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EXPERIMENTAL RESULTS OF ACTIVE LONGITUDINAL VIBRATION CONTROL ON A HELICOPTER GEARBOX STRUT

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Abstract
The paper deals with the experimental evaluation of the feasibility and effectiveness of active control of longitudinal vibration on a helicopter gearbox support strut. The aim is to test practical solutions for helicopter interior noise reduction using active control techniques. Very annoying components of cabin noise are associated with gearbox meshing tones. A preliminary transmissibility analysis of the vibration path between the gearbox and the helicopter fuselage showed the predominant contribution of the longitudinal vibration. Thus the experiments were arranged and performed on a strut under longitudinal disturbance conditions. The strut was connected with two end masses to roughly reproduce terminal impedances and equipped with a pair of surface-bonded piezoelectric patches. The control algorithm was the feed-forward FXLMS. The primary excitation was generated on one end-mass by an electro-mechanical shaker aligned with the beam longitudinal axis. The analysis of the high voltage requirements of the control devices led to the implementation of a frequency-shaped FXLMS algorithm, by including a set of digital band-pass filters designed to concentrate the control action on a priori selected disturbing tones. A careful study has been conducted on the type of pass-band filters to ensure low delay response, high cutting properties, no ripple phenomenon and limited computational burden. Experimental results revealed the effectiveness of the proposed approach. Complete rejection of large amplitude narrow band disturbances was achieved with limited control effort.

INTRODUCTION

One of the most important application field of active noise and vibration control (ANVC) systems is noise reduction inside vehicles: cars **[1]**, aircrafts **[2]** and helicopters **[3]**. Inside a helicopter cabin, a typical source of structure-borne noise comes from the main rotor gearbox, which is usually connected to the fuselage by a set of rigid struts. Because the main function of the gearbox support struts is to maintain a rigid link between the drive unit and the fuselage, they offer little isolation and consequently constitute the main structural vibration transmitting path 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 (500-3000Hz).

Previous studies conducted on flexural and longitudinal vibrations transmitted by helicopter gearbox struts **[4]** revealed that it is possible to significantly reduce the total kinetic energy of the receiving structure by controlling only longitudinal vibrations. It seems clear from previous explanations that the control of struts vibration could offer one solution for structure-borne cabin noise. In this direction many authors **[5] [6]** have proposed different solutions in terms of control techniques, actuation devices and target requirements.

The aim of this work is to contribute to the investigation of the potentiality of such beam control. Before testing the control on a helicopter mock-up, a gearbox support strut has been set up in the laboratory under longitudinal disturbance conditions to evaluate the feasibility and effectiveness of an active feed-forward FX-LMS control algorithm **[7]** to suppress longitudinal beam vibrations. The reference signal was at first derived by the disturbance signal (nominal condition), and consequently acquired directly by an accelerometer close to the excitation point. The error signal was derived by an accelerometer on the opposite end of the beam. Both signals were filtered in order to concentrate the control action, supplied by two piezoelectric actuators, only on tonal disturbances. A hard real time control on single and multiple tones disturbances were implemented using RTAI-Lab **[8]**.

TEST FACILITY AND ACQUISITION SYSTEM DESCRIPTION

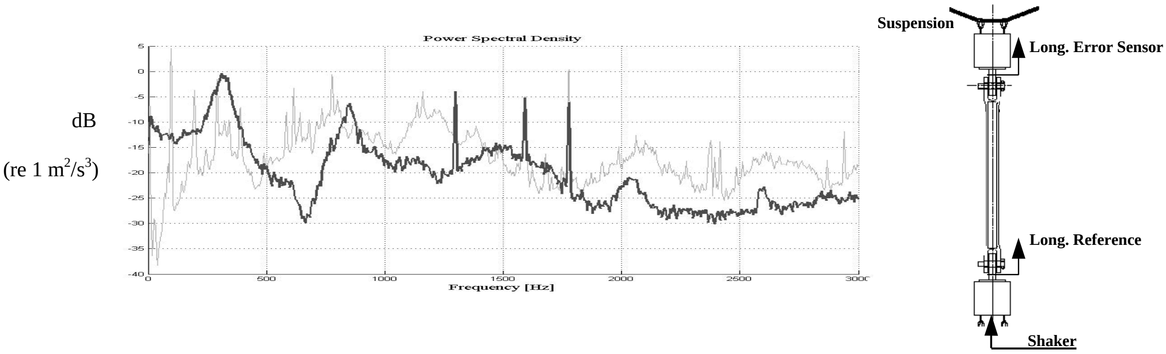
The test structure was a H section aluminium alloy beam, approximately 500 mm long, 35 mm spars and 28 mm web. It was suspended by an elastic system made of steel wire and four springs to reproduce a free-free suspension. The strut was connected to two 5.2 Kg end-masses to roughly simulate the structural impedance of the gearbox housing and the receiving structure. The connection between the beam and the end-masses was made by spherical joints. The test facility configuration was completed by an electro-mechanical shaker aligned with the beam longitudinal axis and connected to the lower end-mass.

The laboratory facility was validated by performing a transmissibility analysis on the test rig facility and on the helicopter mock-up actually mounting the test strut. The helicopter mock-up consist of a gearbox housing connected to a fuselage skeleton. The gearbox is powered by two electrical motors. Two aerodynamic brakes give a correct meshing load to simulate the effect of the main rotor.

Analysis of the longitudinal vibration transmission path on the helicopter allowed to select a typical reference level of accelerations to be reproduced in the test facility. Moreover, measurements on the helicopter struts attachment devices showed the presence of some important tonal components generated by the gearbox vibration.

Since human ear naturally attenuates noise up to 1 KHz, it was decided to focus the attention on the tonal disturbances falling within the frequency range 1-3 KHz. In particular it was possible to recognize three tones at 1290 Hz, 1590 Hz and

1780 Hz whose contribution was really high even with respect to the sound pressure level measurements inside cabin. Comparison of vibration level between strut facility and helicopter mock-up (flight operative condition, 6000 RPM) is shown in *Figure 1*.



F*igure 1- Longitudinal accelerations:Helicopter mockup (Faint line), test facility (Solid line).*

As shown in *Figure 1*, the test strut was equipped with two accelerometers, one on the lower end-mass to provide an estimate of the incoming disturbance and one on the upper end-mass to provide the control error signal. All accelerometers used were PCB Piezotronics model 333B32 with a frequency range between 0.5 Hz and 3 KHz, supplied by a PCB signal conditioner model 481. In order to prevent aliasing, all measured signals were filtered using a Kemo Inc. VBF 29 filter, with 8^{th} order Bessel low-pass filters. The cut off frequency was set to 3 KHz.

A couple of piezoelectric actuators (Ferroperm Pz21 50-30-0.5 mm) was bonded approximately at ¼ of the strut length from the bottom and driven in phase to generate a longitudinal action. The output control voltage was supplied by a home-made four channel inverting amplifier, based on PA85 Apex components, with a maximum gain of 26 dB (maximum voltage at piezo 150 V), operating over a frequency range up to 20 KHz.

The digital controller was implemented on a general-purpose 2 GHz AMD Athlon XP 2400 processor running RTAI-Linux, an open-source real-time extension of Linux operating system. The acquisition and control software were designed and tested using an advanced RTAI tool, called RTAI-Lab **[8]**, connected to the Simulink/Real-Time-Workshop environment of the MATLAB software. The sample frequency was set to 8 KHz.

S.I.S.O. FILTERED SINGLE TONAL CONTROL

Preliminary control tests showed that a single couple of piezoelectric patches was unable to control the tonal components of longitudinal vibrations of interest. This is shown in *Figure 2*. Only one tone was completely rejected by the active FXLMS controller. The other tonal components remained almost at the same level of the open-loop case. This was due to the saturation of the piezoelectric actuator.

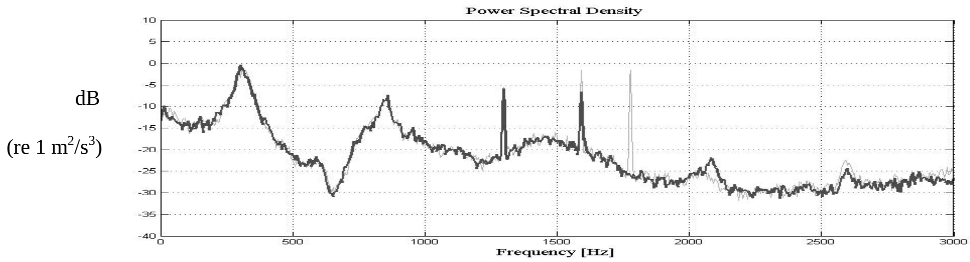


Figure 2 – Controlled (Solid Line) and Uncontrolled (Faint Line) Longitudinal Vibration.

In fact, the controller was trying to reduce vibration over all the frequency range of interest by using the broadband information of the reference signal. As said above, the most annoying part of the disturbance in helicopters cabin is related to tonal components at relatively high frequencies. Thus it was decided to focus the attention only on the rejection of tonal disturbances. In practise, we wanted the controller to concentrate energy only around the tonal disturbances rising far above the broad band plateau. To do so the error signal was filtered with suitable band-pass filters around the frequencies of interest. As presented below and in the following sections, a detailed analysis of the filter features was performed.

The filter designed to select the frequency of interest was a symmetric linear-phase FIR filter **[9]** with an equiripple weighted approximation error**.** The main reason of this selection was that such filters are optimal in the sense that, for a given set of specifications (frequency pass-stop band values and peak permissible errors in the pass band), they have the lowest order. Thus a direct-form implementation of the digital filter requires the smallest number of operations. Pass band filters were centred at the frequency of the selected tonal disturbance, with 10 Hz frequency pass band amplitude, in order to accommodate disturbances frequency shift, and 20 Hz for the frequency stop band.

Preliminary results are here discussed with respect to the control of a single tonal vibration component with a direct measure (nominal condition) of the incoming disturbance. The general case of multiple disturbances tones with reference sensor are addressed in the next sections.

The results of the filtered controller designed on a single tone at a time revealed the effectiveness and feasibility of the new control approach. A total tone rejection has been obtained (see *Figure 3* for the tone at 1290 Hz), jointly with a relatively fast convergence rate.

In each case, the analysis of the power spectral density of the control voltage clearly showed the presence of the tone at the design frequency. Moreover, control outputs never exceeded the saturation limit.

dB

(re 1 m^2/s^3)

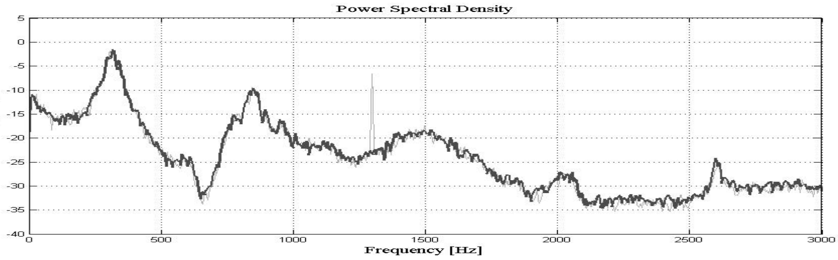


Figure 3 – Controlled (Solid Line) and Uncontrolled (Faint Line) Longitudinal Vibration.

Tests revealed that the control voltage values were deeply affected by the amplitude of peaks and by the value of the plateau level. This was confirmed by the low value of voltage (16 V) required to control the tone at 1780 Hz (plateau at -30 dB) respect to 62 V for the tone at 1290 Hz and 52 V for the tone at 1590 Hz.

S.I.S.O. FILTERED MULTI TONAL CONTROL

The single tone rejection results stimulated the adoption of the same approach to a more general situation, involving multiple tonal disturbances having large amplitude levels. High disturbance levels involve higher voltage control values. Thus, further analysis of the filters used to appropriately select the frequency zones of interest was carried out. In fact, the filters previously designed and used were not fully satisfactory due to the presence of significant ripple in the band pass frequency range. It has been noted that an amplification at the frequency of the tone causes an increment of the power required for the control. To solve this problem, a non symmetric filter has been designed and implemented using different amplitude values for the two band stop frequency ranges. Respect to the symmetric filters, these filters present a 0 dB amplification at the frequency under control.

The results of the multitonal control (*Figure 4*) showed that it is possible to completely reject multiple high frequency tonal disturbances with reasonably low control power.

dB

(re 1 m^2/s^3)

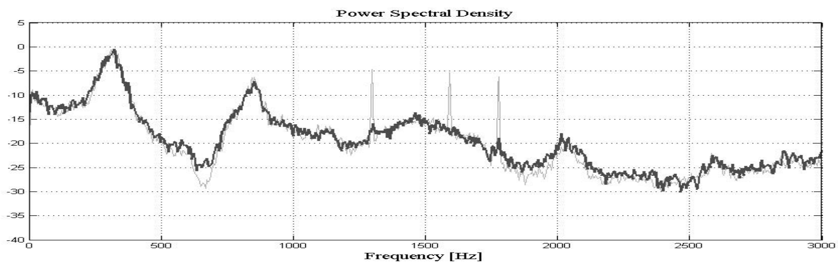


Figure 4 – Controlled (Solid Line) and Uncontrolled (Faint Line) Longitudinal Vibrations.

A comparison with results plotted in *Figure 2* validates the new approch for the multitonal longitudinal vibration control problem.

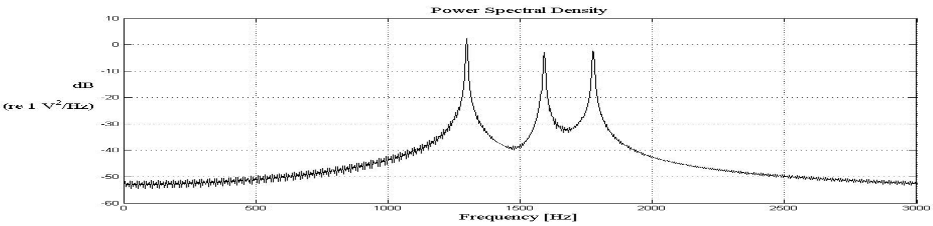


Figure 5 – Frequency shape of the Pre-Amplified Output Control Voltage.

The frequency response of the control voltage is shown in *Figure 5*. As expected, the frequency spectrum is mainly characterised by the presence of three tonal components at the selected disturbance frequencies. The stability and performances of the controller are show in *Table 1*.

Elapsed Time	[s]	180	240	300
Tone Reduction (dB) at **1290**	[Hz]	-10	-11	-11
Tone Reduction (dB) at **1590**	[Hz]	-11	-11	-12
Tone Reduction (dB) at **1780**	[Hz]	-12	-12	-13
Maximum Control Voltage +/-	[V]	86	90	92

Table 1 – Tone Reduction and Control Voltage requirements.

It can be noted that the active control system achieves good tone reduction with acceptable output voltages, only three minutes after the start. After five minutes the maximum value of 92 V was reached without compromising the actuation capability of the piezoelectric patch.

MULTI TONAL CONTROL WITH REFERENCE ERROR SENSOR

The last step of the present activity was related to the adoption of a sensor to measure the incoming disurbance and use it as reference signal for the FX-LMS algorithm. As discussed above, an accelerometer sensor was placed on the lower end-mass where the electromechanical shaker excites the strut. The single-axis accelerometer was directed to measure the longitudinal vibration. This configuration could offer a practical solution for on board helicopter control implementation.

In order to implement a filtered multi tonal control, it became necessary to filter also the reference acquired signals. The high-order filters previously adopted led to problems related to the real time implementation of the control algorithm. Moreover, a small shift of the frequency under control could cause a significantly increment of the power requirements because of the presence of ripples within the pass bandwidth (see *Figure 6-b*).

A study has been conducted in order to design low-order filters having flat responses in the pass band frequency range. FIR filters were replaced with IIR digital filters and a comparative study was conducted on the most frequently used filters (Bessel, Butterworth, Chebyshev type 1, Inverse Chebyshev and Elliptic). The design trade off was between achieving magnitude response specifications with the lowest filter order *n* and the increased group-delay nonlinearity for the sharper roll off filters types. As a results of the analysis, an inverse Chebyshev **[9]** 6^{th} order pass band filter was selected. As shown in *Figure 6-a*, it responds to the required specifications while other filters of same order presents limitations related to the cutting properties.

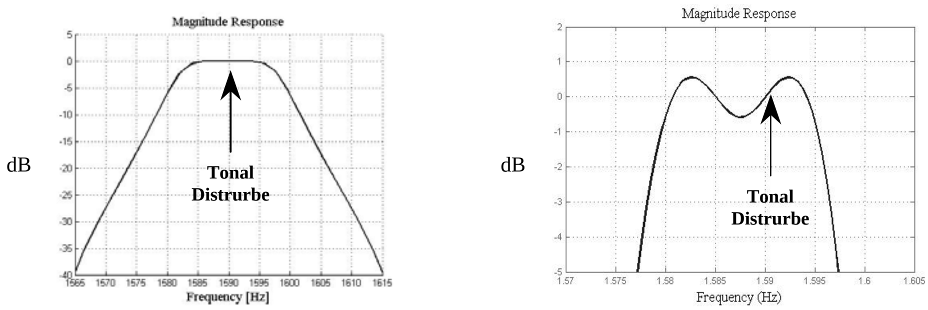


Figure 6 – a) Inverse Chebyshev Filter *b) Non Symmetric FIR Filter.*

The result of the control with a reference error sensor is reported in *Figure 7*.

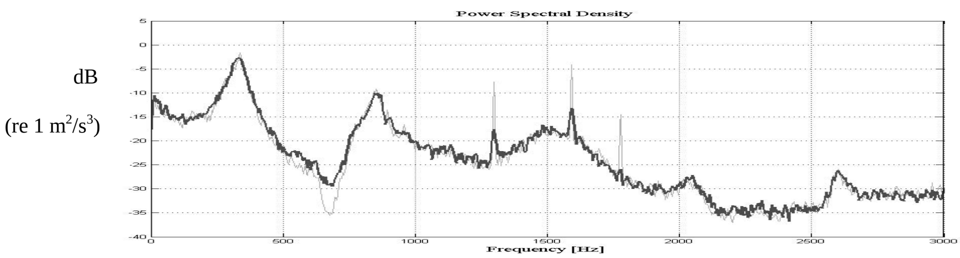


Figure 7 – Controlled (Solid Line) and Uncontrolled (Faint Line) Longitudinal Vibration.

As it can be observed the control system reduces all tonal components of interest. Again the control output voltage never exceed the saturation limit (see *Table 2*).

Elapsed Time [s]	180	300
Tone Reduction (dB) at **1290** [Hz]	-7	-10
Tone Reduction (dB) at **1590** [Hz]	-6	-9
Tone Reduction (dB) at **1780** [Hz]	-7	-12
Maximum Control Voltage +/- [V]	44	66

Table 2 – Tone Reduction and Control Voltage requirements.

CONCLUSIONS

The results obtained from the tests conducted on the helicopter strut facility showed that it is possible to obtain considerable longitudinal vibration reduction in the nominal configuration, i.e. with a reference directly derived from the disturbance signal, and in a more practical one, i.e. with the reference measured by an accelerometer sensor. The total tone rejection for longitudinal vibration was impossible using a broad band reference signal (higher control output requirement). In order to overcome the problem, filters for the error and reference sensors were adopted. Moreover, a fast convergence velocity, which is a fundamental requirement in real time signal processing, has been reached.

Results of applied control reveal that it is possible, using only one couple of piezoelectric actuators, to reduce large amplitude, high frequency tonal disturbances up to 3 KHz (three in the proposed studies). The relevance of peak reduction, from 10 dB to 12 dB, confirms the validity of the control approach and set up implementation, and suggests the possibility to obtain the same results directly on the helicopter mock up under operative conditions.

Future steps involves the application of the designed controller directly on the helicopter mock-up in order to investigate the real vibration reduction and the effect of such control on the reduction of interior cabin noise.

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