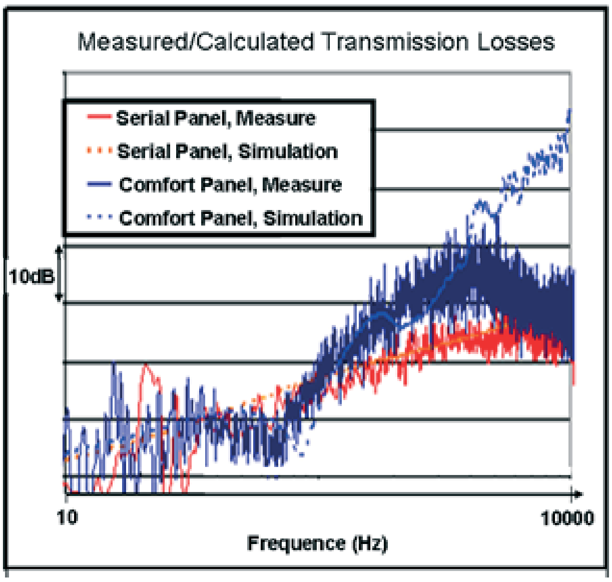

Figure 10 – Transmission loss measured and calculated, example of former and new sound-proofing panel

The 2 panels having roughly identical weights, it can be seen from this figure a very good improvement between the initial and modified panels. The dilatation frequency of the new panel is positioned in a frequency band with relatively low excitation levels, and much lower than the disturbing tonal components generated by the MGB, to benefit from a high attenuation on the latter.

The same approach was used for the windows, except that, in this case, the transmission loss curves were optimized to attenuate the energy generated by the aerodynamic turbulent boundary layer. The use of both thickened laminated windows with damping layer and double glazing was implemented on the demonstrator in order to be able to assess the performances of these two concepts. The implementation of these new performing windows for both acoustics and thermal comfort, also required some extensive work on their definition to integrate others constraints in their definition (jettisonable windows, optical effects).

3.4. Laminated bearings on Main GearBox struts

Another target of this research program was to develop a device aiming to reduce the structure-borne transmission of Main Gearbox (MGB) Noise ([13]), that was pointed out during the diagnosis. Even if the assessment of the contribution of structure borne and airborne path is made very difficult from the strong interaction that exists between these two paths, the transfer through the MGB struts clearly plays a predominant role in certain frequency bands.
The innovative concept of laminated ball joints at MGB support strut foot was chosen (Figure 11). Appropriate studies of the required static and dynamic stiffness were carried out using Finite Element Analysis and non linear models.

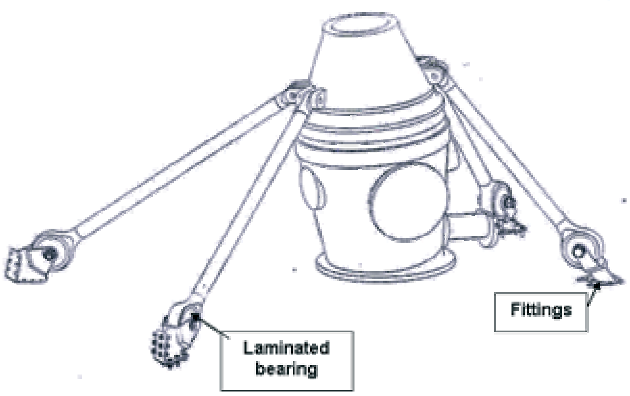

Figure 11 – Laminated bearings on MGB struts

This concept, developed in collaboration with PAULSTRA, was then tested in laboratory so as to check the compliance of the parts to the specification and to evaluate its vibration filtering performances. The effects of temperatures, static and dynamic loads on the dynamic stiffness and on the filtering effect were assessed. All the studies and justifications needed to fly this device on a critical helicopter part were then performed, taking into account the potential failures of the device in flight. The laboratory tests results have demonstrated the high potential attenuation of vibro-acoustic excitation transferred through MGB struts, especially in the frequency band with high tonal components levels.

4. RESULTS

The noise measurement campaigns performed during this research program enabled to develop a. big experimental database, which will be useful for the new sound-proofing developments. This paragraph gives a partial assessment of the results obtained, with a comparison of results obtained on a serial aircraft and on the demonstrator helicopter.

4.1. Noise Levels reduction

The measurements have been performed in stabilized flight configuration at several forward speeds, at the 11 locations in the cabin presented on Figure 12. 29 accelerometers were also used to check the vibro-acoustic behaviour of the aircraft.

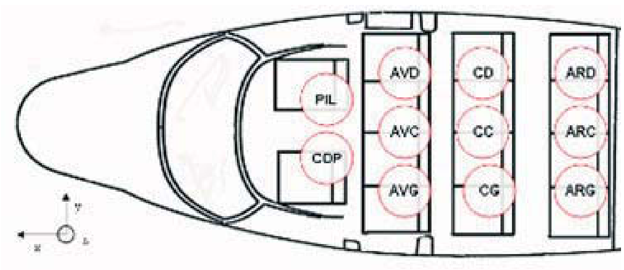

Figure 12 - Measurement positions

The measurements at same positions and for same flight configurations were already available on a serial helicopter equipped with offshore sound-proofing.

The results obtained before and after embodiment of sound-proofing concepts presented in section 3 are presented on Figure 13 (example of dB SIL4 noise levels measured in stabilized forward flight configuration at 145kts).

The levels obtained show a significant attenuation of 7 dB SIL4 in average in the cabin. This reduction is global, and substantial noise improvement is obtained in the rear part of the cabin, where highly performing solutions have been embodied (double-glazing, laminated bearings, and high quality sound-proofing panels).

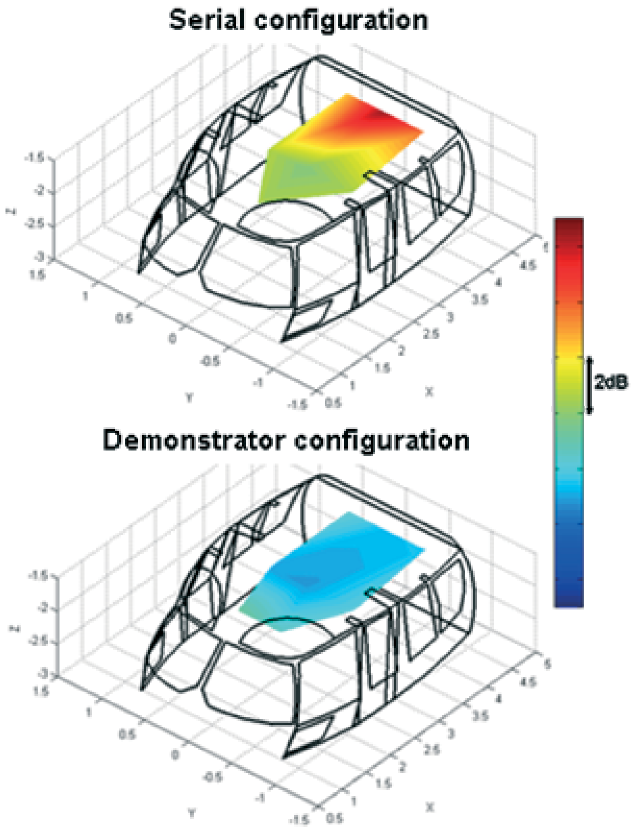

Figure 13 - Comparison of internal noise levels (dB SIL4) measured on a serial H/C and on the demonstrator

Looking more in detail to the frequency content, it can be seen that noise reduction is achieved throughout the frequency band, and that this attenuation increases with the frequency, which is consistent with the intrinsic characteristics of most of the technologies implemented on the demonstrator (see Figure 10). Figure 14 shows an example of measured spectra before and after modifications.

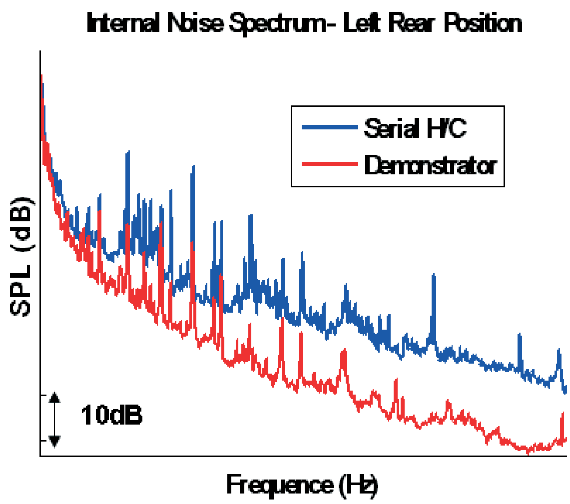

Figure 14 - Internal Noise Spectra, Serial & Demonstrator H/C

It can be seen that both aerodynamic broadband noise and tonal components are impacted positively by these modifications.

In order to identify more precisely the reductions obtained, it is interesting to dissociate the reduction obtained on the broad band noise from the one obtained on tonal components (mechanical noise, notably from MGB gear meshing).

A simplified method based on the use of a Finite Impulse Response averaging filter is proposed here, that enables to extract and analyze the tones noise levels at each position and in each flight configuration. The broadband spectrum is derived from the filtered raw data, and the tonal components are identified by the difference between raw data and extracted aerodynamic noise. An emergence threshold is set for the identification of tones, which are automatically identified. An example of the results is shown below:

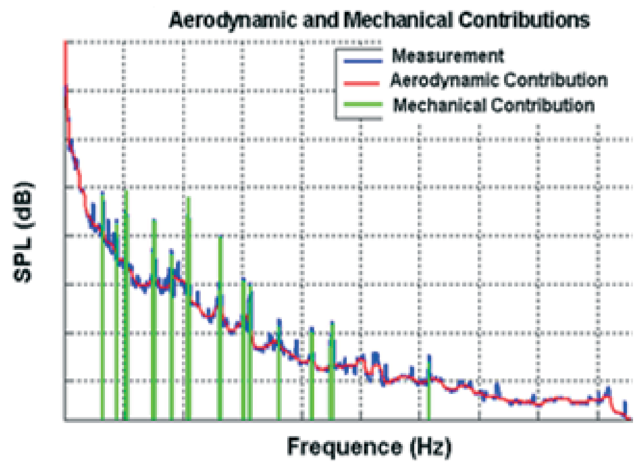

Figure 15 - Separation of Tonal and broadband components

From this analysis at all measurements positions at MCP speed, the mean reduction obtained in cabin on all MGB tonal components is 9.9dB, whereas some particular lines are reduced by 15 to 20dB. And not only are the noise levels reduced, but also the emergence of these tonal components in the spectrum. This reduction significantly impacts the comfort felt in the helicopter, for which numerous psychoacoustics studies show that tonal components and their emergence account for a significant part of annoyance in the helicopter.

Moreover, measurements were carried out in stabilised level flight at several speeds : 40 knots (kt), 60 kt, 80 kt, 100 kt, 120 kt and 145 kt. Figure 16 presents the mean levels in cabin on serial and demonstrator helicopters and the attenuations obtained. The results show that the 7 dB attenuation obtained at MCP affects all speeds and that this attenuation is approximately constant with speed. This shows that the soundproofing modifications embodied are efficient throughout the flight envelope, although the prevailing sources may vary with the forward speed.

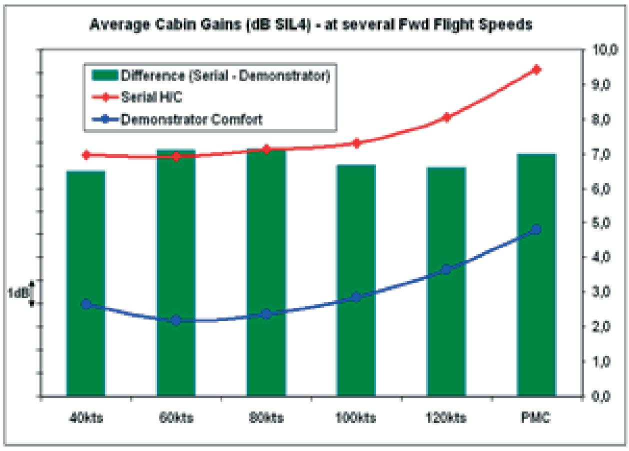

Figure 16 – Average Cabin Gains (dB SIL4) as a function of Fwd Flight Speed

4.2. Source Localization

NAH measurements in the same configuration as on the previously measured Serial H/C ([3]) have also been performed in order to identify the main remaining noise sources. Example of the sound-pressure mapping in dB SIL4 is presented on Figure 17 below.

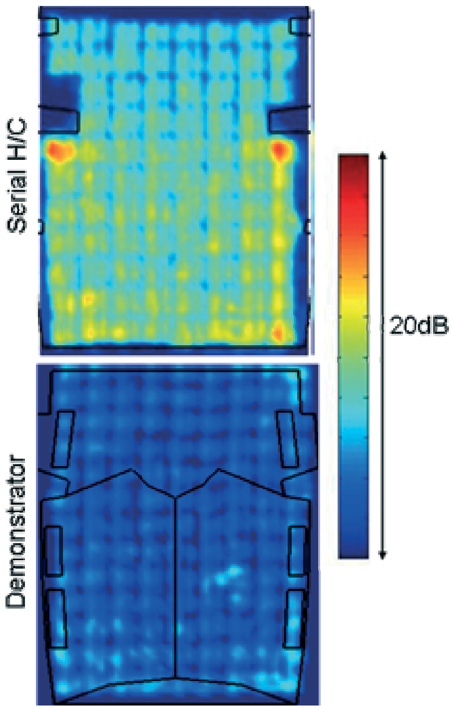

Figure 17 – NAH Measurement Result on Roof panel on Serial (Top) and Demonstrator (bottom) H/C

The results show that the radiated noise levels on all the measured surfaces have been largely reduced (example of the roof panel). The analysis also points out that the noise levels measured on the demonstrator present a better homogeneity than on the serial H/C where some emerging noise sources with high levels were identified. This assessment is consistent with the significant noise reductions obtained at passenger's ears. The NAH measurements also show that some sources that were initially negligible have gained in importance and should be treated to further improve the comfort.

4.3. Comfort Improvement

One of the first things that corroborated the substantial noise reduction achieved in the cabin is the crew feeling after flight tests. The internal comfort was judged as "muffled" by the crew.

Nevertheless, a quantitative approach has also been developed to evaluate the comfort. Indeed, this research program enabled to develop some comfort evaluation methodology, for which some of the results obtained on the demonstrator are presented hereafter. The chosen methodology relies on the development of a comfort equation for the helicopter based on psychoacoustic studies, as the simple analysis of noise levels in dB SIL4 or in dB(A) is not sufficient to quantitatively assess the comfort.

Theses "psycho-acoustic" studies included both "subjective tests" with artificially filtered measured signals tested on several listeners, and the "objective" calculations of several psychoacoustics metrics for these signals. The metrics calculated are the following: dB SIL4, dB(A), dB(B), dB(C), dB(G), Loudness, Sharpness, Fluctuation Strength, Roughness, and Tonality.
These 2 approaches were correlated so as to build an "appropriate comfort equation" based on a polynomial combination of the most significant psychoacoustics metrics, weighted by coefficients determined from subjective experiments.

This equation was validated and finally exhibits some very good consistency with listening tests conducted on 12 helicopter signals. Figure 18 below presents the correlation between measured and calculated preferences on such signals.

This validated equation was applied to the measured sound pressure signals in helicopter cabins of Dolphin range with distinct existing sound-proofing configuration, and for the demonstrator. The calculated "comfort scores" are projected on a scale from 0 to 10, where 0 represents some quiet comfortable signal (relatively for helicopter) and 10 means a very unpleasant signal. The results are presented on Figure 19.

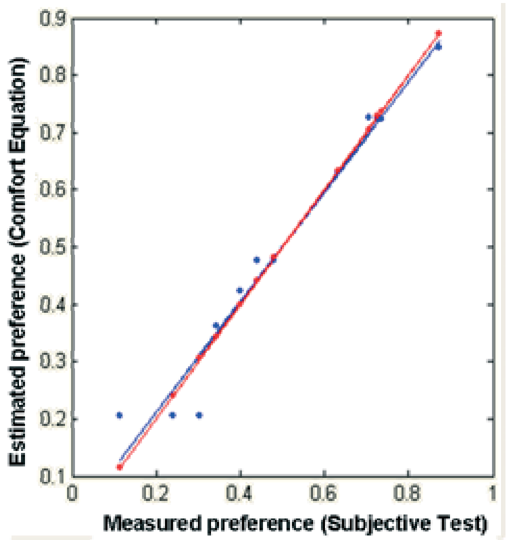

Figure 18 - Correlation Measured/Calculated signal preferences

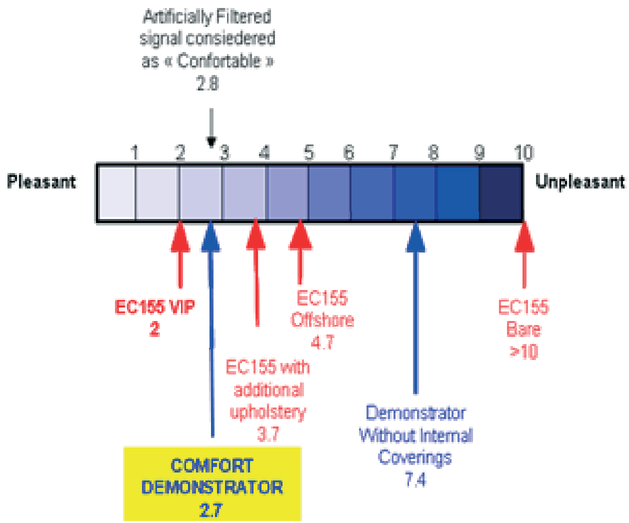

Figure 19 - Comfort Assessment

The results show that the comfort calculated from the noise measurements in the demonstrator (2,7) is closer to a VIP configuration (2) than to basic offshore configurations with and without additional sound-proofing, though added sound-proofing weight is very close to the existing additional upholstery and very low compared with VIP configuration.
Moreover, the comfort assessment on the demonstrator signal is very close to an artificially filtered signal considered qualitatively as comfortable during subjective tests performed on several listeners.

As a consequence, the conclusions drawn from this comfort assessment are very positive, and they confirm the good performances of sound-proofing technologies implemented on the demonstrator.

4.4. Comprehensive methodology validation

As presented in the first section of this paper, the purpose of this research program was not only to propose and integrate technologies allowing reduction of the internal noise in helicopter cabins, but also to develop and improve methods and tools allowing simulating and mastering these improvements. In this scope, it is interesting to compare the measurement results obtained on the comfort demonstrator with numerical calculation results based on the methodology presented in section 2.

The average calculated and measured spectra in the cabins of both serial helicopter and technological demonstrator are presented on hereafter Figure 20. The calculated spectra for the demonstrator are obtained from Nearfield Acoustical Holography measurements on the serial H/C, on which measured and calculated panels transmission loss have been implemented according to equations (3)and (4).

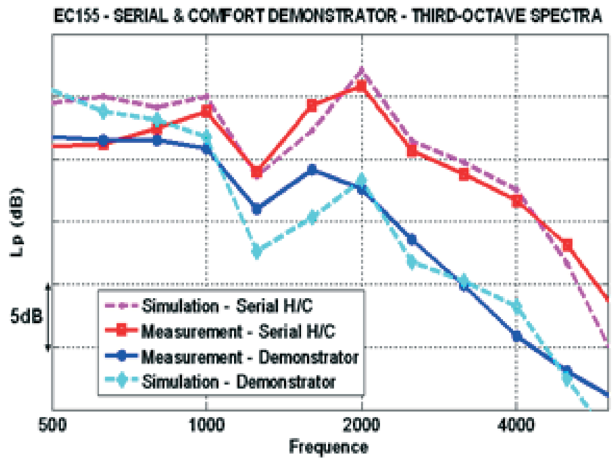

Figure 20 – Comparison measurement simulation for both serial and demonstrator (average cabin)

The following conclusions can be drawn. As previously shown in section 2, the methodology coupling NAH normal velocity measurements and geometrical beam-tracing calculations gives well correlated results on the serial helicopter, except for frequencies lower than 1000Hz for which calculations overestimate the real measured levels.

The application of the comprehensive methodology presented in this paper for the demonstrator, requiring the calculation or measurement of the transmission loss before and after modifications, also provides satisfying results. And yet, it is to be noticed that the implementation of the new structure damping material is mainly taken into account considering the mass effect, while the laminated bearings are not even considered in this analysis. Despite this assessment, the low frequencies are still

overestimated but the overall results are very close to the measured levels.
As a consequence, the methodology proposed in this paper provides good results, enabling to well estimate the impact of sound-proofing modifications. Further improvements of internal noise level are thus awaited, by the application of this methodology and of several of the developed technologies. In particular, the new sound-proofing panels and windows, the laminated bearings on MGB struts and the new structure damping materials should be applied for the retrofit of existing aircrafts and for the development of future Eurocopter products.

5. CONCLUSIONS AND PERSPECTIVES

This paper presents the comprehensive approach chosen by Eurocopter for the diagnostic of main noise sources in a helicopter cabin, for the analysis of the contribution of these sources to the sound pressure level at passenger's ears locations, and for the estimation of sound-proofing modifications impact on the internal noise level. The first part describes this methodology coupling measurements with Nearfield Acoustical Holography technique, cabin modelling with geometrical acoustics numerical method, and calculations or measurements of panels' transmission loss characteristics. Then, several noise reduction concepts which have been developed in the frame of this research program are highlighted. These innovative technologies are validated with laboratory tests and implemented on a demonstrator helicopter. The overall results are assessed and compared with similar data acquired on a serial aircraft. The analysis performed shows the significant noise levels reductions obtained at all positions in the cabin, for all measured flight conditions, on a wide frequency band and for both aerodynamic broadband noise and mechanical tonal components. It is also shown that this reduction is translated into a significant comfort improvement, which is assessed quantitatively. Moreover, the results obtained on the demonstrator prove to be very close to the estimations performed with the comprehensive modelling approach presented in this paper. Further noise reductions can thus be achieved and the application of this methodology should account for the optimization of the internal noise levels at given weight, space, and cost constraints, in the Eurocopter product range.

ACKNOWLEDGEMENTS

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