REDUCTION OF VIBRATIONS TRANSMITTED TO HELICOPTER AIRFRAMES USING ACTIVE GEARBOX STRUTS

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Abstract

This paper concerns the preliminary evaluation of the feasibility and effectiveness of an active feedforward control system to reduce the transmission of the gear-meshing vibrations to the helicopter airframe. The present activity is part of a research program aimed at investigating active control solutions for noise suppression inside a generic middle-size helicopter cabin.

Typically, the most intrusive and annoying components of the interior noise spectrum of modern helicopters turn out to be large amplitude high frequency tones associated with the gearbox and propulsion system. The gearbox is generally connected to the airframe via a set of rigid struts, which represent the main path along which the vibration is transmitted to the fuselage and efficiently coupled with the acoustics of the cabin. The effort of this study has been focused on the active reduction of vibrational energy through such structural transmission path.

The active solution involves the use of surface piezoelectric patches directly glued onto conventional struts without any redesign of the support structure. The control system is the feedforward multi-input-multi-output FXLMS algorithm and a reference signal (well correlated with the gearbox disturbance vibrations) is supposed to be available. The controller has been first verified on an isolated active strut connected with two end-masses and elastically suspended to a rigid support frame. Then, it has been evaluated on a simplified helicopter mockup composed of a middle-size cabin skeleton onto which a gearbox is supported by means of two front and two rear struts.

Introduction

The analysis of the interior noise of several kinds of common transportation vehicles (Ref 1) reveals that helicopters are the noisiest with levels that, for certain flight conditions, may overcome 110 dB(A). The recent wide adoption of such kinds of vehicles in civil applications have pressed a lot of effort in the analysis of the main sources of noise and transmission paths inside the cabin and in the investigation and design of effective suppression solutions. This effort is documented by the activation of many research programs aimed at studying and developing feasible and embeddable active noise and vibration control (ANVC) systems. The goal is to achieve higher levels of passenger and crew comfort with small weight and space penalties, thus providing cost effective system benefits.

Roughly speaking, the noise sources of a helicopter can be divided into two main groups: those arising aerodynamically (airborne noise) and those arising mechanically (structure-borne noise) (Ref 2). The first group includes the turbulent boundary-layer-induced noise, the main and tail rotor noise, the jet engines noise and the direct gearbox-induced noise. The vibration of the airframe that radiates noise into the cabin originates the structure-borne noise. Intense structural excitations are generated by the vibrations of the gearbox and propulsion system, and are transmitted to the helicopter fuselage via mount elements that have to be statically as stiff as possible to support the gearbox/engine at the most severe flight conditions. The stiffness requirements are in contrast with the goal of isolating the two connected parts in order to reduce the gearbox/engine vibrations transmitted by the mount element.

The noise sources listed above collaborate to generate an interior noise spectrum having three main features (Ref 3): 1) large amplitude – low frequency rotor harmonics; 2) random broadband noise; 3) large amplitude – high frequency structure-borne distinctive tones. The low frequency tones in the range from 20 to 200 Hz arise from the main and tail rotor harmonics and are not really annoying to the passengers and crew members because of the natural attenuation of the human ear at low frequency. On the contrary, high frequency tones (typically > 600 Hz) fall into a region where the human ear is highly sensitive. They interfere with the speech and generally rise far above the broadband noise plateau with peaks over 20 dB. Therefore they are generally considered the most irritating component

of noise in a typical middle-size helicopter cabin. Discarding the usage of headsets, which are disliked by most of passengers, the overall reduction of interior noise levels can be obtained by adopting two distinct approaches: the passive and active approach. Each one has advantages and drawbacks, so that a wise integrated solution of active control systems with passive treatments would lead to the best performances.
The most common passive means are soundproofing of the helicopter cabin and resonance absorbers. The cabin soundproofing can be obtained by increasing the damping of the fuselage panels and/or improving the sound transmission loss by double panel partitioning with fibreglass blankets and absorbing materials. The resonance absorbers minimize the local vibrations in the attachment points between the mount elements and the fuselage skin. The first solution involves a significant weight increase, while the passive absorbers can be tuned around a fixed frequency and are unable to cope with the variable rotor speed.
The active approach can be divided into two main categories: acoustic control systems, aimed at reducing the cabin noise directly, and vibration control systems, arranged to reduce either the vibration transmission from the airframe to the fuselage or the noise transmission and radiation by the fuselage walls. The first approach (Ref 4) uses acoustic sensors (microphones) and acoustic sources (loudspeakers) inside the enclosure. The loudspeakers are driven to create a control acoustic field that destructively interferes with the acoustic field in the cabin. Active noise control (ANC) techniques could be very effective because they operate directly on the undesired sound field providing local zone control, but they are almost always bulky, invasive and costly solutions. Active vibration control (AVC) systems (Ref 5) employs structural actuators that operate onto selected structural parts in such a way to suppress the vibration of the fuselage skin so that the interior noise is attenuated. They can be generally classified as “source” and “transmitting path” vibration controllers (Ref 2). The first category includes active structural acoustic control (ASAC) systems that act directly on the sound-radiating cabin panels. The second category includes systems operating on the control of gearbox-to-airframe and/or engine-to-airframe transmission of structural vibration. The context is formally an active vibration isolation problem. As said above, a dominant source of structure-borne interior noise is the meshing of gears in the main rotor gearbox. This study is focused on the design and evaluation of an effective AVC system that is able to reduce this structure-borne noise. The AVC system is realized by operating on the gearbox support beams, which are equipped with piezoelectric actuators. The selected configuration follows the so-called “smart strut concept” (Ref 6), which is described in the next section.

Active gearbox struts

Typically the gearbox is connected to the airframe via a set of rigid struts (Figure 1), which represent the main path along which the vibration is transmitted to the airframe and is efficiently coupled with the noise radiation into the cabin. Since the struts are highly stressed structural elements having to carry the in-flight quasi-static load of the helicopter, the introduction of elastomeric isolators in correspondence of the junctions would certainly affect the dynamic stability of the main rotor since they would be placed along the primary load path of the helicopter. An attractive solution which maintains the required static stiffness and provides the expected compliant properties can be obtained by using an active strut constituted by the passive structural mount element supplied with actuators that fight against the vibration transmission. These actuators can be realized in many different ways. Two configurations that have been previously designed with this objective in mind are the inertial actuator concept (Ref 7) and the smart strut concept (Ref 8).

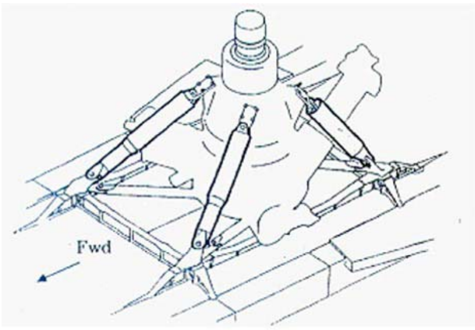

Figure 1. Schematic view of the gearbox support structure.

The inertial actuator uses an inertial mass forced to oscillate by a piezoelectric stack or by a magnetostrictive element. In order to excite both longitudinal and flexural vibrations, three independent controllable actuators are necessary. They are mounted on a collar connected to the strut and introduce forces into the strut to cancel the vibrations coming from the gearbox. The great disadvantage of such a solution is the relatively large space required for the mounting of the active elements and the weight penalty.
The so-called smart strut concept offers more

technical feasibility than the inertial configuration along with very small weight increment. The smart strut is provided with low invasive and lightweight piezoelectric patches directly bonded on the surface of the passive original strut. The transmission of the rotor gearbox vibration is controlled by applying a control voltage to the piezoelectric element that is strained and contracted in its longitudinal direction so that shear forces are originated on the guest structure (Ref 9). The piezo actuators are driven by a control system devoted to reduce the flow of vibrational energy (structural waves) from the tip of the strut attached to the gearbox to the tip of the strut connected to the helicopter airframe.

In the present application, the smart strut concept has been realized by applying two pairs of piezoelectric patch actuators to the mockup rear struts. The first pair is in correspondence of the middle of the struts, the other at one quarter of the total length. In this way the structural integrity of the structural component is saved. Each actuator has dimensions of $40\times60\times1$ mm and it is made of lead zirconate titanate (PZT) piezoelectric material PIC 151 commercially marketed by Physike Instruments GmbH. The pair in correspondence of the centre of the strut has been driven in such a way to deform the structure in bending, i.e. an electric field was applied to the two surfaces of one piezoelectric in the direction that cause expansion and reversed on the opposite-side patch in order to cause contraction. The other pair has been driven so that the guest structure is deformed in extension, i.e. an electric field was applied across both piezoelectric in the direction that causes expansion. The choice of using four coupled piezo patches allows achieving high control authority for both longitudinal and lateral vibrations.

The physical configuration and the kind of excitation of interest entering the support beam are highly suitable to the application of a feedforward control scheme (Ref 5). In fact in our case the primary disturbance arises from rotating machinery, such that it is harmonic with distinctive tones corresponding to the meshing of the gears. Moreover the propagation path is down a waveguide where the disturbance at any given point is a function of the disturbance at an “upstream” point some time previously. Therefore the disturbance entering the structure can be used as a reference for the control signal generation. Feedforward controllers rely on the availability of a causal reference signal unaffected by any control input and well correlated with the impending primary disturbance. Such a reference can easily come from a tachometer and remains unaltered despite of the action of the control actuators. Conventional feedforward control systems operate in an open loop fashion with a frequency or impulse response having fixed characteristics. Nevertheless they may not give satisfactory performances when the input signal and/or the system response vary with time, such as the case of different flight conditions. Therefore many of the electronic systems used in feedforward control systems adjust or tune the coefficients of the controller in order to make it adaptive. The most popular adaptive control technique used in ANVC systems is the normalized filtered-X least-mean-square (FXLMS) algorithm (Ref 10). It has been considered suitable for this application because it is appropriate for systems characterized by both broadband and narrowband disturbances, its architecture allows fast implementation on standard DSP chips or standard PC with single-instruction-multiple-data (SIMD) instructions, it is robust in the presence of uncertainties in the physical modelling and variable amplitude primary disturbances, and it is relatively simple to set up and tune in a real-world environment.

The controller implementation

There are many versions of the FXLMS algorithm. The form implemented in this work is based on finite impulse response (FIR) digital filters and uses the normalized least mean square (LMS) algorithm to adjust the weights of the filters. This section explains the main steps of the formulation directly related to the adopted configuration, which encompasses two control sources (piezoelectric patches) and two error signals (accelerations). The accelerometers are responsible to measure the residual vibration transmitted by the strut to the airframe. For further details of the derivation of the FXLMS algorithm the reader is referred to the literature on this topic (Ref 10).

The multi-channel implementation includes a common reference signal, two FIR filters realizing the controller and four FIR filters estimating the secondary paths from each actuator to each error sensor. This path represents a dynamical system with a transfer function containing the physical structural path from the actuator to the error sensor and all the electrical and electronic components of the digital feedforward controller, such as the actuator and sensors, the analogue-to-digital and digital-to-analogue converters, the power amplifiers, and the antialiasing and reconstruction filters. It is necessary to compensate for the secondary path transfer function in order to include its inherent time lags and group delays in the feedforward control design. Assuming this path is linear and time-invariant, it can be modelled by a FIR filter $\mathbf{S}(z)$ and identified off-line by applying a broadband training signal (white noise) to the actuators. The filter weights are tuned by minimizing a cost function that includes the instantaneous squared error between the response at the sensor location and the generated white noise. The off-line estimation scheme is represented in Figure 2 where it is shown the active gearbox strut in the laboratory test configuration with one end-mass.

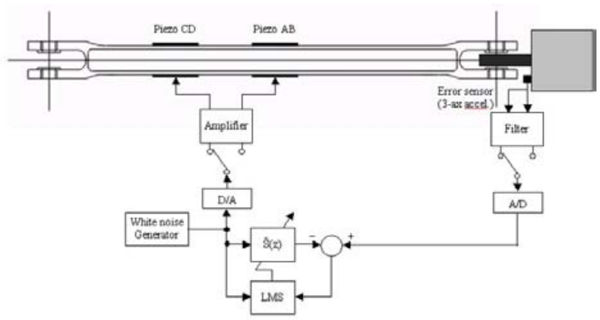

Figure 2. Schematic representation of the secondary path off-line identification procedure.

The multi-channel control algorithm architecture is depicted in Figure 3 where the excitation system providing the reference signal is also shown. The controller **W**(z) is a 2×1 matrix containing, in each row, the FIR filtering of the common reference signal to lead to the corresponding control output. The LMS blocks contain the FIR filter weights updating expressions that operate on the filtered reference signal generated by passing the original reference signal through the estimation matrix of the secondary paths.

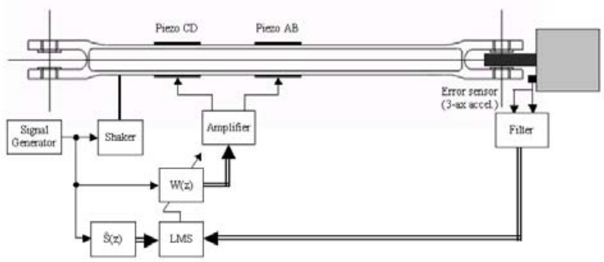

Figure 3. Schematic representation of the multi-channel FXLMS control algorithm.

The stability, convergence speed and performances of the FXLMS technique are governed by the order of the controller and secondary path filters, **W**(z) and **S**(z), the LMS convergence coefficient, and the reference signal power. For narrowband input signals, the number of filter weights should be selected to obtain sufficient resolution in time to model the required response. To optimise the speed of convergence as well as maintaining the desired steady-state performance in an independent way from the reference signal power, the LMS convergence coefficient has been normalized with respect to the controller FIR filter order and the power of the filtered reference signal. This expedient has the goal of achieving the same closed-loop performances at the different flight conditions.

Preliminary analysis on a test assembly

A preliminary activity has been carried out on one isolated gearbox strut in order to assess the feasibility of the smart strut concept with the available configuration.

Numerical testing

First, the performances of the selected FXLMS control algorithm has been predicted on a numerical model of the support beam. The model has been obtained with a finite element technique. Solid elements (CHEXA) have been used. The tip flanges were modelled considering also the two buckles linked with rigid elements to a mass element of 5 kg whose aim is described later. The model includes also the four spring elements that were used to elastically suspend the whole structure to a rigid portal fixed to the ground. The presence of the piezoelectric patches bonded onto the surface of the strut has been modelled with plate elements having the density, compliant properties and thickness of the piezoelectric patch. Therefore both the stiffness and mass modifications due to the piezoelectric materials have been taken into account. The piezoelectric actuation is derived using the pin-force model (Ref 9), which gives the same results of more advanced modelizations for the beam thickness/piezo patch thickness ratio of the strut under testing. In the finite element representation the control force is then distributed over the nodes in correspondence of the side of the piezoelectric element perpendicular to the axis of the beam.

The numerical simulations of the closed-loop performances have been profitably carried out in the state space domain on a reduced modal model of the smart strut up to 5 kHz. The primary disturbance is supposed to be introduced at one end of the strut like a point force, thus reproducing the acceleration condition of the gearbox-side attachment point. The disturbance has been selected in order to reproduce two generic annoying gear-meshing components of the interior noise spectrum, one close to 815 Hz and one around 1825 Hz. A uniform white noise of relatively high variance has been added to the single harmonics in such a way to mimic the random broadband plateau.

The numerical activity has been highly helpful in familiarizing with the range of values of the FXLMS algorithm parameters and suggesting important guidelines on their real-world tuning. The simulation results demonstrated the theoretical effectiveness of the controller, which operates only on the tones that constitute the reference signal. An evaluation of the control power required to obtain such performances revealed it was fully inside the available voltage range.

Test facility

The second step of this preliminary analysis was to assemble a laboratory test facility (Fig 4). In the experimental configuration, the active gearbox strut has been connected with two 5 Kg end-masses, and then suspended by means of an elastic system of steel wires with spring attachments used as dynamics isolators. The end-masses simulate the receiving structure having some structural impedance. The dynamic behaviour of the realized constraints has not been considered a crucial issue in this preliminary investigation. In fact it has been assumed that the FXLMS algorithm should be robust against variable end conditions. In this preliminary phase no realistic static loading conditions were applied. The sensing system consists of one tri-axial PCB Piezotronics accelerometer located on the receiving structure. The primary disturbance was introduced into the system by means of a 4810 B&K model electro-mechanical shaker positioned at the top end of the strut in such a way to apply a force with an arbitrary inclination respect to the beam longitudinal axis.

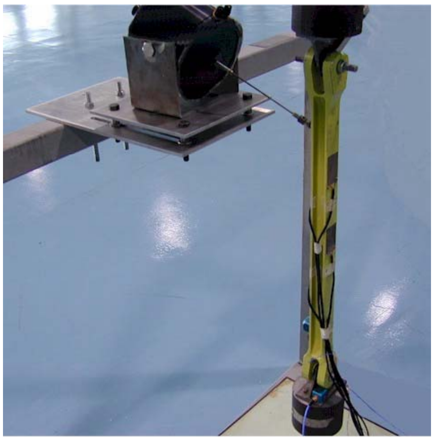

Figure 4. Laboratory test assembly of the active gearbox strut.

The experimental arrangement is completed by one power amplifier and a set of analogue filters. The choice of such components plays a crucial role in the successful implementation of digital controllers. The piezo actuators have to be driven by power amplifiers to obtain the desired levels of voltage and current for correct operation. A homemade four channel inverting amplifier has been built based on PA85 Apex components with a gain of 20 over a frequency range up to 20 kHz. The maximum output voltage is ± 160 V, and the maximum current is 150 mA. Since the control signals are sampled, they contain high-frequency components due to the analogue output board quantization and zero-order hold devices. A smoothing effect has been achieved with low-pass reconstruction filters. The input signals have to be in turn filtered to prevent aliasing. The analogue filters used are eight-order Bessel type and are marketed by Kemo Inc. The PCB accelerometers are plugged into a unity gain 478A16 PCB signal conditioners. The phase shift of the analogue low pass filters may have important consequences on the extent of the cancellation achievable, especially for active control of structures, where the wavespeed of disturbances is generally quite large.

Since it is generally difficult to change the response of a complicated analogue filter, most practical implementations of active feedforward control systems are digital. The multi-channel normalized FXLMS algorithm falls into this category. The current powerful digital technology makes it possible to implement complex and relatively high frequency active vibration controllers on low-cost general-purpose personal computers provided a suitable hard real time (HRT) operating system is used to achieve the correct timing (Ref 11). The multi-channel digital FXLMS controller has been implemented on a AMD-Athlon 2 GHz equipped with two standard multi-functional National Instruments I/O boards, one (PCI-6071E) for data acquisition and the other (PCI-6713) for digital-to-analogue control inputs. The hard real-time platform used throughout this work is a free open source Linux kernel patch called RTAI (Ref 11).

Experimental testing

The reference signal exciting the beam was determined by the superposition of the first and second harmonics of each selected tonal disturbance (815 and 1825 Hz) and has been directly provided to the controller. Clearly this arrangement cannot be used in a more realistic application, but it has been assumed that it will be possible to determine the reference signal from a tachometer signal that measure the rotor shaft speed. Besides the tones of interest, the primary disturbance contains a relatively large amount of unknown random broadband noise to attempt to reproduce the typical helicopter in-flight situation. The total amount of excitation was then introduced into the system by means of the shaker. One tri-axial accelerometer has been attached on the

upper side of the bottom endplate. The signals used as error in the FXLMS algorithm are the lateral acceleration orthogonal to the plane of the actuator side of the beam and the acceleration in the longitudinal direction of the beam. As described before, the active control tests have been carried out using two couples of surface bonded piezoelectric patches as two individual actuators.
The FXLMS control algorithm used in these tests has been implemented at a sampling frequency of 8 kHz with a convergence coefficient equal to 0.001. FIR filters of 350 and 100 weights have been used for the secondary paths and for the controller, respectively.

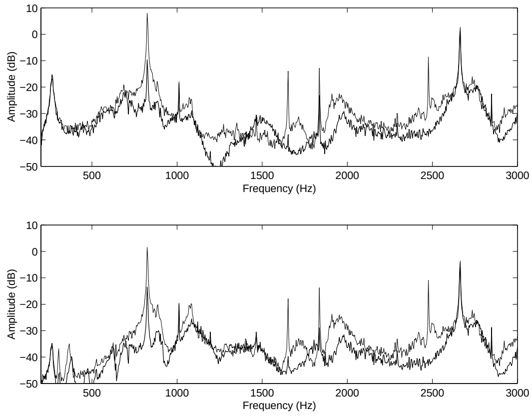

Figure 5. Accelerations on the receiving structure before (grey lines) and after (black lines) control.

Figure 5 shows the error acceleration signals. The grey lines represent the responses of the strut without control. The black lines depict the closed-loop behaviour. Lateral and longitudinal accelerations as collected by the tri-axial accelerometer are depicted in the upper and bottom subplot, respectively. As in the simulation testing, the pair of piezoelectric patches in the centre of the beam has been driven in bending, while the other pair has been driven in axial direction. The analysis of the autospectrum in correspondence of the error location shows that the accelerations in both the directions are well attenuated with a complete rejection of the first and higher harmonics of the tonal disturbances exciting the plant. The amplitude of these unwanted tones has been lowered down to the level of the random noise plateau as desired by the main control objective. Note that the feedforward controller works only against the vibration components that are correlated with the reference signal. Such a configuration seems to be suitable for the scope of vibration transmission control and has been selected as the right candidate for the application on the simplified helicopter mockup.

<u>Activity on the helicopter mockup</u>

The active strut system has been examined on a full-scale simplified helicopter mockup consisting of a gearbox housing connected to a middle-size fuselage skeleton via two conventional front and two active rear struts. The gearbox vibrations were generated by a shaker mounted on one lateral side of the gearbox housing and attached to an endplate suspended from a ground-fixed portal by means of steel wires. A multi-tonal signal composed by the basic harmonics at 815 and 1825 Hz has been used to drive the excitation system.

Figure 6. Detail view of the error sensor located on the strut connection support.

Figure 7. Detail view of the error sensor located inside the cabin just under the rear strut attachment point.

Each active strut has the same control configuration of the test rig beam, with two couples of piezoelectric patches, one driven in bending and one in axial direction. Since the effect of the control sources of a strut on the other one can be considered very small, two identical decoupled multi-channel filtered-X LMS controllers have been implemented. In this way each controller operates on the mated transmission path. Each active system is completed by two tri-axial accelerometers used as error sensors in order to adjust the weights of the adaptive FIR filters. They are located on the receiving structure, one in correspondence of the strut-to-airframe connection device (Figure 6) and the other just under the strut attachment point inside the helicopter cabin (Figure 7). In both cases the signal representing the acceleration normal to the support surface has been fed back to the LMS algorithm, because the out-of-plane vibration is well coupled with the near-field radiation of the surface.
The monitoring system is represented by four

microphones to evaluate the reduction obtained by the active control solution in terms of sound pressure. They have been positioned in selected locations inside the cabin where the passengers are assumed to be seated. Two microphones have been placed in correspondence of the head of the passengers in the rear seats, which is supposed to be very close to the rear gearbox struts attachment points. The other two microphones have been placed in correspondence of the front passenger seats at a distance of 1.2 m from the rear panel of the cabin skeleton.
As for the test assembly, the harmonic counterpart of the excitation signal to the shaker has been used as reference for the feedforward controller. The first and second harmonics of the fundamental tones has been added to the reference signal provided to the control system in order to simulate the availability of a tachometer measurement.
The same values of the FXLMS control parameters adopted in the test rig have been used in the experimental activity on the mockup. The good closed-loop performances obtained with such a set of parameters demonstrates the usefulness of the preliminary test apparatus on the isolated beam and the satisfactory robustness of the control algorithm in presence of different configurations and boundary conditions. Both the multi-channel controllers have been run on the same PC as two separate real time processes.
Figures 8 and 9 show the error acceleration signals of the sensors mated to the left and right active strut, respectively. The upper subplot represents the acceleration just under the strut, while the bottom depicts the vibration inside the cabin. The grey lines represent the responses of the system without control. The black lines depict the closed-loop behaviour. The open loop vibration spectrum obtained with the selected excitation signal is quite simplified compared to that resulted by a typical in-flight condition. Nevertheless it clearly reproduces the main characteristics with a broadband low-level plateau and some high level distinctive harmonic tones. Note that the amplitudes of the vibrations on the right side are typically lower than in the left side due to the asymmetrical positioning of the excitation system. The analysis of the closed-loop autospectrum shows that the vibration results are quite satisfactory. Both the accelerations are well attenuated with a complete rejection of the harmonic disturbance. The amplitude of these unwanted tones has been lowered down to the level of the random noise plateau as desired by the main control objective. As in the test rig activity, the feedforward controller is effective only against the vibration components that are correlated with the reference signal, without affecting the open loop behaviour in the remaining bandwidth.

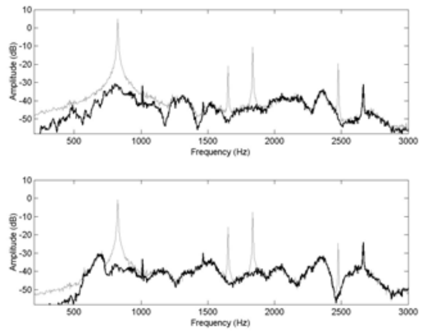

Figure 8. Left rear strut vibrations.

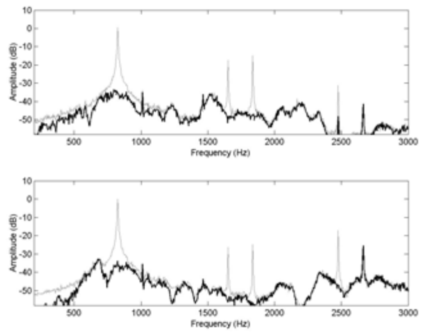

Figure 9. Right rear strut vibrations.

Figures 10 and 11 show the sound pressure levels with (black lines) and without control (grey lines) in correspondence of the rear seats right and left microphones, respectively. The plot amplitudes scale is not calibrated. Four peaks are of interest: the fundamental tones around 815 and 1825 Hz, and the first and second harmonics of the 815 Hz tone. The autospectra show that the controller is able to reduce the interior noise in correspondence of the selected peaks. The average reduction over the frequency range is about 5 dB. No undesired noise amplification outside the controlled narrow band has been observed. This preliminary activity assesses that the reduction of vibration at strut mounting points is rather correlated to the reduction of the near-field noise inside the cabin. The smart strut concept seems to be quite effective. The passengers at these locations would certainly experience better acoustic comfort. Nevertheless, the front seats monitoring microphones revealed that here the closed-loop performances has not been equally good. The noise reduction was at most of about 2 dB around some peaks. This would suggest that operating only on the rear struts is not enough. In the adopted configuration and context, the smart strut solution seems to have only a local effect, limited to the area very close to the strut attachment points.

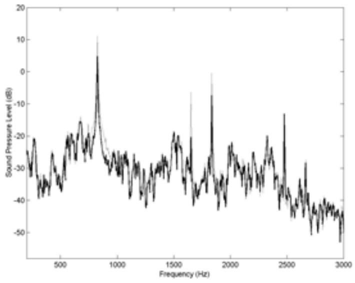

Figure 10. Sound pressure levels with and without control in correspondence of the rear seats right microphone.

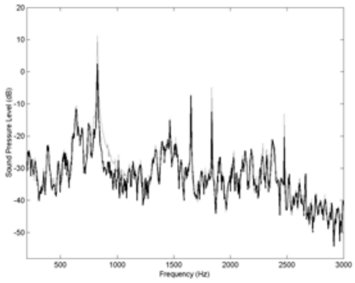

Figure 11. Sound pressure levels with and without control in correspondence of the rear seats left microphone.

Conclusion

The scope of this study has been to investigate the feasibility and effectiveness of an active control system aimed at reducing the transmission to the helicopter airframe of the harmonic gear-meshing vibrations. It has been implemented by equipping conventional gearbox struts with surface bonded piezoelectric patches, driven by a feedforward FXLMS multi-channel controller. The system has been tested on the rear struts of a gearbox mounted on a middle-size simplified helicopter mockup. The behaviour of the active solution has been described by presenting vibration and acoustic results. The vibration transmission performances showed that the accelerations at the strut-to-airframe mounting points have been well attenuated with a complete rejection of the harmonic disturbances. The amplitude of these unwanted tones has been lowered down to the level of the random noise plateau as desired by the main control objective. The suppression of cabin noise has been satisfactory only in localized area close to the active strut attachments, where the selected tones has been reduced by about 5 dB. The increase of effectiveness of the adopted solution involves future investigations, which comprise the fully independent control of each of the four piezoelectric actuator segments, the adoption of different configuration of error signals both in terms of accelerometers number/location and minimization strategies, and the integration with other active systems operating on different airframe structural components, e.g. the overhead cabin panel.

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