Active Control of Helicopter's Gearbox Vibrations and Effects on the Cabin Noise

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Abstract: In the framework of the European project FRIENDCOPTER, the Department of Aerospace Engineering of Politecnico di Milano is involved in developing active control systems aimed at reducing the vibration transmission from the gearbox to the cabin in medium-size civil helicopters. An AgustaWestland A109MKII mock-up was used to perform vibroacoustic measurements and control tests. The active configuration consists of two smart rear struts with 4 piezoceramic actuators pairs each and a smart anti-torque plate with 6 piezo pacthes on each side. Four independent narrowband FXLMS vibration controllers are designed and implemented to control each beam and the two sides of the plate. From open-loop vibration and acoustic analysis, a set of annoying tones in a frequency band up to 4 kHz are targeted to be reduced. A movable rack of microphones is placed inside the cabin to monitor the acoustic field over a grid spreading the whole cabin width in an area close to the passenger back seats. Vibration reductions up to 20 dB of the target tones are obtained on the accelerometer error sensors. Acceptable noise reductions of a few tones are achieved over certain zones, but the result cannot be extended to the whole cabin. The control configuration described in this paper will be tested on a flying helicopter in cooperation with AgustaWestland. Some experiment was also performed in order to regulate cabin acoustic changing the gear-box mass distribution.

INTRODUCTION

Improvement of passengers acoustic comfort in helicopters is a challenging task. It is known that this kind of vehicle is one of the most noisy due to its configuration [14]: the rotor and the engine/gearbox units are directly connected to the fuselage through mount elements which are designed to be as stiff as possible to guarantee stability at the most severe flight conditions. However, they provide very poor vibration isolation and so high level broadband and narrowband disturbances are introduced into the cabin. Low frequency narrowband noise is generated by the blades passage and related harmonics. Higher frequency tonal noise comes from gearbox meshing and creates an annoying acoustic field which is the most responsible for degradation of the acoustic comfort inside the cabin. Currently, passive means such as acoustic treatments are widely adopted in helicopter industry due to their efficiency at high frequency and ease of installation. However, they are quite inefficient in the low-mid frequency range due to low weight and space limitation requirements. In recent years, a great amount of work has been focused on the application of active noise and vibration control systems. Three main strategies can be envisaged (see [9][10][12][13][14]): 1) active noise control inside the acoustic environment using microphones and loudspeakers; 2) active control of the vibrating surfaces (fuselage panels) responsible of sound radiation inside the cabin; 3) active vibration isolation of the power generation structures (gearbox) from the receiving structures (the fuselage). Following the last strategy, mount elements are equipped with suitable actuators driven by a digital control aimed at reducing disturbance coming from the gearbox at selected locations. In this study, an active vibration isolation system is implemented on a full scale helicopter mock-up fuselage. The present work is a the carrying on of a previous preliminary study on the same test-bed [2][3][4]. The active configuration and control architecture are fully described. Both vibration and acoustic results are presented.

1. Controller description

As outlined above, reduction of some selected annoying tones corresponding to gearbox meshing can provide a significant improvement of the acoustic comfort inside a helicopter cabin. Therefore, the present work is focused on isolating the helicopter gearbox from the cabin at some target narrowband disturbances falling between 1.5 and 6 kHz. The physical configuration and the kind of excitation of interest are suitable to the implementation of a feedforward control scheme. A narrowband multi-input-multi-output (MIMO) FXLMS controller based on FIR filters is adopted in this study [5][6][8][11]. The basic idea is to feed the adaptive digital FIR filters with reference signals well-correlated with the disturbance entering the plant. The coefficients of the control filters are updated towards the minimization of the instantaneous square error values detected at desired locations. In this work the various secondary paths, i.e., the dynamic of the actuator to sensor path, are estimated off-line by FIR filters of appropriate length. Note that long secondary path filters are required when dealing with lightly damped structural systems and long control filters are associated with broadband disturbance rejection. The overall general scheme of a MIMO FXLMS controller is quite complex since all the reference signals are connected to the secondary path and control filters. Each control filter is then updated using several error sensors. The resulting computational requirements are very high and actually represent the main limitation for the closed-loop bandwidth achievable in a real-time implementation with currently available hardware.

If broadband disturbance rejection is of interest, a natural reference signal is usually adopted to feed the control filter. In our case, this could be implemented by an accelerometer located on the gearbox to give a confident measure of the incoming disturbance. When one is interested in a few narrow tones of the whole disturbance spectrum, different strategies can be adopted, such as using a narrowband reference signal coming from a sensor capable to measure only the selected tones, using appropriate band-pass filters with a broadband reference signal or, after carefully detecting the target tones, providing a digitally synthesized reference signal to the control algorithm. As described below, this last strategy is followed up in the present study since it allows optimizing the control effort on the selected frequency bands as well as reducing the computational load by shortening the FIR control filters. A multi-reference scheme is implemented to include all the target tones to be rejected.

2. Test description

The master plan target is the experimental testing of a functioning active control system on a flying AW109 helicopter. The active control system will be tested on three different flying condition: hovering out of ground effect (*HOGE*), maximum level-flight airspeed (*VH*) and leveled flight from 40 up to 140 Kts. An helicopter mock-up was prepared at Politecnico laboratories in order to develop and test different configurations before final in-flight tests. All laboratory control tests have been carried out on a Agusta Westland A109MKII mock-up. The mock-up is supported on three points on the ground as shown in fig. 1(a) and it is only partially set up. In particular, there is no tail, no avionics, no interior decoration and also the gearbox cover is missing. The jet engines are replaced by electric motors able to drive the gearbox at the same regime of the cruise condition. An aerodynamic brake (see fig. 1(b)) has been designed and mounted as a substitute of the original blades. In this way an equivalent aerodynamic drag is provided to reproduce the in-flight torque loading conditions of the running gearbox. As a matter of fact, the aerodynamic brake does not provide any lift. Thus, the structural elements supporting the gearbox/rotor system do not experience any vertical load. This configuration is able to qualitatively reproduce the in-flight interior acoustic spectrum as shown for the sound pressure level (SPL) comparison reported in fig. 2(a).

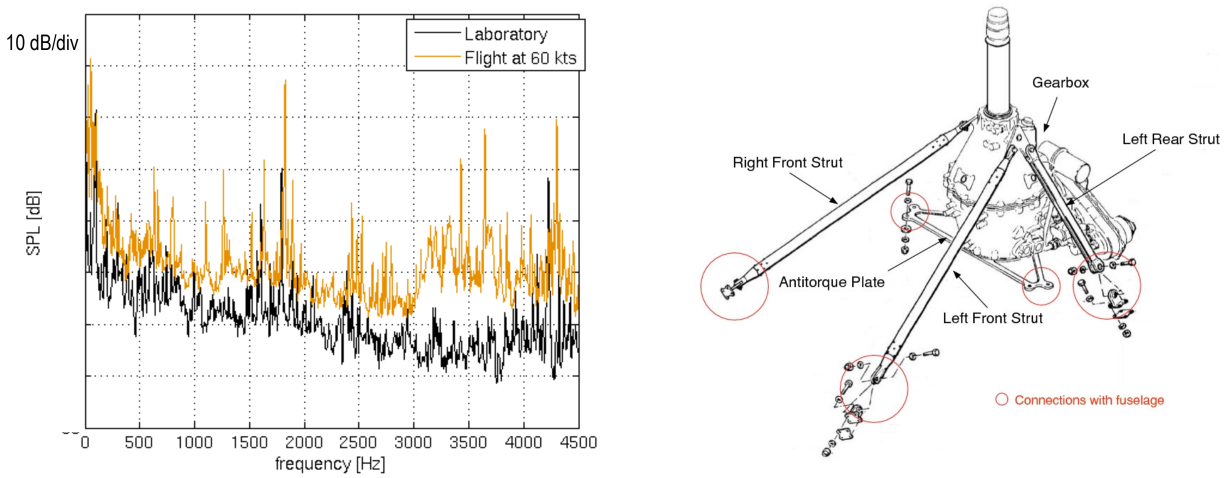
(a) Mock–up (b) Aerodynamic brake

fig. 1 Laboratory installation

The gearbox is connected to the fuselage by means of two rear H-section struts, two front tubular struts and a D-shaped thick antitorque plate. The plate is responsible for the torque transmission between the rotor and the cabin as depicted in the schematic drawing in fig. 2(a). The rear struts and the plate are very stiff and represent the main transmission paths between the vibrating gearbox/rotor unit and the cabin. The active control systems described herein aim at reducing the vibration transmission through such mount elements by using flat PZT patches (Ferroperm PZ21A) as control actuators. Each rear strut is equipped with four pairs of PZT patches bonded on the surface as shown in fig. 3. Each pair is driven in-phase to generate longitudinal control waves along the strut. The antitorque plate is provided with six pairs on each side and each pair is driven out-of-phase to generate flexural control waves (see fig. 3). The PZT patches are driven by a high voltage amplifier (Elbatech T506HV) with selectable gain (10/20), input voltage from -10 V to 10 V, output voltage from -200 V to 200 V and output current up to 200 mA for each channel.

The FXLMS control algorithm previously described is usually implemented on powerful DSP devices. However, as shown in Ref. [1], general purpose processors are more versatile and flexible than DSP in a laboratory testing environment and can provide similar computational and hard real-time performance. In this work, all the control algorithms have been coded and run on common desktop PCs running a real-time patched Linux operating system. The PCs are equipped with general purpose data acquisition boards from National Instruments. Low pass analog filters from Kemo are also used to avoid aliasing and to smooth analog output signals. Error signals used to update the FIR control filters are provided by ICP accelerometers from PCB Piezotronics.

After identifying the main structural paths, the experimental test-bed was tuned to reproduce a vibration and interior noise field similar to those experienced in-flight. As already stated, the vibration and acoustic spectrums are highly characterized by gear meshing and other rotating accessories regimes as can be deducted from table 1.

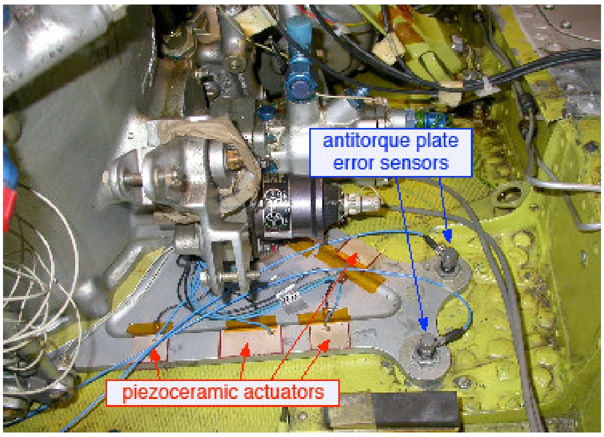


(a)SPL at 60 kts

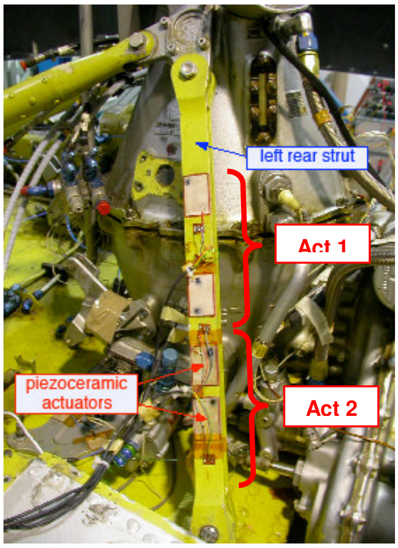
(b) Gearbox description

fig. 2 In–flight and laboratory spectrum and gearbox description

In the laboratory tests, the actual rotational regime of the electrical engines is set to 5865 rpm instead of 6000 rpm. This implies that the 1826 Hz tone is actually shifted at a lower frequency (1785 Hz). A common configuration for sensors is adopted. As depicted in fig. 3, four accelerometers are placed on the bolts connecting the anti-torque plate with the cabin roof panel. One accelerometer is placed on the connecting element of each rear gearbox strut.



(a) Anti–torque plate actuators/sensors configuration



(b) Left rear strut actuators configuration

fig. 3 Actuators location

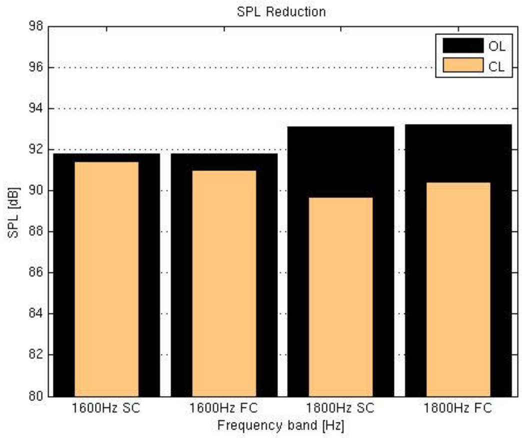
2xSource	Number of teeth/blades	2xRPM	Frequency [Hz]
ENGINE			
Gearbox output shaft	–	6000	100
ROTOR			
Main rotor	4	385	25.7
TRANSMISSION			
Input pinion	43	6016	4311
Input spiral bevel pinion	25	4383	1826
Input spiral bevel gear	72	1522	1826
Collector gear	59	4384	4311
Idle gear	57	4538	4311
Sun	43	1522	815
Ring gear	127		815
Planet gear	42	1223	815
Accessory drive gear	26	4215	1826

table 1 Main rotating elements and associated frequency

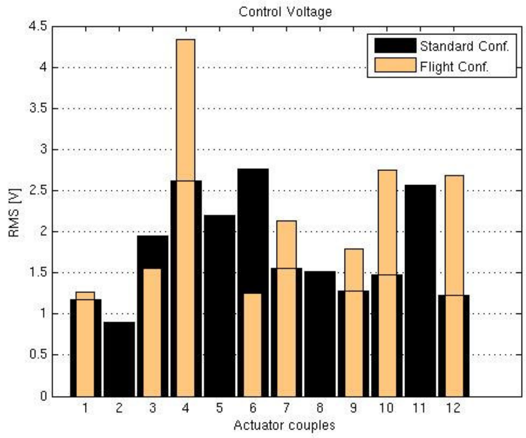
3. Fly-test hardware configuration

As described above, an active control system involves a large number of electronic devices, which must be compatible with the available space and power of the helicopter during in-flight tests. In general, the amount of hardware is directly related to the number of control actuators and sensors. A study was carried out to select the configuration having best closed-loop performance with less number of input /output channels. The final set for in-flight tests involves 20 control signals and 4 error signals driven by 3 PCs equipped with general I/O boards.

A configuration with 8 actuators pairs on the anti-torque plate and 4 actuators on each struts was finally adopted (called *reduced* or *flight configuration* - *FC*). This choice was suggested by comparing control performances between the full and reduced number of available control signals. Comparison tests between the *standard configuration* (SC, with 6 PZT pairs of actuators) and the *reduced configuration* are shown in fig. 4. Secondary path filters of length 200 and control filters of length 100 were used, respectely. As depicted in fig. 4, the reduction of the number of actuators on the anti-torque plate introduces slightly variations in the closed-loop SPL and acceptable increase in the control power.



(a) Comparison between SPL reduction (mean on 50 measurement points) inside cabin in standard configuration (*SC*) and reduced configuration (*FC*)



(b) Comparison between RMS control voltage using standard configuration and reduced configuration (flight conf.)

fig. 4 Comparison between different configuration parameter for in-flight test

Control software was also modified be activated by an AgustaWestland flight tester thourgh a simple button control box. The button control box of fig. 5 was designed and realized at Politecnico with the following functions: enable/disable rear struts control, right side of the anti-torque plate left side of the anti-torque plate, enable control sequence and turn off active control. The control sequence has the following functions: 1) save error sensors time history with control off 2) enable active control 3) save error sensors time history with control on after a transient time 4) wait turn off command with active control enabled while flight tester measure acoustic responses inside cabin. The sequence also verifies possible control output saturation and disable active control if saturation persists for a while prescribed amount of time.

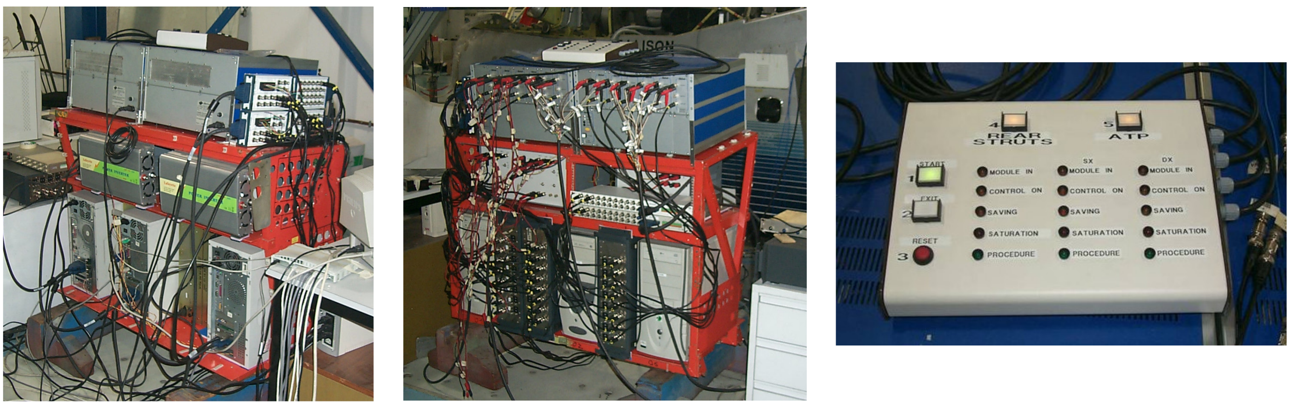


fig. 5 In-flight rack and control button box

4. Active solution results

The present section provides an overview of both vibration and acoustic performance of the active control systems. In the first case, the performance of the control system is measured by comparing the open and closed loop acceleration at the sensor position. Acoustic results are presented by showing the SPL distribution over an area close to the passengers head. To this end, a movable microphone rack is placed inside the cabin underneath the anti–torque attachment points. The cabin width is spanned from side to side to obtain a final grid of 50 measurement points. The SPL values are collected at 16384 Hz by a Scadas box and processed by LMS Test.Lab software. A 1/12th octave analysis is performed to show results. Since three narrow frequency bands to be reduced by the active control systems are selected, i.e., at 1600, 1800 and 4250 Hz, only the frequency bands around the target tones are reported. In the present study, the following hardware/software configuration are adopted. Active control on the rear struts is performed by using one PC with two independent FXLMS controllers so that every controller manages four control signals and one error signal. Active control on the anti-torque plate is carried out by using two PCs with one FXLMS controller for each side of the plate so that every PC manages six control signals and two error signals. The sampling frequency is set to 14 kHz and every channel is low-pass filtered after 5 kHz. A multi-reference configuration is adopted, i.e., one digital reference signal is provided for each target tone. FIR filters of length 200 are used to model the secondary paths, whereas control filters of length 20 are enough for a good narrowband disturbance rejection.

Figures 6(a) to (c) show the vibration response at the error sensors with and without active control, as well as the closed-loop disturbance rejection in dB. The mean value of the acceleration reductions on tones are reported. It has to be noted that the control action is focused on the target frequency bands without any appreciable spillover and good rejection of about 20 dB is obtained for all cases.

Figures 7 and 8 show the acoustic response with and without active control at the target tones, as well as the SPL reduction over the grid of measurement points. The analysis of acoustic performance can provide useful information on the effectiveness and efficacy of the design of the active vibration isolation system previously described. Looking at fig. 8 one may notice that a mean reduction of 3 dB is obtained for each target frequency band over the whole measurement area. Some effect is also achieved over the range from 1800 to 2300 Hz where slight reductions of 1-2 dB are shown. Figures 7(a) to 7(c) reveal that there are wide zones where the SPL reduction of the selected annoying tones is quite promising (about 5-10 dB). However, in other zones the SPL is actually increased by a significant value. Various strategies to overcome this limitation are currently under study. Joining active solutions with passive ones it's a possible way and a main gear-box mass re-distribution study is described in the following.

5. Passive solution through mass distribution

It's widely known that adding mass can have beneficial effects on the vibration and acoustic radiation of the structures, especially at higher frequencies. After testing different kinds of actuators, it was found that concentrated masses placed on the structural attachments of the anti-torque plate can heavily affect the acoustic filed inside the cabin. Results with four masses of 0.8 and 1.5 Kg on the four attachment bolts are presented in this section and depicted in figs 9 and 10. These pictures summarize the mean acoustic regulation on the 50 microphones measurements presented in the previous section. This plots depict the SPL only beginning from 1.7 KHz band because since below this value there is no change in the cabin acoustic field. The progressive mass adding increase the reduction at high frequency, but with less gap. Differences between the configuration with 0.8 Kg and 1.5 Kg are reported in fig. 11. It has to be noted that only 2.4 Kg on the anti-torque plate decrease the 4250 Hz 1/12th octave band of 9 dB.

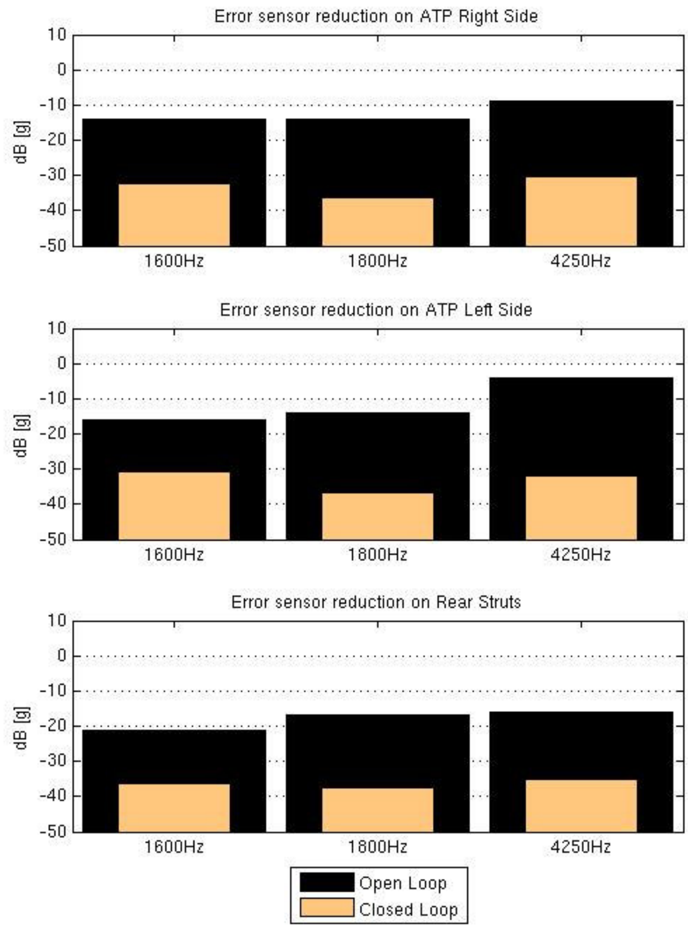


fig. 6 Error sensor vibration reduction respectively on anti-torque plate and struts: dark bar are measured in open loop and clear bar in closed loop.

Tone [Hz]	SPL in Open Loop [dB]	SPL in Close Loop [dB]	Maximum Reduction [dB]
1600	98.56	95.12	11.40
1800	97.39	95.34	11.07
4250	101.44	98.70	10.67

table 2 Performance indexes of active control

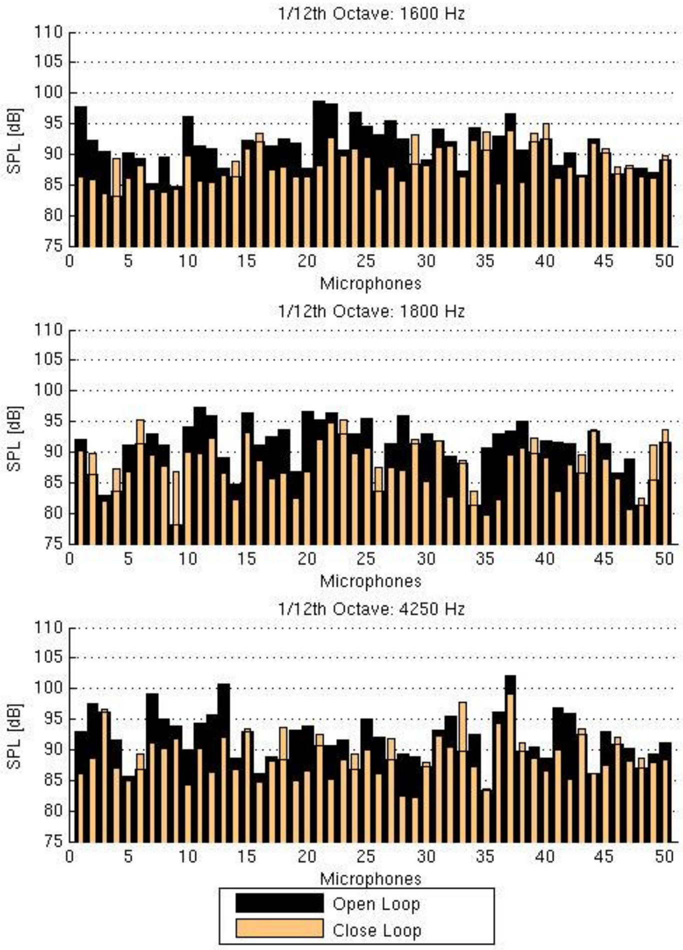


fig. 7 FXLMS: acoustic performance on the 50 measurement points on the three controlled tones

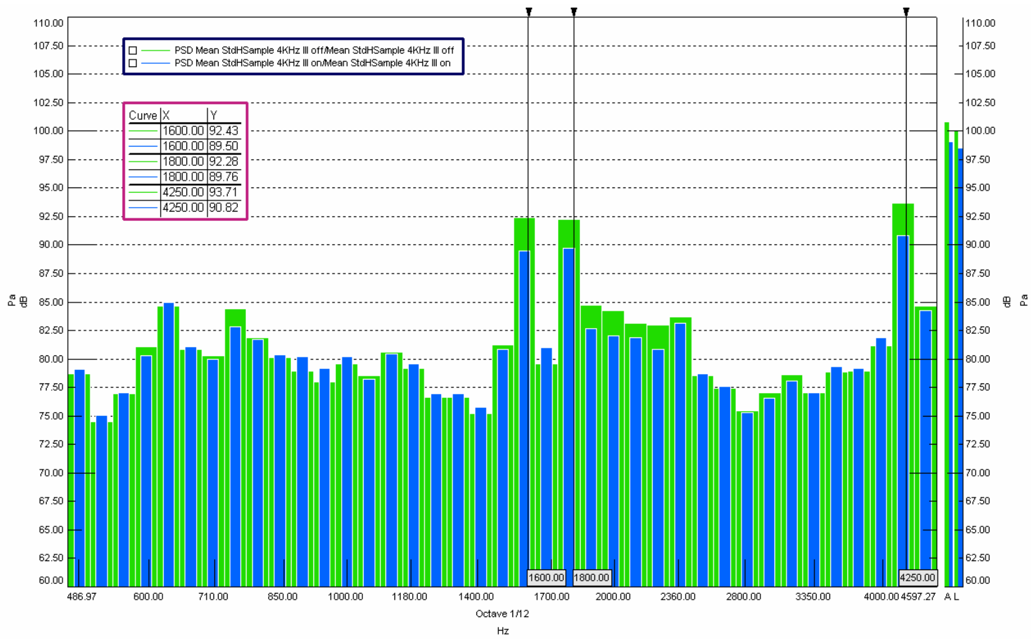


fig. 8 Mean SPL regulation measured on 50 microphones: green bar in open loop, blue bar in closed loop

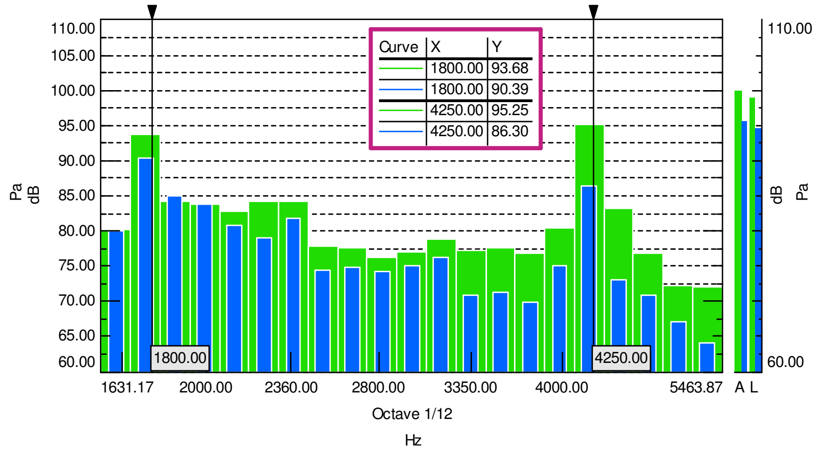


fig. 9 Mean SPL regulation with 4 masses of 800 grams: green bar without mass, blue bar with mass on anti-torque plate bolts

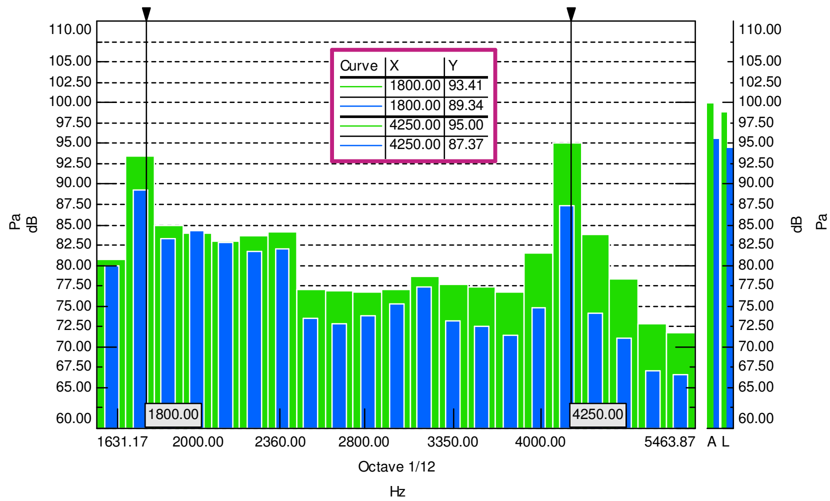


fig. 10 Mean SPL regulation with 4 masses of 1500 grams: green bar without mass, blue bar with mass on anti-torque plate bolts

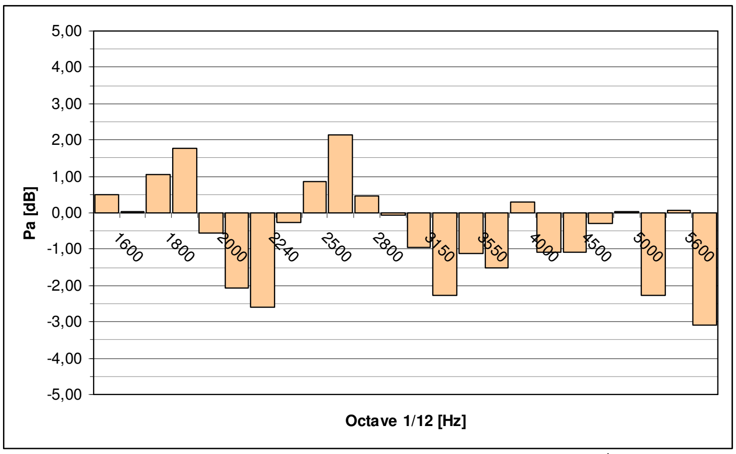


fig. 11 SPL variation passing from 0.8 Kg to 1.5 Kg in 1/12th octave band

Conclusion

The results here presented have shown that acceptable acoustic performance are achieved by the active control systems. A general reduction of 3 dB is obtained in the 1600 Hz 1/12th octave frequency band whereas a reduction up to 8 dB can be experienced at 1800 Hz. Finally a more diffuse reduction is obtained on the 4211 Hz tones. A final configuration is ready to be tested on an experimental AW109 helicopter as final task of Friendcopter European project. The in-flight activities will be done in strict cooperation with AgustaWestland, monitoring acoustic field in 6 fix points inside cabin.
Acoustic filed can also be modified changing the mass distribution on the anti-torque plate, the structural element that connect the main gear-box with the cabin roof. Especially the high tones emission can be varied adding mass of less than 1 Kilograms on each connecting bolts.

Acknowledgments

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