

DETC2009/VIB-87383

EXPERIMENTAL GUIDELINES FOR NVH IMPROVEMENTS IN HELICOPTER VIBRO-ACOUSTIC COMFORT

Emiliano Mucchi
Engineering Department
University of Ferrara
Ferrara, Italy
emiliano.mucchi@unife.it

Elena Pierro
DIMeG
Politecnico di Bari
Bari, Italy

Antonio Vecchio
LMS International
Leuven, Belgium

ABSTRACT

The noise of helicopters has started to become an important issue and the next level technical challenge is to include new design parameters such as vibro-acoustic comfort in the design process of a modern rotorcraft. In this scenario a wide experimental campaign has been performed on a EC-135 helicopter cabin in order to assess the effectiveness of several techniques for NVH (Noise Vibration and Harshness) improvements. Vibro-acoustical modal analyses of the cabin internal and external surface as well as a pure acoustical modal analysis of the cabin enclosure have been performed in order to verify the vibro-acoustical coupling between the cabin cavity and the cabin mechanical structure. Secondly a detailed leakage point detection on the cabin walls has been carried out by a few techniques finding out possible noise sources. Through such experimental analyses, some guidelines are suggested as well as particular techniques/instrumentations in order to improve human comfort on the helicopter cabin.

1 INTRODUCTION

In the last decennia, sound/noise levels of helicopter have become more and more important. From one side, government regulations are imposed to contain noise pollution while on the other hand customers do not accept any longer a noisy product. On top of all this, the competitive pressure to bring products faster to market has made that NVH (Noise Vibration and Harshness) designers are looking for tools giving them an insight on where the noise is coming from. In this scenario, extensive experimental campaigns have been carried out on the helicopter EUROCOPTER EC-135 since the requirement of a quieter helicopter needs a systematic study of its NVH

behavior. In particular, two experimental analyses on the helicopter cabin have been performed: modal tests and localization of leakage points.

Firstly, in Section 2 several vibro-acoustical modal tests have been carried out on the cabin internal and external surface as well as a pure acoustical modal analysis of the cabin enclosure in order to verify the vibro-acoustical coupling between the cabin cavity and the cabin mechanical structure. In fact, proper design choices in helicopters can not be carried out without a complete structural dynamics knowledge in terms of vibration response of the rotorcraft cabin in the frequency range of interest. Such a range is strictly related to the input force spectra, meaning that attention must be paid in the design process in order to avoid resonances in flight operational conditions, reducing fatigue problem and improving human comfort. This goal is commonly achieved through the classical experimental modal analysis (EMA), which enables to identify the critical spectrum areas. Nevertheless, the helicopter cabin represents a typical real life example of vibro-acoustical system characterized by a fluid-structure interaction. The common practice in experimental modal analysis of helicopters is to acoustically excite the structure with a volume acceleration source located inside the cabin, and to measure the acoustical responses in the cavity by means of microphones, while the structural responses of the cabin internal surface are obtained through accelerometers. The aim of such a practice is to compare the modal parameters obtained from the two different sets of FRFs (Frequency Response Functions), i.e. acoustical/acoustical and structural/acoustical, in order to assess the coupling and to distinguish pure acoustical modes

from coupled ones. The complexity of the structure as well as the complexity of the internal furnishing of the helicopter are considered the main causes of some information attenuations in terms of modal properties, through the path from the cabin internal to the external surface. Because of such an attenuation, some coupled vibro-acoustical modes which characterize the cabin internal surface, could not be detected on the external part. Therefore, the cabin external surface is thought lightly vibro-acoustically coupled to the internal enclosure, and the only strong vibro-acoustic coupling is thought to be between the cavity and the cabin internal surface, justifying the previous comparison, i.e. between the two sets of FRFs. Via the three above-mentioned modal tests (an acoustical modal analysis of the cabin enclosure, an experimental modal analysis of the cabin internal surface and an experimental modal analysis of the cabin external surface) it will be shown that this last statement - i.e. that only the cabin internal surface is strongly coupled to the internal enclosure - must be reviewed.

Secondly, in Section 3 an experimental localization of leakage points has been carried out by using two different techniques: ultrasonic and P-U (acoustical pressure and particle velocity) measurements. The leakage points actually are possible noise sources or locations through which the noise can propagate, they are due to non-homogeneity, fractures or cavity on the material, defects during assembly (e.g. improper alignment of the seals along the cabin doors or incorrect coupling between cabin surfaces due to split rivets), etc. The detection of leakage points on the cabin surface is of high interest for NVH designers because it is an useful tools for quality control of the cabin and furthermore, such points can cause high noise levels on the cabin and human discomfort during flight. Details are given about the pros and contras of both experimental techniques for such a field of application.

This research is carried out in the frame of the project "FRIENDCOPTER", which aims at developing innovative technologies and tools to support the vibro-acoustic design of modern helicopters.

2 MODAL TESTS

2.1 Background on vibro-acoustically coupled systems:

Vibro-acoustical systems are characterized by a consistent energy exchange between the fluid and the structure. This means that, exciting the system either acoustically or structurally, the responses from the two subsystems (the acoustical and structural ones) are related one to each other. The mathematical consequence is that in the equilibrium equations mixed terms appear and, moreover, this leads to a nonsymmetrical system matrix. From the finite element formulation it is possible to easily obtain the second-order coupled equations. In particular, the equations of motion for the structural behaviour include both an external structural loading, as well as a coupled acoustical loading which is the pressure on

the structure over the boundary surfaces. The same is for the acoustical subsystem, where the acoustical excitation and the structural vibration on the boundaries are the forcing terms in the motion equation. In [1]-[2] it is shown that the final matrix form of vibro-acoustical systems can be written as follows:

$$\begin{bmatrix} \mathbf{K}^s & -\mathbf{K}^c \\ 0 & \mathbf{K}^f \end{bmatrix} \begin{Bmatrix} x \\ p \end{Bmatrix} - i\omega \begin{bmatrix} \mathbf{C}^s & 0 \\ 0 & \mathbf{C}^f \end{bmatrix} \begin{Bmatrix} x \\ p \end{Bmatrix} - \omega^2 \begin{bmatrix} \mathbf{M}^s & 0 \\ \mathbf{M}^c & \mathbf{M}^f \end{bmatrix} \begin{Bmatrix} x \\ p \end{Bmatrix} = \begin{Bmatrix} f \\ \rho \dot{q} \end{Bmatrix} \quad (1)$$

where $\mathbf{M}^{s,f}$, $\mathbf{C}^{s,f}$, $\mathbf{K}^{s,f}$ are mass, damping and stiffness matrices ($(\cdot)^s$ is for the structural vibration, $(\cdot)^f$ for the fluid part), x is the structural displacement, p the sound pressure, ω the angular frequency, ρ the fluid density, f (structural force) and \dot{q} (volume acceleration) the external loads. The matrices \mathbf{M}^f , \mathbf{C}^f and \mathbf{K}^f describe the pressure-volume acceleration relation in case of a rigid wall structure and do not reflect directly physical properties of the fluid. The non symmetry of the system matrix is due to the coupling submatrices \mathbf{M}^c and \mathbf{K}^c , and leads to different right and left eigenvalues, but it has been proven [1] that no matter involves in the modal model derivation itself. The main consequence of the vibro-acoustical coupling in modal analysis is the existence of cross-FRFs. In particular the following transfer functions obtained considering a structural force excitation f_j at location j , have been derived in [1]:

$$\frac{p_p}{f_j} = \sum_{h=1}^n \left[\frac{P_h \psi_{fhp} \psi_{shj}}{(z - \lambda_h)} + \frac{(P_h \psi_{fhp} \psi_{shj})^*}{(z - \lambda_h^*)} \right] \quad (2)$$

where p_p is the acoustical pressure response inside the cavity at location p , P_h the modal scaling factors, n the number of modes in the frequency band of interest, z the Laplace domain variable, ψ and λ respectively the eigenvectors and the eigenvalues of the system matrix, $()^*$ is the complex conjugate and the subscripts f , s , h stand for fluid response, structural response and mode number, respectively. Similar transfer functions can be obtained considering an acoustical excitation \dot{q} at location k :

$$\frac{x_m}{\dot{q}_k} = \sum_{h=1}^n \left[\frac{P_h \psi_{shm} \psi_{fhk}}{\lambda_h^2 (z - \lambda_h)} + \frac{(P_h \psi_{shm} \psi_{fhk})^*}{\lambda_h^2 (z - \lambda_h^*)} \right] \quad (3)$$

being x_m the structural displacement at location m . This modal description (2)-(3) is then used for the parameter estimation (mode shapes, modal frequencies and modal

damping) by means of standard algorithms [2].

Starting from this theoretically consolidated result, an extensive modal testing on the helicopter EUROCOPTER EC-135 has been carried out.

2.2 Experimental set up:

In order to assess the degree of coupling existing between the helicopter enclosure and the interior as well as the external walls, three different experimental modal analyses have been carried out. In such three analyses, the structure has been acoustically excited with a random signal (white noise) by means of a volume acceleration source (LMS-Qsource) located inside the cabin near the pilot's seat.

In the first one - the Acoustical Modal Analysis of the cavity - 190 points have been measured by means of condenser microphones (1/2" prepolarized), as shown in Figure 1a. A horizontal bar, holding five microphones spaced by 25 [cm], was used to measure the response of the system. Seven measurement planes were considered, spaced by 50 [cm], while the vertical spacing between the lines was 20 [cm]. The sound pressures were acquired in time domain with a sampling frequency of 8192 [Hz] for approximately 30 [s] using LMS hardware and software instrumentation. A Hanning window has been used to reduce leakage and 32 averages have been performed for noise reduction.

In the second analysis - the EMA of the cabin internal surface - the acceleration of the wall has been measured by means of piezoelectric accelerometers (1-10kHz of frequency range) on 195 points, in the left, right and roof part, as shown in Figure 1b. The accelerometers were mounted on the inside walls of the cabin, measuring only the surface normal acceleration. Also in this case the sampling frequency was 8192 [Hz], the acquiring time was approximately 30 [s], a Hanning window has been used and 32 averages were performed. The measurements on the interior of the cabin lead to collect two sets of FRFs: pure-acoustical FRFs [$\text{Pa}/(\text{m}^3/\text{s}^2)$] for the cavity and acoustical-structural FRFs for the cabin internal surface [$(\text{m}/\text{s}^2)/(\text{m}^3/\text{s}^2)$].

At last, in the third analysis - the EMA of the cabin external surface - the velocities of the points on the surface have been measured by a 4x4 Microflown sensor array, with a 10 [cm] spacing between the sensors both horizontally and vertically. The structural responses of 1158 points on the right, left and roof part of the cabin external surface (see Figure 2a) have been acquired as velocities. The Microflown, also called PU-probe (pressure - velocity), is a specially conceived sensor for the measurement of the acoustic intensity since it integrates in a unique casing a hot-wire particle velocity sensor and a very small pressure transducer [3]. The distance between the Microflown sensors and the surface is so short that the very-near-field assumption is verified. The particle velocities, as consequence, simply represent the velocities of the cabin

surface, revealing to be particularly efficient for modal analysis applications [5],[6].

The reason of using such sensors instead of classical accelerometers, lies in the possibility of getting with just one measurement the needed data for both a modal analysis and an acoustic intensity calculation for noise source identification [6]. The responses were acquired in time domain with a sampling frequency of 8192 [Hz], acquiring the data for 30 [s], by using LMS hardware and software instrumentation. A Hanning window has been used to reduce leakage and 300 averages have been performed to reduce the high noise level in the data, with an 80% of overlapping, yielding smooth FRFs.

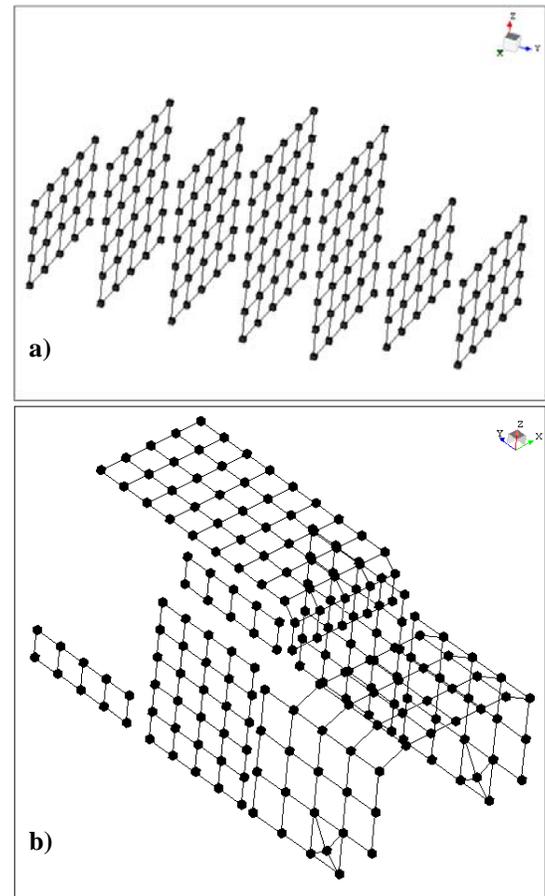


Figure 1. a) Measured points in the helicopter cavity by means of microphones and b) on the cabin internal surface by means of accelerometers.

3 LOCALIZATION OF LEAKAGE POINTS BY ULTRASONIC AND P-U MEASUREMENTS

The evaluation of the leakage points on the cabin of an EC-135 helicopter is carried out by using two different experimental techniques - such leakage points can be considered as noise sources that reduce the human comfort in flight operational conditions. The first technique makes use of ultrasound transmitter/receiver and the second one is performed by using P-U (acoustical pressure and particle velocity) probes, namely

Microflown. This second technique is performed in operational conditions and in controlled conditions (i.e. where the excitation is measured and applied by using a volume acceleration source). Both techniques have their advantages and disadvantages that will be explained later on in the paper.

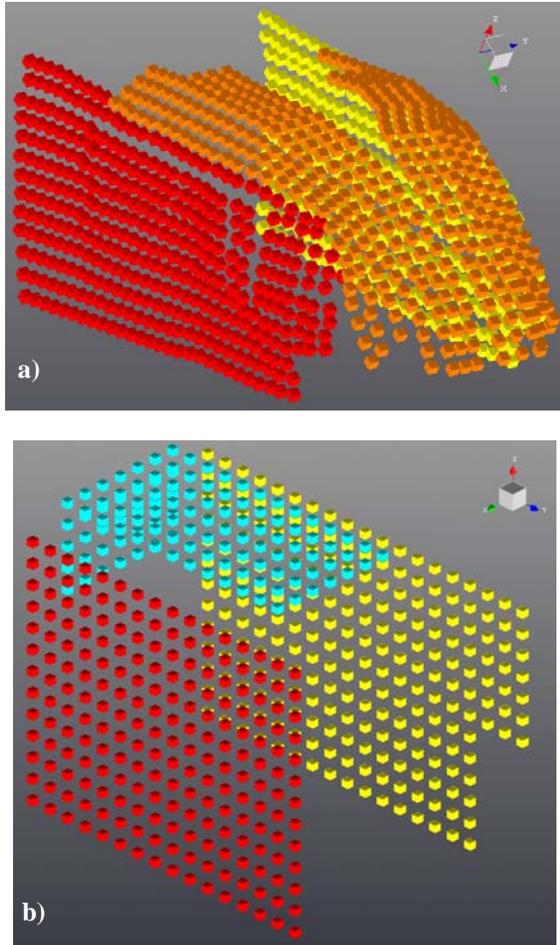


Figure 2. a) Measured points of the cabin external and b) internal surface by means of Microflown sensors.

Ultrasonic sensors utilize transducers, which transform an electrical signal into an ultrasonic wave and vice versa. Ultrasound covers a frequency range from 20kHz to about 1 GHz, however for technical applications the range 20kHz to 10MHz is the most important one [15]. Ultrasound enables instruments to be non invasive and also non intrusive because the acoustic wave can penetrate walls. Furthermore, high frequency sounds are more directional than lower frequency ones: this makes it easier to pinpoint the source even in the presence of other background noise. Obviously, the propagation of acoustic waves through multi-layered structures depends on the acoustics impedance mismatch at each of the boundaries the ultrasound has to pass, furthermore it depends on the attenuation of the ultrasound in the different materials

and finally in some cases on the relationship between the wall thickness and the wavelength of the ultrasound waves [15]. In particular, firstly an ultrasonic transmitter (SDT 8MS) producing an omni-directional tonal noise at the frequency of about 40kHz has been used inside the helicopter cabin while the ultrasonic receiver (SDT 170) was on the external surface of the cabin scanning the entire external cabin surface. Thus, the location of the leakage points can be evaluated by this first simple measurement, in fact when the receiver detects a point through which the level of ultrasonic noise exceed a threshold level, an audio sound signal occurs highlighting a leakage point. This measurement deals with the transmissibility of the tested surface to the ultrasonic waves. Obviously, the surface transmissibility is increased in correspondence of fracture or inhomogeneity on the material, malfunctioning of the seals, etc. It is important to underline that in helicopter operational conditions, the noise comes from the exterior to the interior of the helicopter cabin, on the contrary during this first measurement, as well as on the further measurements described hereafter, the noise comes from the interior (by means of the ultrasonic transmitter) and the detection is performed on the exterior. This can be considered acceptable under the assumption that the helicopter cabin satisfying the reciprocity principle, as demonstrated in [14],[8]. Furthermore, in order to localize the leakage points with more spatial precision, a second ultrasonic measurement is carried out exciting on the internal cabin side in correspondence of the above-detected leakage points and measuring the value of the wave crossing the cabin panel (from the interior to the exterior) by means of the same ultrasonic receiver. In this second test, an ultrasonic transmitter (SDT 200mW) producing a one-directional tonal noise at the frequency of about 40kHz has been used as excitation inside the cabin giving more accuracy in the measurement.

Simultaneously with the acquisition of the particle velocity on the external surface described in Section 2, the acoustical pressure has been measured in the same acquisition points: the test is carried out by using P-U probes (Microflown technologies). The Microflown array was positioned close to the external walls so the very near field assumption is verified and therefore the particle velocities simply represent the velocities of the cabin external surface. Therefore, such measurements allow the calculation of the acoustic intensity [10] on the cabin external surface. Finally, the last experimental test performed concerns measurements on the internal surface of the helicopter cabin (Figure 2b) by using the same above-mentioned 4x4 Microflown sensor array. The measurements were taken in conditions close to the operative one, i.e. helicopter blocked on the ground with the rotor rotating with the blades parallel to the ground, so without generating any lift while the two engines were limited to 60% of the maximum power; Figure 2 shows all the grid points measured during the tests. The pressure and velocity measurements are acquired in the time domain measuring for 18 [s] at the sampling frequency

of 8192 [Hz] by using LMS hardware and software instrumentation [11].

The information containing the location of the measured points - on the internal and external surface - and the active acoustic intensity data were exported from LMS Test.Lab as universal file and then imported in LMS Virtual.Lab environment [7] allowing a 3D representation of the intensity map as shown hereafter.

Unlike the measurements on the external surface where the excitation comes from a volume acceleration source located inside the cabin, in the test concerning the internal surface the excitation comes directly from the engines, gearboxes and blades being the main noise and vibration sources in helicopter. Therefore, the intensity maps obtained from the external measurements represent the response to a random excitation while the maps obtained from the internal measurements represents the response to an excitation made mainly of tonal components and a few broadband noise as can be seen in a previous work of the authors [14]; in such a work the vibro-acoustical passport of an helicopter engine in operational conditions was acquired and the contribution of the different noise sources (gearbox, engine, etc) with respect to the global noise produced by the helicopter was pointed out.

4 RESULTS AND DISCUSSION

A modal analysis in the frequency range 20-200 [Hz] has been carried out for each set of acquired FRFs (Section 2), i.e. pure-acoustical for the cavity, acoustical-structural for the cabin internal surface and acoustical-structural for the cabin external surface. The PolyMAX algorithm included in LMS Test.Lab [12] has been used for the modal parameter estimation. PolyMAX is a frequency domain algorithm and it is a polyreference version of the least-squares complex frequency-domain method (LSCF). Since it avoids the singular value decomposition (SVD) step to decompose the residues, the closely spaced poles can be separated [15]. A complete background on frequency-domain system identification can be found in [8].

In Table 1 the results for the modes lying in the 20-200 [Hz] frequency range are listed for each analysis, in terms of natural frequency F_n and modal damping ζ . The good correspondence between the modal properties (F_n and ζ) obtained from the analyses confirms that the cabin external surface is acoustically coupled to the enclosure, in fact the walls of the helicopter cabin (structural parts) vibrate at the same natural frequencies as the cabin internal cavity (fluid part). This is moreover assessed comparing the mode shapes between the external and internal surfaces. An example is reported in Figure 3 for the first mode shape, where the red colour areas indicate the maximum out of plane displacement. It is clear that in the first mode shape the right and the left sides

of the cabin exhibit a high level of displacement, both in the internal as well as in the external part.

The importance of this result is related to the common idea that the cabin external surface is not highly vibro-acoustically coupled to the internal closure, therefore it is not well excited through an acoustical loading. The structural complexity of the helicopter cabin equipment is considered the reason of such a low fluid-structure coupling. Not only this statement has been proven to be wrong, but performing only a pure structural excitation for the experimental modal analysis of the cabin external surface, some vibro-acoustical coupled modes can be neglected. Indeed, if the helicopter is just structurally excited, e.g. by means of shakers, some coupled modes could be ignored because of the indirect excitation. In this context, since only a proper prediction of the vibration response of the rotorcraft cabin can guide the designer to reduce the possibility of resonances in flight operational conditions, the excitation mechanism is of pivotal importance in such modal analysis tests.

Table 1. Natural frequencies (F_n) and modal damping (ζ) for the three modal analyses performed on the helicopter cabin.

Mode no.	Acoustical modal analysis		EMA-internal part		EMA-external part	
	F_n [Hz]	ζ [%]	F_n [Hz]	ζ [%]	F_n [Hz]	ζ [%]
1	46.5	2.8	46.3	2.9	45.2	1.6
2	65.1	2.1	66.5	1.9	65.4	2
3	86.1	2.9	86.4	1.9	85.3	1.6
4	98.1	0.4	97.5	1.2	98.3	1.4
5	109.7	1.5	110.2	1.2	108.6	1.3
6	124.4	2.6	124.3	1.1	123.3	1.3
7	139.4	2.5	136.4	1.1	139.3	1.5
8	160.8	1.1	168.9	1.4	167.6	1.1
9	175.5	6.1	188.4	0.7	188	0.6
10	189	2.7				

Figure 4 and Figure 5 show the leakage points (red dots in the figures) found by means of the above-described ultrasound technique. These points represent locations where the ultrasound wave can propagate from the interior to the exterior, in particular they are located on the boundary of the doors where the seal between the door and the cabin is not so efficient from an insulation viewpoint. The knowledge of the location of these defects is of primary importance for the designer that has to find solutions in order to improve the cabin insulation. In fact, the test is carried out exciting the interior of the cabin and measuring in the exterior, but as stated before, due to reciprocity, the same results can be obtained exciting the exterior and measuring the ultrasound wave on the interior of the cabin. This means that such a test gives information about the locations from which the acoustic radiation can propagate

on the cabin impoverishing the acoustic comfort of the passengers and pilots.

Similar results can be obtained from the intensity maps of the external surface (Figure 6, the dB values are omitted for confidential reasons). As described in Section 3 such a test is carried out exciting the cabin from the interior side with a flat broadband noise (white noise), then the active acoustic intensity is evaluated as the real part of the crosspower between pressure and particle velocity, being the measurements carried out by P-U probes. In Section 2 the same measurements were used for EMA purpose obtaining the mode shapes at the natural frequencies, here the sound intensity maps are evaluate at every frequency in the measured frequency range. Such maps depicted at the natural frequency of the cabin are obviously similar to the mode shapes of the cabin external surface, due to the contribution of the particle velocity acquiring in the very near field and being representative of the structural vibration of the panels. On the other hand, the maps depicted at frequency far from the natural frequencies and for example corresponding to the tonal excitations of the gearbox (e.g. meshing frequency of the collector gear in the pinion shaft, or meshing frequency related to the input gear) highlight high intensity values in the same locations as the pictures of Figure 4 and Figure 5 show (compare same characters on the figures). In fact the active intensity represents the energy flow that a surface radiates and therefore is very sensible to leakage point localization.

Figure 7 shows an example of intensity map on the internal surface obtained in operational conditions and depicted at the frequency corresponding to the meshing frequency of the input shaft in the gearbox. The map is able to identify the same leakage points found by the intensity map on the external surface and by the ultrasound technique (consider the corresponding characters in Figures 4, 5, 6, and 7). It is interesting to note that both the ultrasound techniques and the intensity measurements are effective tools for the identification of leakage points. The first technique is simpler to apply, the cost of the instrumentation needed is cheaper than the second techniques, but the intensity maps gives more information than ultrasonic techniques, in fact since they represent the active sound intensity they are effective for panel efficiency evaluation too [16]. Moreover the intensity maps can be calculated on the entire measured frequency range, allowing calculation of the energy flow dissipated by the leakage points as a function of frequency.

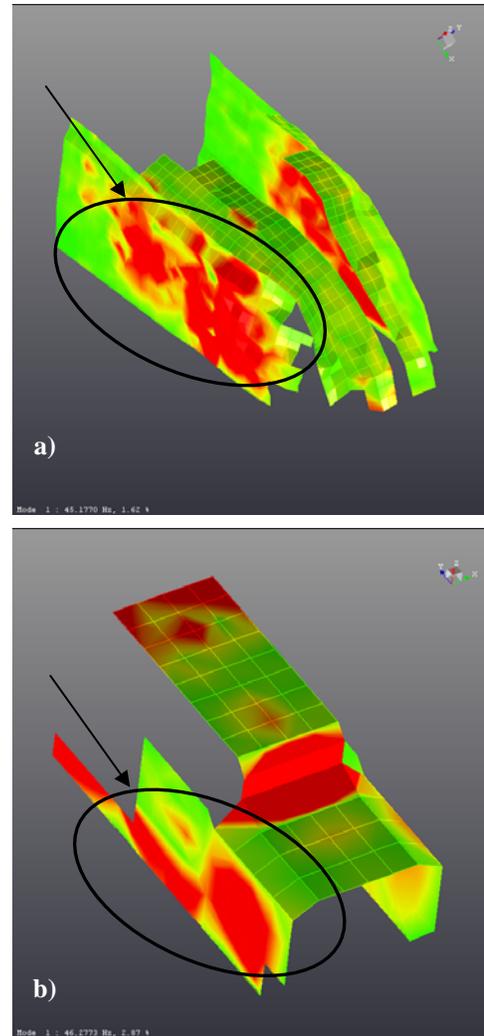


Figure 3. First mode shape coloured map of the cabin external surface (a) (45.2 [Hz]) and the cabin internal surface (b) (46.3 [Hz]).



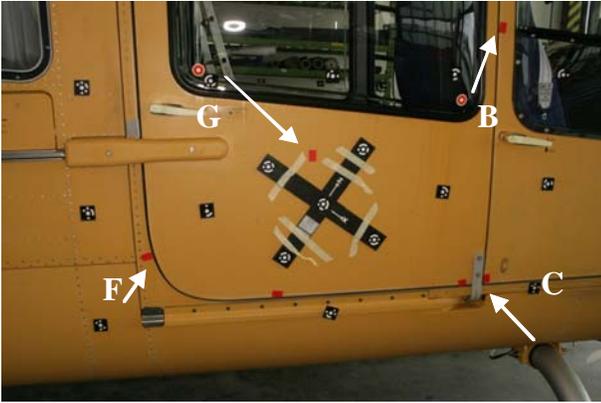


Figure 4. Leakage points (in red) on the helicopter cabin found by means of the ultrasound technique (cabin right panels)

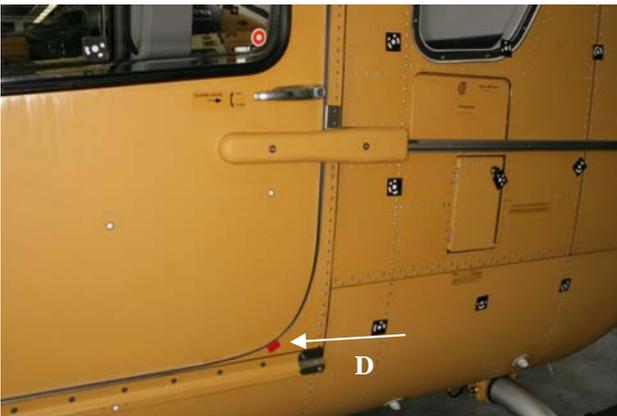
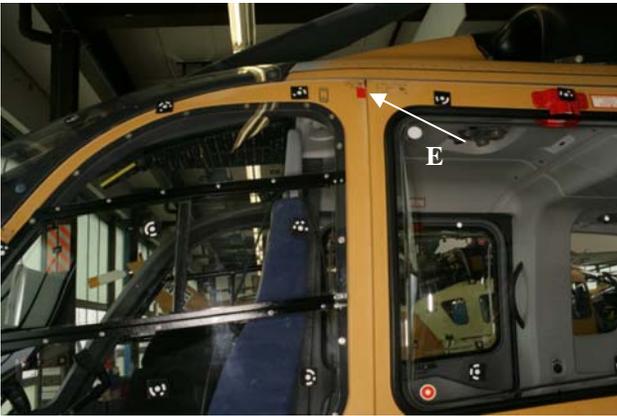


Figure 5. Leakage points (in red) on the helicopter cabin found by means of the ultrasound technique (cabin left panels).

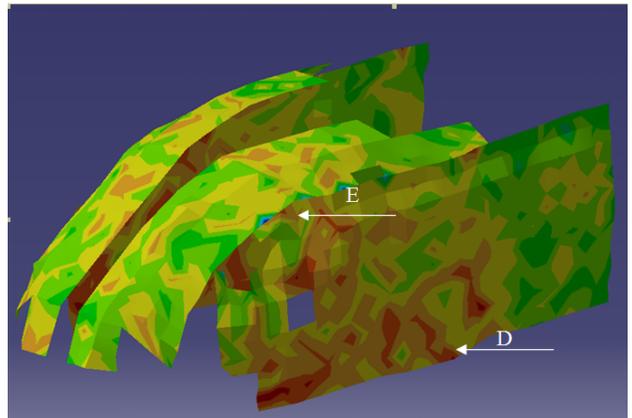
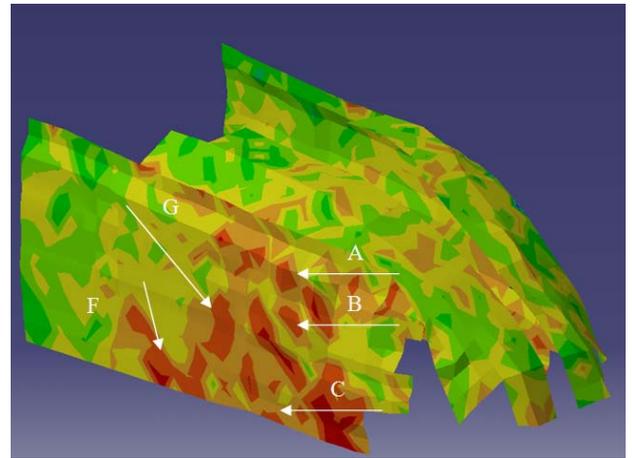


Figure 6. Intensity map in dB of the cabin external surface at the meshing frequency of the input gear in the gearbox.

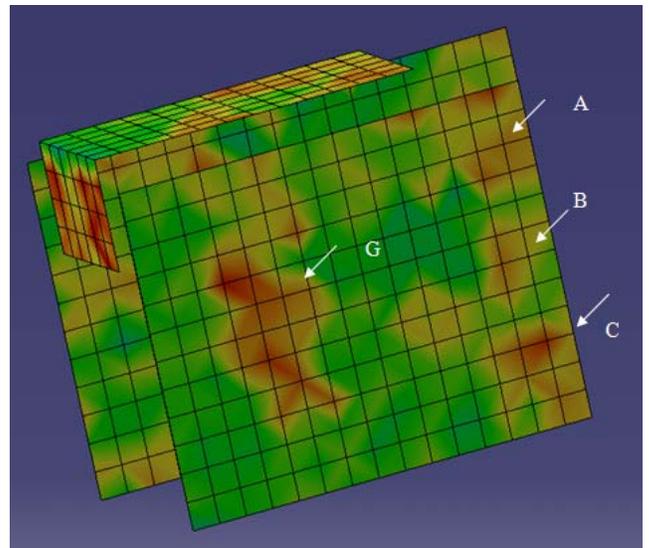


Figure 7. Intensity map in dB of the cabin internal surface at the meshing frequency of the input gear in the gearbox.

5 CONCLUDING REMARKS

Several experimental analyses have been performed on a EC-135 helicopter cabin in order to assess the effectiveness of such techniques for NVH improvements.

In particular, several vibro-acoustical modal analyses have been carried out, on the cabin internal and external surfaces as a pure acoustical modal analysis of the cabin enclosure. The aim of this massive testing campaign was the establishing of the vibro-acoustical coupling between the cabin enclosure and the two surfaces, internal and external one, besides the knowledge of the vibration response of the helicopter, extremely important in the design process. In particular, the vibro-acoustical coupling is one of the cabin interior noise responsible, i.e. the structural vibrations of the walls produces an acoustical vibration of the fluid particles, yielding a noisy environment. In this paper it has been stated that not only the internal cabin surface but also the external surface of the helicopter cabin is acoustically coupled to the cavity. This inspection is crucial since any external structural loading acting on the helicopter (e.g. from the ambient excitation) may then cause internal noise due to coupling, involving the necessity of particular attention from the designer in order to well identify all the critical frequencies. Furthermore, it has been proven that if the helicopter is structurally excited, e.g. by means of shakers, some coupled modes could be ignored because of the indirect excitation. In this context, since only a proper prediction of the vibration response of the rotorcraft cabin can guide the designer to reduce the possibility of resonances in flight operational conditions, the excitation mechanism is of pivotal importance in such modal analysis tests.

Eventually, the results concerning the ultrasonic measurements and the intensity maps clearly shown that both techniques are useful tools for fast precise and efficient identification of leakage points on the helicopter cabin surface. However the intensity technique is more accurate from the spatial and frequency resolution standpoint with respect to the ultrasonic analysis.

6 ACKNOWLEDGMENTS

This research was performed in the framework of the 6th European Commission Frame Work Program - Integrated Project - FRIENDCOPTER Integration of Technologies in Support of a Passenger and Environmentally Friendly Helicopter. The support of the European Commission is gratefully acknowledged. In addition, Eurocopter is acknowledged for the available data.

7 REFERENCES

[1] Wyckaert, Augustinovicz, F., Sas, P., 1996, "Vibro-

- acoustical modal analysis: Reciprocity, model symmetry and model validity", *Journal of Acoustical Society of America*, 100 (5).
- [2] Göransson, 1993, "Acoustic finite elements" in *Advanced Techniques in Applied and Numerical Acoustics*, edited by P. Sas (K. U. Leuven), Part VI.
- [3] Heylen, W., Lammens, S., Sas, P., 2007 "Modal Analysis Theory and Testing", KUL Press, Leuven, Belgium.
- [4] Microflown USP Manual, Microflown Technologies, Zevenaar, www.microflown.com.
- [5] Vecchio, A., Valent, L., Bregant, L., 2005, "Impact of test data uncertainties on modal models extracted from multi-patch vibrations test", *Symposium Le Mans (France)*, pp.27-29.
- [6] Piero, E., Mucchi, E., Vecchio, A., 2008, "Using P-U probes for the experimental vibro-acoustical modal analysis of a helicopter", *Proceedings of ISMA2008*, Leuven September 15-17.
- [7] Hauptmann, P., Lucklum, R., Puttmer, A., Henning, B., 1998, "Ultrasonic sensors for process monitoring and chemical analysis: state of the art and trends", *Sensors and Actuators A67*, pp.32-48.
- [8] Pintelon, R., Schoukens, J., 2001, "System Identification: a Frequency Domain Approach", New York: IEEE Press.
- [9] Piero, E., Mucchi, E., Soria, L., Vecchio, A. 2009,, "On the vibro-acoustic operational modal analysis of a helicopter cabin", *Mechanical Systems and Signal Processing*, doi:10.1016/j.ymssp.2008.10.009.
- [10] Testa, L., Vecchio, A., Bregant, L., 2008, "Transfer path analysis of the Agusta Westland AW-109 performed by means of in-flight data and Polymax synthesized FRFs", *Proceedings of ISMA2008*, Leuven September 15-17.
- [11] Fahy, F., 1995, "Sound Intensity", Taylor&Francis.
- [12] LMS Test.Lab 8A, LMS International, 2008.
- [13] LMS Virtual.Lab 7A, LMS International, 2007.
- [14] Mucchi, E., Vecchio, A., 2008, "Acoustical signature analysis of a helicopter cabin in steady-state and run up operational conditions", *Proceedings of ISMA2008*, Leuven September 15-17.
- [15] Guillaume, P., Verboven, P., Vanlanduit, S., Van der Auweraer, H., Peeters, B., 2003, "A poly-reference implementation of the least-squares complex frequency-domain estimator", In *Proceedings of IMAC 21*, the International Modal Analysis Conference, Kissimmee (FL), USA.
- [16] Wallace, C.E., 1972, "Radiation resistance of a rectangular panel", *The Journal of the Acoustic Society of America*, Vol.51, N. 3, Part2.