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### Paper #1

# REDUCTION OF INTERIOR NOISE IN HELICOPTERS BY USING ACTIVE GEARBOX STRUTS – RESULTS OF FLIGHT TESTS

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# REDUCTION OF INTERIOR NOISE IN HELICOPTERS BY USING ACTIVE GEARBOX STRUTS – RESULTS OF FLIGHT TESTS

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## 1 Abstract

The main noise source in helicopter cabins is the gearbox. Comprehensive measurements have shown that the structure-born noise path via the gearbox struts is dominant. Active control of the structure-born noise by applying control forces to the struts is a promising concept to improve the comfort for passengers and crew (Ref. /1/, /2/). Such an active high frequency vibration isolation system has been developed by Eurocopter Deutschland (ECD) and the EADS (former DaimlerChrysler) research and technology group in a step-by-step approach.

A brief review of the important steps in the layout and modelling phase of the active struts as well as of the important former tests is given. The results of the latest flight tests performed on a BK117 test helicopter are presented and the noise reduction potential of the active control system is demonstrated.

## 2 Introduction

The high tonal noise components at the gear-meshing frequencies (typically 500 Hz - 3 kHz) are often more than 10 dB above the broadband noise in the helicopter and therefore annoying to passengers and crew members. The gear-meshing noise is mainly caused by the vibrations of the gearbox induced into the cabin structure via the gearbox struts. This was proven by detailed measurements of the noise transmission paths conducted on BK117 helicopter (Ref. /3/)

As illustrated in Figure 1, the reduction of interior noise levels can be achieved by applying passive and active means. Passive means like soundproofing of the helicopter cabin or resonance absorber are not adequate to effectively minimise the discrete gear-meshing noise (Ref. /4/, /5/). Resonance absorbers for example can be tuned to reduce vibration and noise in narrowband frequency range only, but they are unable to cope with the variable rotor speed in modern helicopters. A general disadvantage of passive means is the significant increase of helicopter weight.

Active Noise Control (ANC) and Active Structural Acoustic Control (ASAC) of panels represent the two active approaches for interior noise reduction at low frequencies. A typical ANC system consists of loudspeakers used to minimise the sound pressure at given microphone locations in the helicopter cabin (Ref. /6/, /7/). ANC has been successfully applied to automobiles and propeller airplanes. ASAC systems use actuators which are directly attached to the sound-radiating interior panels. These actuators actively control the vibration of the structures in such a way that the sound field inside the cabin is minimised (Ref. /8/). Both systems can achieve significant reductions in the lower frequency range. Due to the fact that the number of actuators and sensors has to be substantially increased at higher frequencies, these systems are not adequate for active control in the range of the gear-meshing frequencies.

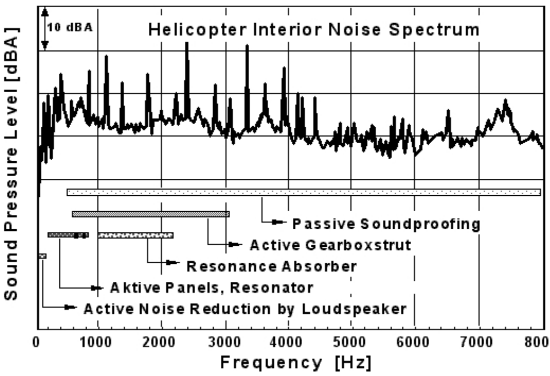

Figure 1 Helicopter interior noise spectrum and possible reduction measures

The most promising concept to improve the comfort in helicopter cabins is the active control of the high frequency gearbox noise by applying additional control forces to the struts. Such an active vibration isolation system has been developed by Eurocopter Deutschland and the EADS research and technology group in an evolutionary process. After a layout and modelling phase of the active strut concept, the system has been tested under laboratory conditions on a EC135 prototype helicopter. Based on this experience, the currently used active system has been developed, which consists of active piezo struts (active piezo layers which are bonded directly onto series gearbox struts), vibration sensors and an adapted control unit. This active vibration isolation system has been tested on a BK117 helicopter in ground runs as well as in flight.

This paper is focused on the results of recent flight tests with a BK117 helicopter, which was equipped with a complete set of active gearbox struts and various accelerometers and microphones inside the cabin used for monitoring. The noise reduction potential of the active gearbox strut system is documented for several flight conditions like hover and forward flight with different flight speeds.

## 3 The Active Strut Concept

There are two different concepts which have been considered for the realisation of the active gearbox struts.

The first more classical approach is based on inertial actuators (shakers) which are mounted on a collar which is connected to the strut. The control forces generated by the vibrating shaker are introduced via collar into the strut in order to cancel the primary forces from the rotor/gearbox unit (Ref. /1/, /2/, /9/, /10/). To induce forces in both, longitudinal (axial direction of the strut) and transversal direction at least two inertial actuators per strut have to be used. The inertial actuator concept implies a considerable weight penalty and may be difficult to integrate because of the restricted space around the struts.

A more attractive and promising concept which was developed by ECD and the EADS research group is the “smart strut”. This concept is based on actuators which consist of piezoelectric (e.g. PZT = lead zirconate titanate) layers bonded directly onto the strut (see Figure 2). By applying a control voltage to the outer and inner surface of the layer the piezo can be strained or contracted in longitudinal direction. (This phenomenon is known as the inverse lateral piezo effect or “d31-effect“). The strain of the piezo causes a pair of shear forces acting on the struts at the end of the actuator layer.

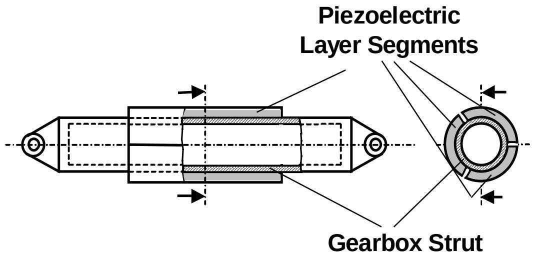

Figure 2 Active gearbox strut with piezoceramic actuators

In addition, the piezoelectric shell is divided in three segments along the circumference (Figure 2) which allow to control the longitudinal as well as lateral vibrations of the strut.

The smart strut concept offers several advantages:

- simplicity of design
- technical feasibility: piezoceramic shells are add-ons to the original production struts
- small weight penalty
- low actuator costs
- easy maintenance
- fail safe design

## 4 Layout of the Active Strut

The layout of the smart strut requires the estimation of forces and displacements necessary to isolate the gearbox vibration. The concept model of the gearbox/strut unit presented in Figure 3 was developed for this purpose. From the beginning, the smart strut was conceived as a “force isolator”. This principle can be explained as follows: the forces from the gearbox unit are compensated by the inertial forces of the effective gearbox mass. This can be achieved by active displacements at the gearbox side equal to the displacement of the gearbox mass created by the primary force from the rotor/gearbox unit. Thus, no forces are transmitted to the fuselage structure.

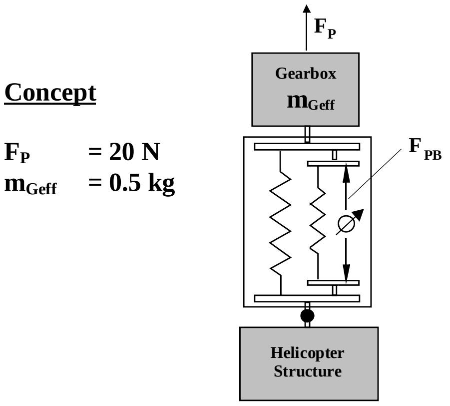

Figure 3 Concept model of the smart strut

The layout of the smart strut was focused on the dominant gear-meshing frequency of the BK117 aircraft at approximately 1900 Hz. Vibration and impedance measurements conducted on this helicopter type led to the following data:

| | |
|---|---|
| Primary force ($F_P$) | 20 N |
| Effective gearbox mass ($m_{Geff}$) | 0.5 kg |
| Piezo segment length | 100 mm |
| Resulting strut displacement (at the gearbox side) | $0.3 \cdot 10^{-3}$ mm |

Based on this data, the piezoceramic shells were designed as add-ons to the series struts of the BK117 helicopter. The optimisation of the actuator design considered also further aspects like low electric power consumption and moderate actuator voltages. The following design parameters of the smart strut can be derived:

| | |
|---|---|
| Max. control voltage | ± 450 V |
| Piezo layer thickness | 1.5 mm |
| Piezo segment length | 100 mm |
| Dynamic strut deformation<br>(at max. control voltage) | $2.0 \cdot 10^{-3}$ mm |

A smart strut realised for the tests with the BK117 helicopter is shown in Figure 4.

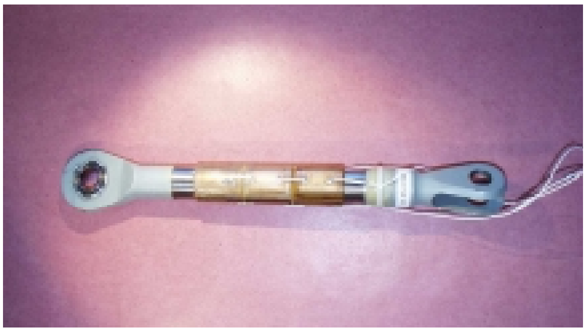

Figure 4 Concept model of the smart strut

## 5 Review of Tests with Active Struts

In this chapter a brief review of the measurements performed with the smart struts is given. The objective of these tests was to examine the aspects which are essential for the realisation of the active gearbox system. The following points were of main interest:

- to determine an optimal actuator/sensor configuration for noise reduction in the cabin,
- to examine the actuator performance and to evolve the actuator design,
- to develop a control concept suited for the application in helicopters.

### 5.1 Laboratory Tests

The active strut system was first examined on an EC135 prototype. The test assembly consisted of a gearbox housing which was connected to an EC135 fuselage via four vertical smart struts. The gearbox vibrations were simulated by a shaker mounted on the gearbox housing. A sinus sweep signal between 700 Hz - 2000 Hz was used for the excitation of the gearbox and fuselage.

The active system included four smart struts and four 3-axis accelerometers as error signal sensors attached at the fuselage mounting points of the struts. The control concept used for this tests is based on a multi-channel filtered-x LMS algorithm. This time-domain controller has been in use for various control tasks and was adapted for applications in the helicopter environment. The control strategy is to minimise the sum of the mean square of the sensor signals by adjusting the output of the actuators. To achieve this goal, the controller requires a reference signal which is correlated with the disturbance and the transfer functions between actuators and sensors.

An array of 14 microphones was used to evaluate the sound field in the cabin and the reduction due to the active gearbox strut system.

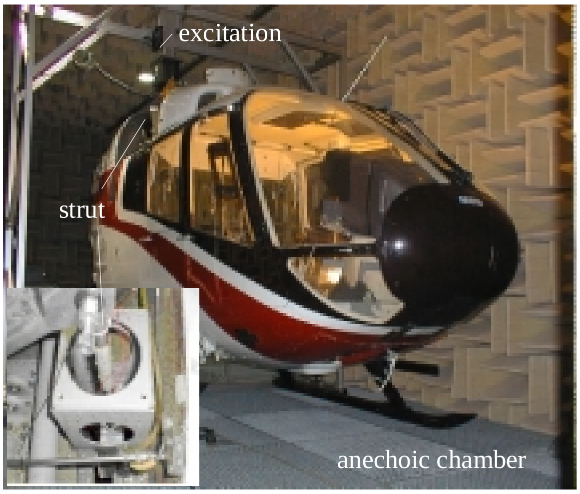

Figure 5 EC135 prototype fuselage / Smart strut (detail view)

The measurements included different actuator/sensor configurations but were focused on two basic cases. In the first case, the 4 struts were controlled by the piezo actuators in longitudinal direction only. This was achieved by using the same control output signal for each of the 3 piezo segments bonded onto the strut. In the second case, the struts were actuated in both longitudinal and transversal direction by controlling the three rows of the piezoceramic shells independently. 12 accelerometers (one 3-axis accelerometer pro strut) were used as error signal sensors for the controller. Figure 6 and Figure 7 show the sound pressure levels with and without control averaged over the 14 microphones in the cabin. The good performance of the active system is evident: for both configurations the interior noise can be considerably reduced over a wide frequency range (700 Hz - 2000 Hz). The general conclusions of the laboratory test can be summarised as follows:

- the reduction of vibration at strut mounting points is correlated to the reduction of cabin noise,
- a complete set of accelerometer sensors – for this particular application a 3-axis accelerometer per strut – is mandatory for good vibration and noise isolation of the cabin,
- the multidimensional control of the struts (3 independently controlled actuator segments)

leads to higher noise reduction compared to the longitudinal actuation.

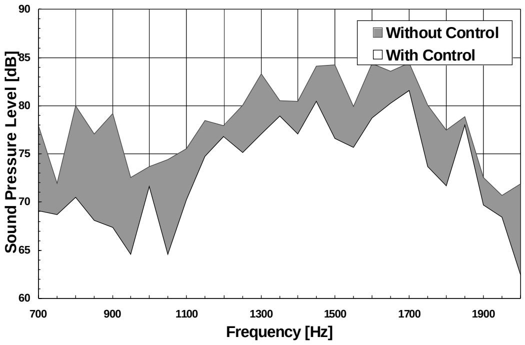

Figure 6 Average sound pressure level – Longitudinal control (4 actuators × 12 sensors)

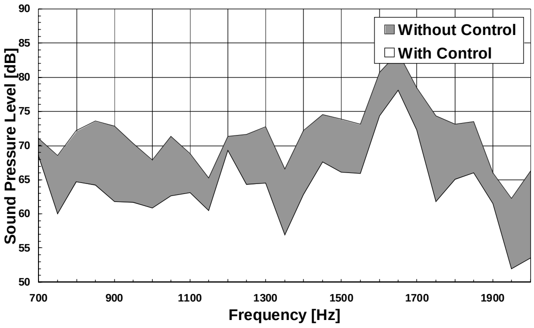

Figure 7 Average sound pressure level – Multi-dimensional control (12 actuators × 12 sensors)

### 5.2 Ground Tests

The ground tests were conducted on a BK117 helicopter (see Figure 10). The BK117 transmission system including 4 vertical struts (z-struts), 2 torque struts (x-struts) and 1 lateral strut (y-strut) is depicted in Figure 11. All seven struts were replaced by the corresponding smart struts described in chapter 4. Seven 3-axis accelerometers (one per strut) were used as error sensors for a control system similar to that applied in the laboratory trials.

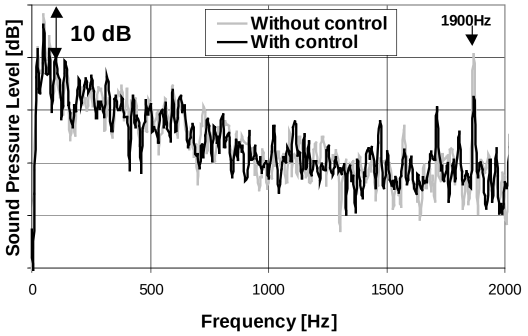

Figure 8 Interior noise spectrum – reduction at the frequency of 1900 Hz

Again an array of 14 microphones was used to monitor the sound field in the cabin. Only three 4-channel amplifiers were available for the ground tests, thus reducing the number of active actuators from a total of 21 to 12. The tests therefore concentrated on the configuration in which the 4 z-struts were independently controlled (4 × 3 actuator segments) to suppress the vibration at the gear-meshing frequency of 1900 Hz. The ground runs were performed with the helicopter operating at 100% rotor speed and about 20% torque.

The reduction of interior noise at a frequency of 1900 Hz can be seen in Figure 8. Looking at Figure 9 it is remarkable that the noise could be globally minimised at all 14 microphones with an average reduction of nearly 5 dB.

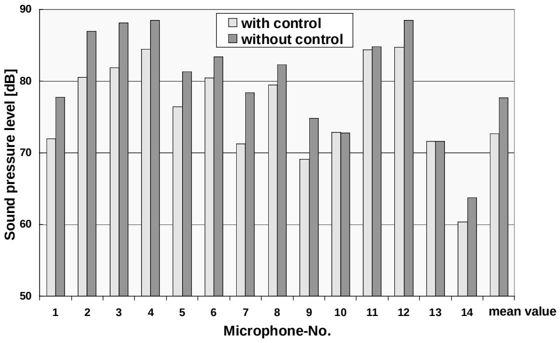

Figure 9 Reduction measured at the 14 cabin microphones (1900 Hz)

The turbulent weather conditions on ground (which caused unexpected high disturbance forces from the gearbox) and the restricted number of 12 active actuators prevented higher reductions.

## 6 Flight tests on a BK117 Helicopter

The challenging target of this test campaign was to demonstrate the noise reduction capability of the active gearbox struts in a series helicopter for real flight conditions.

Figure 10 Eurocopter BK117 Helicopter used for active noise control tests

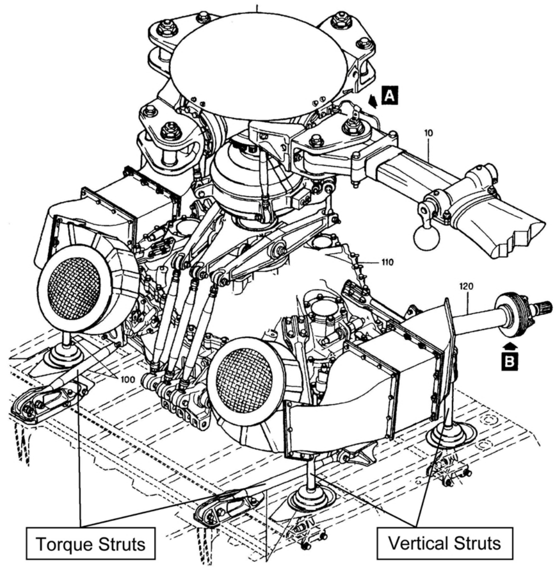

Figure 11 BK117 transmission system

The active system concept examined in ground runs was adopted for the flight tests with the BK117 test helicopter (see Figure 10). A schematic view of this system is given in Figure 12. It is based on the multiple filtered-x controller which controls a total of 21 piezoceramic actuators and 21 accelerometer sensors. The RPM of the helicopter serves as reference signal for the controller. Compared to the ground tests the number of amplifier channels was increased to 21. Thus, all 7 struts of the BK117 helicopter (Figure 11) could be independently actuated in flight.

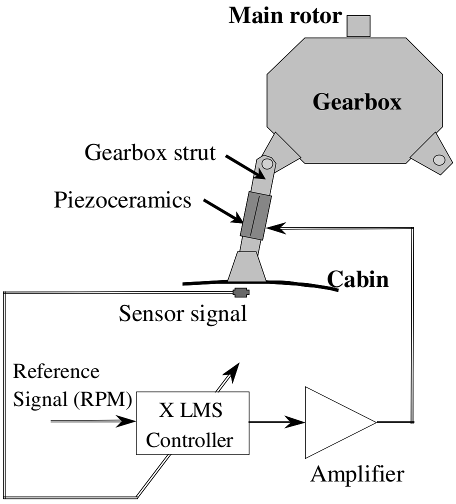

Figure 12 Schematic view of the active strut system used for flight tests

Similar to the preceding tests, the seven 3-axis accelerometers were attached at the fuselage mounting points of the struts. Only these acceleration signals were used as error signals for the controller. The resulting noise reduction inside the cabin was measured with an array of 14 microphones. A multi-channel tape recording system was used to record the relevant data like sound pressure and acceleration.

The equipment required for the flight tests, e.g. amplifiers, filters, controller consisted mainly of laboratory apparatus which was not optimised towards low weight, small volume and power consumption. Electromagnetic compatibility, proper fixing, and suitable power supply were the main considerations with respect to hardware implementation into the test helicopter (see Figure 13).

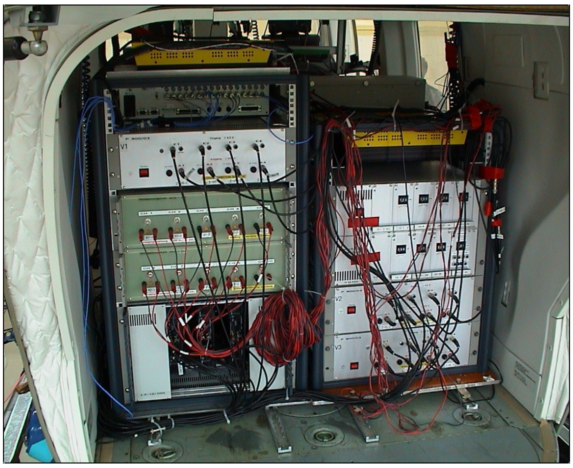

Figure 13 Measurement equipment used for the helicopter flight tests

## 6.1 Test Programme

The test programme conducted with active strut system on the BK117 helicopter is given in Table 1. It included all relevant flight conditions and moreover varying parameters like flight speed and RPM. Prior to each flight a system identification was performed in ground idle conditions. This was to determine the matrix of transfer functions between actuators and sensors which was required for the controller.

| Procedure | RPM | Torque | |
|---|---|---|---|
| Ground Idle | ≈74% | | Sys. Id. |
| Flight Idle | 100% | 16%, 30% | |
| HIGE | 100% | 80% | |
| HOGE | 100% | | |
| Procedure | RPM | Flight Speed [Kts] | |
| Cruise | 100% | 60, 80, 100, 120 | |
| Cruise | 99%, 101% | 120 | |

Table 1 Test matrix of the flight test campaign

## 6.2 Results

The flight tests concentrated on the investigation of the active gearbox strut system operating with the full control authority of 21 actuators × 21 accelerometer sensors at the gear-meshing frequency of approximately 1900 Hz.

The decrease of vibration and the resulting interior noise reduction are summarised in Figure 14. The bar chart illustrates the average values measured with the 14 cabin microphones and the 21 accelerometers used for control. The high control capability of the active struts is obvious. Substantial noise reductions up to 11 dB (forward flight with 60 kts) can be reached for all flight regimes. Even for the most unfavourable HOGE case the noise levels are reduced by approximately 4 dB. The remarkably good correlation between vibration and noise reduction indicates that the seven 3-axis accelerometers are the adequate sensors for controlling and reducing the cabin noise.

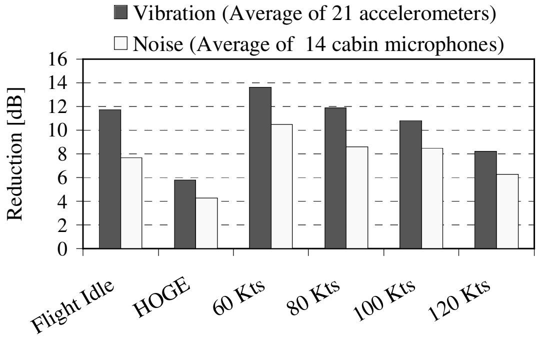

Figure 14 Noise and vibration reductions at the gear-meshing frequency of 1900 Hz

The interior noise spectra for the particular case of the forward flight with 60 kts are shown in Figure 15. Once again, the effect of active control becomes obvious: the dominant noise peak at 1900 Hz is reduced to a level which is perceived as not annoying by the passengers.

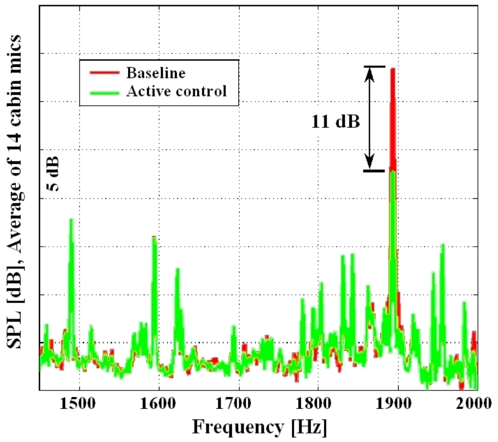

Figure 15 Interior noise at gear-meshing frequency of 1900 Hz (forward flight, 60 kts)

However, the high noise reductions cannot be obtained for all flight conditions. For example for the forward flight, the active system becomes less effective with higher flight speeds. The reason for this effect can be derived from Figure 16. The capability of the active struts to reduce vibrations is apparently not higher then 2.4 g – 2.6 g, whereas the absolute acceleration levels are increasing with flight speed. Due to this limited actuator performance, the noise reductions generally decrease with increasing vibration levels.

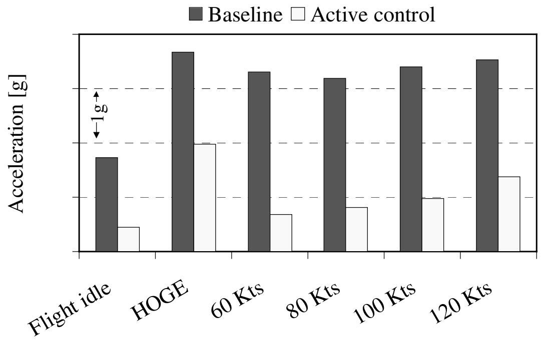

Figure 16 Acceleration levels / Reduction of acceleration at the gear-meshing frequency of 1900 Hz

Based on the experience from the former tests it appears mandatory that every vibration transmission path from the gearbox to the cabin has to be actively controlled. To verify this aspect, a system comprising only 18 actuators and 18 sensors was also flight tested. This reduced system was obtained by excluding the actuators and accelerometers related to the y-strut. The noise and vibration reductions achieved with the inactive y-strut are shown in Figure 17.

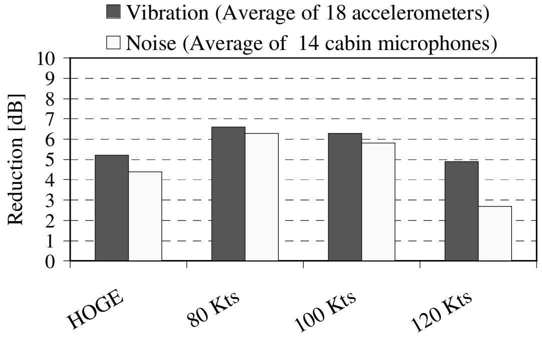

Figure 17 Noise and vibration reductions at the gear-meshing frequency of 1900 Hz (transversal y-strut inactive, actuators and accelerometers disabled)

It can be noticed that the performance is actually reduced. Even though the y-strut is not the main path for structureborne noise the noise reductions are up to 3.5 dB lower compared to the full active system (see Figure 14).

Finally, tests were made with the full active strut system (21 actuators × 21 accelerometers) adjusted to simultaneously control the vibration at two frequencies. In addition to the main frequency at 1900 Hz a second gear-meshing frequency of approximately 1492 Hz was chosen. As pointed out before, the actuator performance seems to be insufficient to reach the potential reductions.

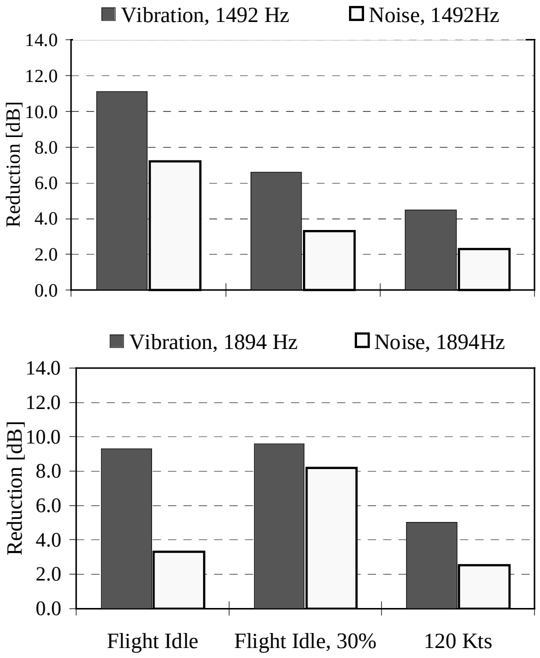

Figure 18 Noise and vibration reductions at the 2 gear-meshing frequencies (1492 Hz and 1894 Hz)

This trend is confirmed by the results illustrated in Figure 18. The active struts are not able to cover the higher displacements, which typically occur at lower a frequency like 1492 Hz. As a result, only moderate reductions of vibration (ca. 4 dB) and noise (ca. 2 dB) could be achieved for the forward flight with 120 kts. Good results were realised for the comparable low vibration levels in flight idle on ground.

The remarkable noise reductions demonstrated for the gear-meshing frequency of 1900 Hz can be extended to more than one frequency only by increasing the actuator performance. Therefore ECD and the EADS research group are currently developing an new smart strut with an optimised actuator design.

## 7 Conclusion

The active strut is a promising concept to reduce the gearbox noise in helicopter cabins. It has been gradually developed to a fully operational active control system and evaluated under laboratory conditions as well as in ground and flight test. The layout processes of the active strut and the important former tests are briefly reviewed in this paper. The results of recent flight tests with a BK117 helicopter equipped with a complete set of active gearbox struts are presented. The substantial noise reduction potential of this active system is demonstrated for several flight conditions like hover and forward flight.

As a next step it is planned to optimise the actuator performance to further improve the capability of the system to reduce the interior noise. This newly designed active strut will be flight tested in the near future.

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