ICSV13 - Vienna
The Thirteenth International Congress on Sound and Vibration
Vienna, Austria, July 2-6, 2006

PRELIMINARY EXPERIMENTAL RESULTS OF ACTIVE TONAL VIBRATION CONTROL INSIDE AND OUTSIDE HELICOPTER CABIN

Lorenzo Dozio[1], Alessandro Forghieri[*1], Gian Luca Ghiringhelli[1], Fausto Cenedese[2]

[1]Department of Aerospace Engineering, Politecnico di Milano
Via La Masa 34, 20156, Milan, Italy
[2]Vibro Acoustic Department, Agusta Westland
Cascina Costa Varese Italy
forghieri.ale@libero.it

Abstract
The paper presents the preliminary testing results of an active gearbox strut control system on a helicopter mock-up, with the goal of improving tonal vibration reduction, under real operative conditions. The gearbox is driven by two electric motors at the nominal rotating speed and a suitable aerodynamic brake is attached to the rotor must to reproduce the load effect of the rotor blades. The normalised FXLMS adaptive control algorithm was implemented to control the rear struts, each equipped with three pairs of piezoelectric patches. The reference signal was supplied by accelerometers positioned on the upper gearbox attachment. Error signals were derived by accelerometers positioned both outside the cabin, on the lower struts attachment devices, and inside the cabin. Appropriate band-pass digital filters were designed and used to limit the required control voltages. Different control configurations, in terms of number and position of actuators and sensors, were tested. Advantages and limitations were discussed, as well as power actuation requirements and convergence rate. In these preliminary tests, only one tone at a time has been considered; results showed that it is possible to reject large-amplitude high frequency tonal vibration disturbances.

INTRODUCTION

The main purpose of this study is to investigate active real time control techniques to reduce vibrations transmitted by the gearbox struts to the helicopter fuselage. Because the main function of the gearbox support struts is to maintain a rigid link between the drive unit, the rotor and the fuselage, they offer little isolation and constitute the main structural vibration transmitting path **[1]** to the helicopter cabin for both the low frequency vibrations generated by the rotor blades (up to 500 Hz) and the vibrations generated by the gearbox (up to 3 KHz).

After extensive tests conducted on a test bed smart gerbox strut **[2]**, the normalised FXLMS control algorithm **[3]** were applied on a helicopter mock-up. In the following tests, a single tone reduction was considered, using different piezo actuator (driven only in axial mode) configurations, and band-pass filters **[4]** to concentrate the control energy around the tonal disturbances of interest. These tests are essential to understand the energy required to control tonal vibration in a helicopter, under operative disturbance condition.

The references signal was supplied by accelerometers positioned on the upper gearbox-strut attachment devices, making the control system independent by internally generated reference, and providing a solution for practical on-board implementation.

The results validate all the assumption with respect to the hard real time control algorithm and experimental implementation, and offer a solution for high narrowband vibration reduction.

HELICOPTER MOCK-UP AND CONTROL SYSTEM DESCRIPTION

A helicopter mock-up has been assembled in the structural dynamics laboratory of the Aerospace Engineering Department at Politecnico di Milano. The actual fuselage of an A109 MKII Agusta Helicopter (*Figure 1-a*) has been used. The gearbox is driven by two electrical motors (10% of the original power) at the nominal speed (6000 RPM). At the top of the mast, two aerodynamic brakes are mounted to reproduce the load effect on the gearbox. Peaks at the gear meshing frequencies reveal amplitudes very close to the ones acquired during in-flight measurements.

The rear struts supporting the gearbox housing (*Figure 1-b*) are aluminium alloy beams, approximately 500 mm long, with a uniform H section, 35 mm spars and 28 mm web. Three couples of Piezoelectric Actuators (PI 151 plate 50-30-0.5 mm) were bonded at ¼, ½ and ⅔ of the strut length and driven in phase. In this way the control actuators generate longitudinal forces.

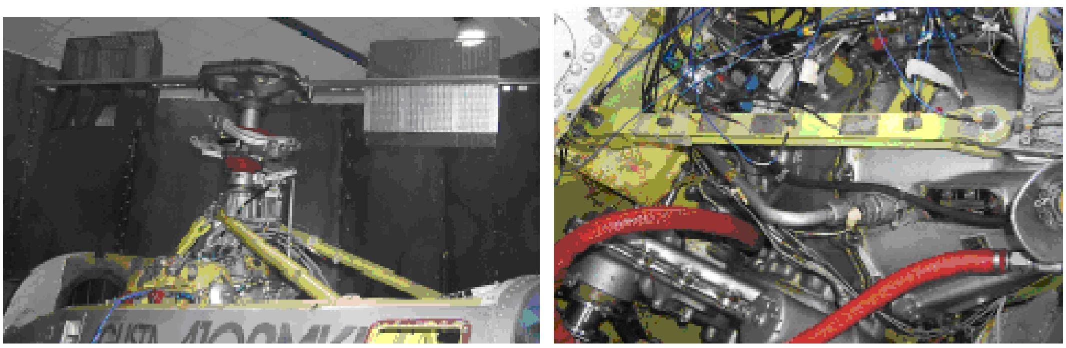

Figure 1 – a) Helicopter Mock-Up *b) Rear Left Strut.*

The PC used for acquisition and control is a 2 GHz AMD Athlon XP 2400 running a real-time multi-tasking operating system. The acquisition and control software were designed and tested using RTAI-Lab **[5]**, an open-source advanced tool relying on the MATLAB Simulink/Real-Time-Workshop environment. National Instruments 12-bit I/O boards were used. To prevent aliasing, all signals were filtered using 8th order Bessel low-pass filters (cut off frequency 2 KHz).

The output control voltages were supplied by a home-made four channel power amplifier, based on PA85 Apex components, working over a frequency range up to 20 KHz and a maximum gain of 26 dB (the maximum control voltage allowed at piezo is 150 V). The sampling frequency of the FXLMS controller was set to 8 KHz.

In this preliminary activity, a single tonal disturbance component at 1780 Hz was considered for active reduction. A multi-input-single-output normalized FX-LMS algorithm [3] was implemented using FIR filters for the controller and secondary path. Off-line tests were first performed to estimate the secondary-path transfer function using internally generated white noise to drive the piezo-electric actuators.

Considering that the longitudinal dynamics of the strut is above the frequency range of interest, the authority of the control, for each couple of actuators, should be insensitive with respect to the position. This can be preliminarily verified by the comparison of the measured secondary paths, between each couple of actuators and the error sensor (*Figure 2*).

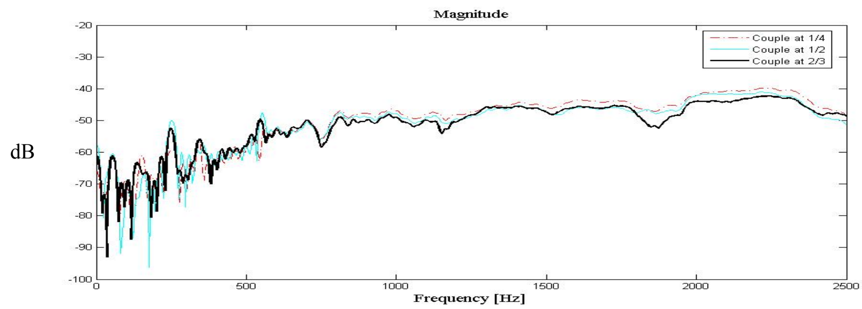

Figure 2 – Secondary Path: Actuators versus Error Sensor position Inside Cabin.

As a consequence, similar control voltages are expected for each couple of actuators.

Filters were applied to the reference and error sensors to overcome saturation problems. A study has been conducted on the most frequently used filters (Bessel, Butterworth, Chebyshev type 1, Inverse Chebyshev and Elliptic). Inverse Chebyshev 6th order pass band filters were selected because of the absence of the ripple phenomenon (which is critical when high vibration levels are involved). Filters were centred on the tone at 1780 Hz, with an appropriate frequency pass band in order to accommodate disturbance shifts.

The effects of the simultaneous use of two and three couples on the left rear strut and the effects of two couples used on both rear struts were analysed.

SINGLE STRUT VIBRATION CONTROL

A first set of tests was conducted on a single strut. They were essential to understand the power required to control vibration in a condition really close to in-flight operative condition, and to analyse the limits of the real time implementation. The left side of the helicopter has been selected because, with respect to the right side, vibration levels were always higher due to the rotation sense of the main rotor.

Two couples of piezoelectric actuators bonded approximately at ¼ and ½ of the beam were selected for the control. Error sensor positions (*Figure 3*) outside the cabin in the lower attachment device, and inside the helicopter cabin, near the passenger head position, were alternatively used.

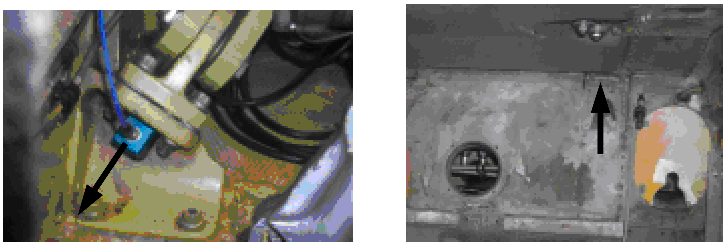

Figure 3 – Error Sensor accelerometer positions a) Outside Cabin b) Inside Cabin.

The outside cabin error measurement is taken in the longitudinal beam direction while for the internal point, the direction is normal to the roof. This means that in the second configuration, the components of flexural struts transmitted vibrations were also sensed by the error and passed to the active control. As a consequence, a higher power requirement can be expected.

In *Figure 4*, the result of the control (3 minutes after the start) applied to the rear left gearbox strut (lower attachment) is reported in terms of power spectral density. As it can be seen the selected tone is completely rejected.

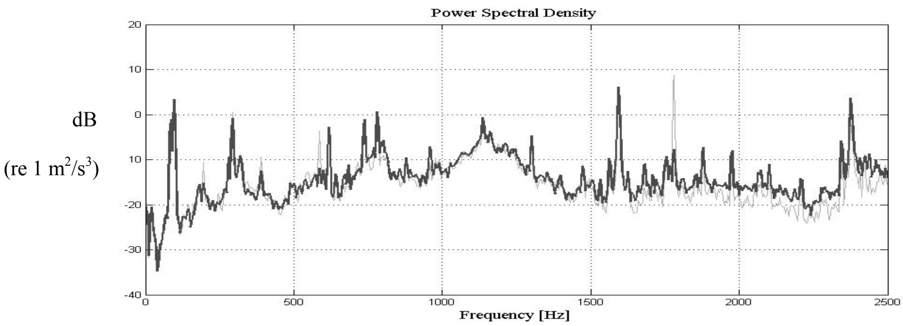

Figure 4 – Controlled (Solid Line) and Uncontrolled (Faint Line) Longitudinal Vibrations.

The control output voltage values (see *Table 1*), for each couple of actuators, are similar and always below the saturation limit.

Elapsed Time [s]	90	180
Tone Reduction (dB) at 1780 [Hz]	-14	-16.5
Max Voltage +/- [V] – Couple at ¼	90	100
Couple at ½	90	100

Table 1 – Tone Reduction and Control Output Voltage for the SIMO Outside Cabin control.

The frequency responses of the two control voltages, are very close as shown in *Figure 5*. As expected, the energy is focused on the single controlled tone.

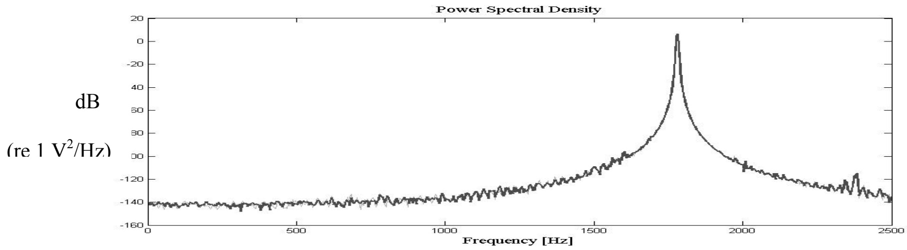

Figure 5 – Output Control Voltages:Couple at ¼ (Solid Line), Couple at ½ (Faint Lne).

The results of the outside cabin vibration control were satisfactory with respect to amplitude attenuation, convergence and control stability. These results suggest that it is possible to implement the longitudinal vibration control also on an actual helicopter environment.

Unfortunately results obtained using the inside cabin reference sensor (*Figure 6*) were not satisfactory because of a general increment in the level of vibration under control and the decrease of the control piezo authority (the distance between the piezo and the reference error is higher then the distance of previous configuration test).

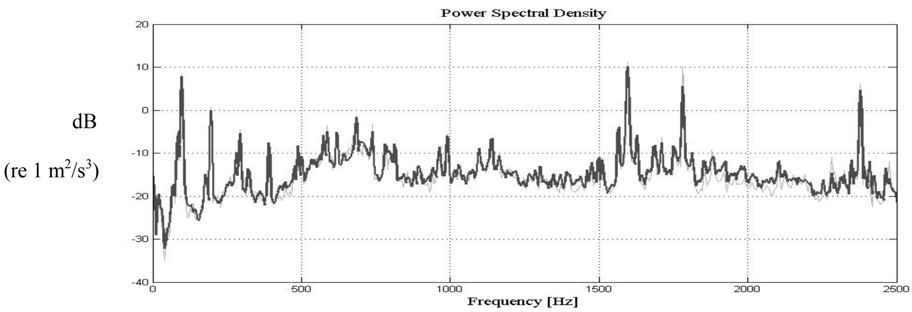

Figure 6 – Controlled (Solid Line) and Uncontrolled (Faint Line) Longitudinal Vibrations.

Consequently the energy required for the control increase and the control output voltage quickly (60 [s]) reaches the saturation for both pairs of piezo (*Table 2*).

Elapsed Time [s]	60
Tone Reduction (dB) at 1780 [Hz]	-5
Max Voltage +/- [V] – Couple at ¼	Saturation
Couple at ½	Saturation

Table 2 – Tone Reduction and Control Output Voltage for the SIMO Inside Cabin control.

The use of the third piezo electric actuator couple (bonded at ⅔ of the strut length) allowed to overcome this problem. The control model and the filter design were not changed. The results of the control, in the case of the external reference sensor, are shown in *Table 3*.

Elapsed Time [s]	120	240
Tone Reduction (dB) at 1780 [Hz]	-20	-20
Max Voltage +/- [V] – Couple at ¼	66	66
Couple at ½	66	66
Couple at ⅔	66	66

Table 3 – Tone Reduction and Control Output Voltage for the SIMO Outside Cabin control.

As can be easily observed, the authority of the control is effectively higher with respect to tone reduction, convergence velocity and control stability. Moreover, voltage values are always inside the saturation range.

The importance of this test is related to the analysis of the control voltage output which drives the piezoelectric actuators. Voltage values reveal that the behaviour of the control voltage is quite linear with respect to the number of actuators. Using two couples of piezo the control voltage for each couple of actuators was 100 V (see *Table 2*), while using three couples of piezo the request reduced to 66 V (see *Table 3*). The increased margin with respect to the saturation limit of 150 V will be helpful in the following implementation. In fact, the use of three piezo actuators yields good results also in the configuration with the error sensor positioned inside the cabin.

Figure 7 shows the complete tone rejection inside the cabin, while *Table 4* shows the convergence and the stability of the control algorithm.

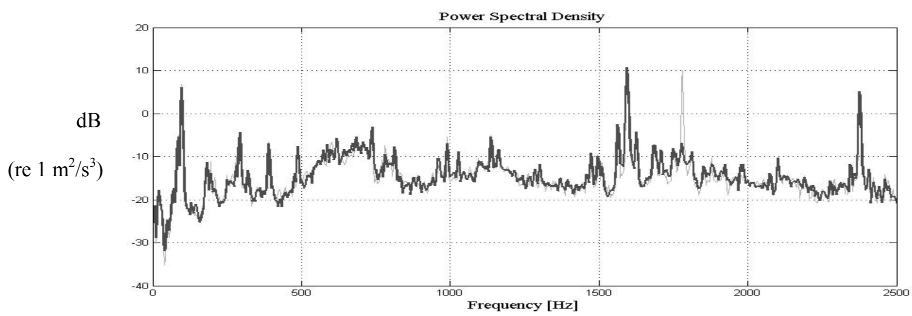

Figure 7 – Inside Cabin. Controlled (Solid Line) and Uncontrolled (Faint Line) Vibrations.

Elapsed Time [s]	120	240
Tone Reduction (dB) at 1780 [Hz]	-17	-17
Max Voltage +/- [V] – Couple at ¼	102	102
Couple at ½	102	102
Couple at ⅔	102	102

Table 4 – Tone Reduction and Control Output Voltage for the SIMO Inside Cabin control.

By the analysis of the voltage values in *Table 4*, and observing the linear trend of the output voltage with respct to actuators number (detected in the external sensor vibration control, *Table 1* and *Table 3*), it is possible to suppose that the saturation reached in the test conducted with two couples of piezos (*Figure 6* and *Table 2*) could be avoided, with a small reduction of the control outputs required.

VIBRATION CONTROL INSIDE THE CABIN: TWO STRUTS

The last step of the present activity is related to the simultaneous control of the two rear struts, in order to reject the tonal component in both internal cabin error sensor positions. Only two couples of piezo bonded at ½ and ¼ of the struts length were used to control vibrations. The use of only two couples led for different advantages: at first a reduced complexity of the control system; it makes the system redundant with respect to actuators failure; moreover a third pair of actuators could be used to reject a mixed longitudinal-flexural vibration strut control implementation.

The results of the longitudinal control verify the previous assumption with respect the saturation problem shown in *Table 2*. *Figure 8* shows the rejection of the tone at 1780 Hz in the left and right side of the rear panel inside the cabin. Moreover, reductions at the two controlling times, reported in *Table 5*, reveals how quickly the target is reached and the stability of the control during a long time period.

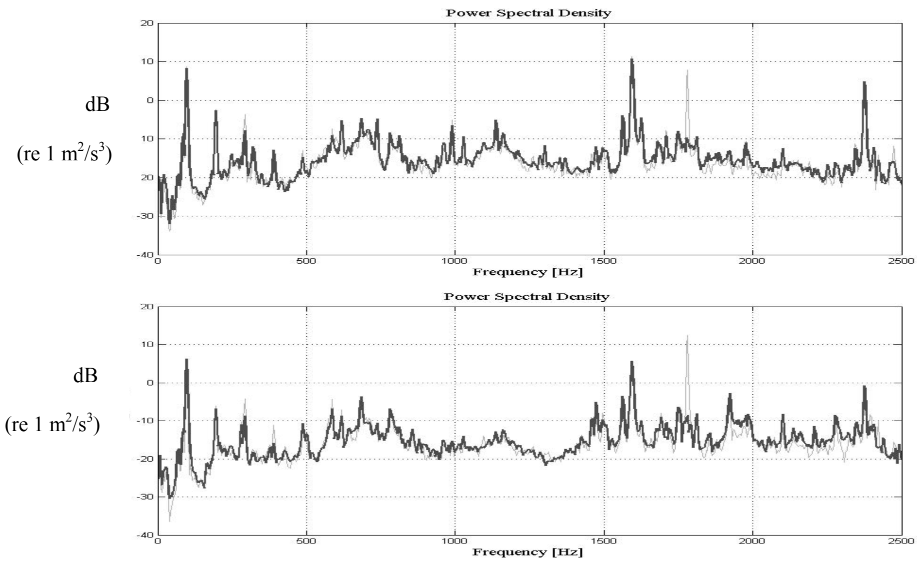

Figure 8–Left&Right Side, Controlled (Solid Line) and Uncontrolled (Faint Line) Vibrations.

Elapsed Time	[s]	120	240
Tone Reduction (dB) at 1780 [Hz]	Left Side	-17	-17
	Right Side	-22	-22
Mean Voltage for each actuator +/-	[V]	134	134

Table 5 – Tone Reduction and Control Output Voltage for the SIMO Inside Cabin control.

CONCLUSIONS

The control of longitudinal vibrations of the gearbox struts of an actual helicopter, under real operative conditions, has been implemented.

Satisfactory reduction of external and internal cabin vibrations with respect to tonal disturbances has been reached. The control outputs were always below the saturation limit. The relevance of peaks reduction confirms the validity of the vibration control technique and digital implementation. Vibration levels reached during the experimental tests were comparable with in flight helicopter vibration levels and consequently control results justify further research activities.

The benefits of the longitudinal struts vibrations control are also appreciable in the measure of the sound pressure level inside the cabin. A preliminary tone reduction has been observed near the inside cabin error positions.

Future steps involve the study of multi tonal control and also a better error accelerometer positioning inside cabin, in order to increase the SPL tonal reduction.

REFERENCES

[1] Brennam, Helliott, Heron " Noise Propagation through helicopter gearbox support struts" Journal of Sound and Vibration (1998), **120**, 696-704.

[2] Dozio L., Forghieri A., Ghiringhelli G.L., "Experimental Results of Active Longitudinal Vibration Control on a Helicopter Gearbox Strut". ICSV 13, Vienna 2006.

[3] Kuo S.M., Morgan D.R., *Active Noise Control System*, John Wiley and Sons, N. Y., 1996.

[4] Eriksson L.J., Allie M.C., Greiner R.A., "The Selection and Application of an IIR adaptive filter for Use in Active Sound Attenuation", IEEE Acoust., Speech, Signal Processing, vol. **35**, 1987.

[5] P. Mantegazza, E. Bianchi, L. Dozio, S. Papacharalambous, S. Hughes, D. Beal, "RTAI: Real-Time Application Interface", Linux Journal, pp. 142-148, April 2000.