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Smart Struts - The Solution for Helicopter Interior Noise Problems

by

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ABSTRACT

The noise situation in modern helicopters is still unacceptable compared to modern aircraft cabins. The piloting crew and the passengers are exposed to a soundfield, which is highly influenced by the noise intensity and the unpleasant tonal components of the gearbox meshing frequencies. Therefore, it is inevitable to concentrate on the reduction of these tonal noise components. Different possible noise reduction measures to improve the interior noise problem are addressed in this paper. The advanced noise reduction capabilities of the smart strut system are demonstrated.

The development steps of this innovative active actuator concept are described in detail. The focus of this paper is the description of some layout and modelling aspects, the latest measurements in the EC135 prototype structure and the ground tests on a BK117 helicopter. The BK117 was equipped with a complete set of smart struts and the measurements were performed in ground runs.

Furthermore, the results of these measurements are reflected for future applications of the smart strut system in a serial production helicopter. A short view on achievable system data, e.g. weight, power consumption and efficiency of a production system is presented.

1. INTRODUCTION

As illustrated in Figure 1 there are two main noise transmission paths from the source (gearbox / engine / auxiliary power unit) into the helicopter cabin. One is the structureborne noise path and the other is the airborne noise transmission path. As could be measured in the BK117 helicopter, the structureborne path is dominant [1], [2].

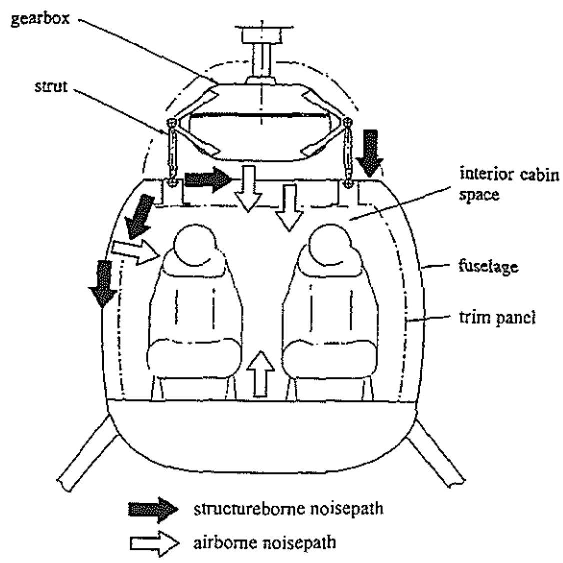

Figure 1: Noise transmission paths from the drive system into the helicopter cabin

The noise spectrum of a helicopter is a broad distribution over the whole frequency range produced by the different noise sources (Figure 2). The tonal noise components felt as most annoying by crew members and passengers are those caused by the gear meshing noise from the gearbox. The vibrations are introduced via the gearbox suspension system into the cabin structure, where they are radiated as noise into the cabin. The high tonal noise components in the spectrum of a helicopter are often 10 or 20 dB above the broadband noise spectrum (see Figure 2 and [3], [4], [5] or [6]). Therefore, reducing these high tonal components of the noise spectrum will lead to an acceptable soundfield in the helicopter.

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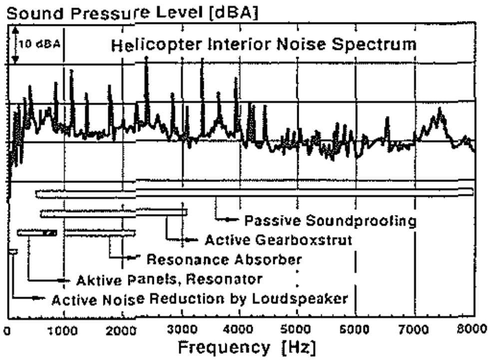

Figure 2: Helicopter interior noise spectrum and possible reduction measures

A way to obtain an effective reduction or even to cancel these noise peaks is the active controlled gearbox strut, the so-called smart strut. This noise control system consists of an active piezo strut (active piezo layers which are glued to the gearbox strut), voltage amplifiers, sensors for either vibration or noise sensoring and an adequate control unit.

There are already systems in service – passive or active – (see [7]), but they are not able to cope with the gear meshing frequencies and can in most cases not be adapted to different and changing frequencies, as it is the case in modern helicopters. Some of the possible measures will be presented in this paper. However, these systems are operated in the low frequency range of e.g. the blade passing frequencies. At the much higher frequencies of gear meshing tones (500Hz to 3kHz) these systems are not effective. The small displacements offered by the smart strut actuators are adequate for the gear meshing frequencies. By feedback of the rotor rotational speed, the system can easily be adapted to rotor speed variations.

The paper describes the way from the design of the smart strut to the latest ground test results which were conducted on a BK117 helicopter. Some measures for the reduction of interior noise as sketched in Figure 2 are briefly described in Chapter 2. Chapter 3 describes the possible active strut concepts and in Chapter 4 the concept layout and manufacture of the strut is reviewed. Some modelling aspects of the smart strut system will be reported in Chapter 5. Latest results from measurements on the BK117 helicopter equipped with the smart strut system in ground runs are the subject of Chapter 6. Furthermore, the possible application of the smart strut system to a series production type helicopter will be discussed in Chapter 7.

2. SOME APPROACHES TO INTERIOR NOISE REDUCTION

The reduction measures for the interior noise reduction can be e.g. subdivided into (see also Figure 2) :

2.1 Passive Soundproofing

The passive soundproofing can be described as :

- Increase of damping on the structure and/or panel
- Increase of structure and/or panel stiffness
- Adding mass to structure and/or panel
- Improvement of acoustic absorption performance

Besides the increase of cabin absorption, which is effective, provided that the cabin reverberation denotes the interior noise field, the measures are all working on the structural loadpath. They have the disadvantage of contra productive increase of the helicopter weight and a decrease in performance. A detailed report of the effectiveness of these means can be found in [8]. Nevertheless, a basic package of passive soundproofing is mandatory.

2.2 Vibration Absorbers

Vibration absorber systems can be used to minimize local vibrations. They are ideal for e.g. the gearbox strut mounts where they decrease the vibratory excitation of the cabin structure panels (see Figure 3). Normally, these absorbers are heavy and need large space. Moreover, they can only be tuned to a specific frequency and are not effective with varying rotor speed. Therefore, absorber systems are often seen as not adequate for noise reduction in helicopter cabins. See also [9] and [10].

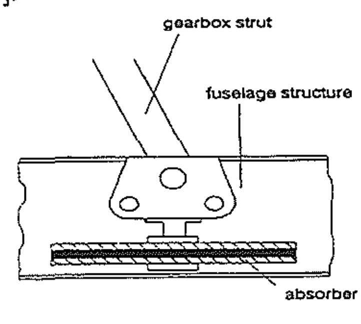

Figure 3: Example of vibration absorbers fixed to the gearbox strut mounting (cabin side)

2.3 Inner Shell Concept

The inner shell concept is an approach which can be compared with the isolation of the driver cabin of modern trucks. The inner cabin is mounted on vibration isolation mountings which must have a special transmission characteristic. A good example for the use of this concept is reported in [11]. The application to smaller helicopters is not possible because of the high weight disadvantage and the loss of cabin volume of the system.

2.4 Active Loudspeakers

The active noise control by loudspeakers uses an array of loudspeakers to minimize the sound pressure level at a number of given error microphone positions inside the helicopter cabin. It may be configured to produce noise reductions at local regions or globally throughout the entire cabin volume. The technology has already been successfully applied to cars and propeller airplanes where reductions of 10 to 20 dB were indicated [12], [13].

For helicopters, active noise control by loudspeakers might reduce the discrete frequencies of the main and tail rotor up to 300 Hz at maximum. However, this system is not able to cope with tonal components of the main transmission noise which are significant in the medium to high frequency range.

2.5 Active Panel Vibration Control

Another way to reduce the interior noise is the active panel control system. Figure 5 gives a schematic view of the system layout. In the past some basic investigations on flat panels were conducted in the RHINO project at EUROCOPTER DEUTSCHLAND and the DaimlerChrysler laboratory. The system was tested on a realistic helicopter structure including panels, actuators and sensors [14].

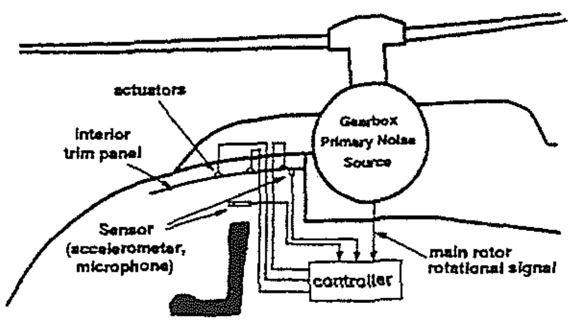

Figure 5: Schematic drawing of the active panel control system

Despite the possible benefits of such a system, numerous sensors and actuators have to be placed on the panels, thus substantially increasing the helicopter weight. The controllable frequency range is from 50 to 800 Hz (low frequency range), whereas the tonal components from the gear meshing have a much higher frequency and cannot be reduced by this system.

3. THE ACTIVE GEARBOX STRUT CONCEPT

The active gearbox strut concept can be realized in two different ways. Figure 6 gives a schematic drawing of both systems.

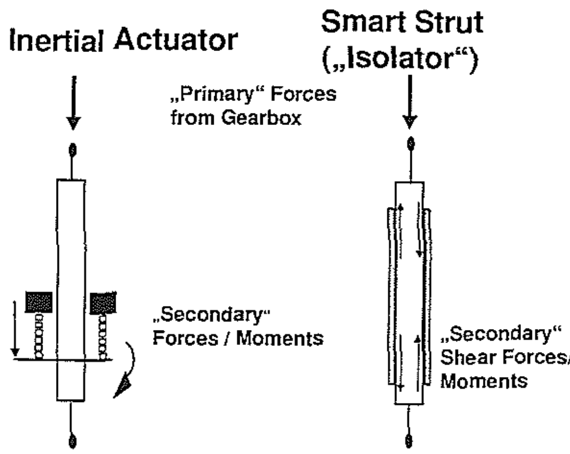

Figure 6: Active gearbox strut concepts

On the left hand side the inertial actuator concept is sketched. Two or three inertial masses are forced to oscillate by a piezoelectric stack (or any kind of linear actuator) which is mounted on a collar connected to the strut. The inertial forces introduced into the strut by these oscillating masses are used to cancel the primary forces from the rotor/gearbox unit.

The physical principle can be compared to a detuned absorber (see [15]). By this system both longitudinal forces as well as moments about the two local bending axes can be introduced into the strut. In Ref. [16] and [17] some measurements with inertial actuators on an EH101 helicopter gearbox strut are described. The first basic tests for the layout of the smart strut were also carried out with inertial mass actuators in the DaimlerChrysler laboratory. Some results of these investigations are presented in [3].

However, the inertial actuator concept is difficult to integrate into the strut design. In most cases the space around the struts is restricted or not even available. Moreover, their unavoidable weight penalty makes their use in helicopters not very attractive.

A very attractive and promising way to reduce or totally cancel the gearbox strut vibrations to the cabin structure is the smart strut system. The working principle of the smart strut is sketched in Figure 6 on the right hand side.

The actuator is an active layer of piezoelectric material (e.g. PZT = lead zirconate titanate) bonded directly onto the strut which allows the introduction of longitudinal shear forces into the strut. A division of the piezoelectric layer into three segments along the circumference allows the control of both longitudinal and lateral vibrations of the strut. Figure 7 shows a simplified sketch of the smart strut.

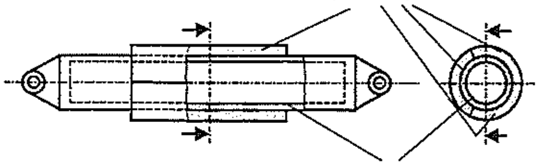

Figure 7: Simplified sketch of the smart strut

The physical principle behind this concept is a so-called force isolator. It will be described in the next chapter.

This concept offers several advantages:

- simplicity of design
- no need for completely new strut design (PZT shells are only add-ons to production struts)
- only small weight penalty
- low actuator costs
- easy maintenance

4. LAYOUT AND MANUFACTURE OF THE SMART STRUT

After a brief description of the working principle of the smart strut, the basic design considerations are briefly reviewed.

4.1 Working Principle

By applying a control voltage between the piezo layer outer and inner surface the piezo can be strained or contracted in the longitudinal direction. This phenomenon is the well-known inverse lateral piezo effect ("d_{31} effect"). The strain of the piezo sheets is introduced by a pair of shear forces at the ends of the piezolayer into the strut (see Figure 6). The theory was first derived by Crawley [18]. Based on this theory, the model depicted in Figure 8 can be used for the layout of the strut. Because the first longitudinal eigenfrequency is approximately 5 kHz and the dominant gear meshing frequency is about 1900Hz, the dynamic effects are neglected in this model.

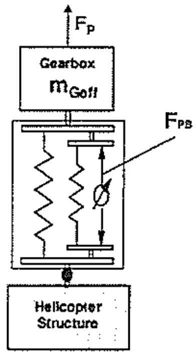

Figure 8: Concept model for the smart strut (longitudinal direction)

The principle of the force isolator can be explained as follows: the forces from the gearbox unit are completely compensated by the inertial forces of the effective gearbox mass. In order to achieve this, the active displacements at the gearbox side must be equal to the displacement of the gearbox mass under the influence of the primary force from the rotor/gearbox unit. If this is the case, no forces are transmitted to the strut and thus to the fuselage structure.

For the special case of the 1900Hz gear meshing frequency, which is the most annoying one for the BK117 aircraft, the following data were derived from impedance and flight measurements:

- Primary force (excitation) F_P = 20 N
- Effective gearbox mass m_{Geff} = 0.5 kg
- Resulting displacement of gearbox side strut end (compensator) $\Delta s = 0.3\ 10^{-3}$ mm

4.2 Design

For the design layout of the piezoelectric strut with bipolar high voltage control the following design parameter were selected:

- Max. electric field strength	300 V/mm
- Max. control voltage	± 450 V
- Piezo layer thickness	1.5 mm
- Piezo segment length	100 mm
- Dynamic strut deformation at max. control voltage	2. 10^{-3} mm

The dynamic strut deformation is almost a magnitude higher than the real displacement as estimated in the last section (confirmed by laboratory measurements). This means, that the actuator displacements in longitudinal direction are sufficient. Similar results are obtained for the lateral direction.

In order to reduce time and costs for the development of an experimental smart strut, BK117 serial production struts were used as a basis. These struts are simple steel tubes with welded mounting ends for the bearings one of which is connected to the gearbox and the other to the cabin structure.

Due to the high technological effort to produce piezo shells with a high length to diameter ratio, the ceramics were divided not only circumferentially but also axially into three equally long sections. So one strut is equipped with a total of 9 piezo segments. Each of these elements has an electrode on its inner and outer surface.

The struts were manufactured in the DaimlerChrysler laboratory at Ottobrunn. Details of the manufacture process are described in [3]. A view on a smart strut as it is was realised for the BK117 test helicopter is shown in Figure 11.

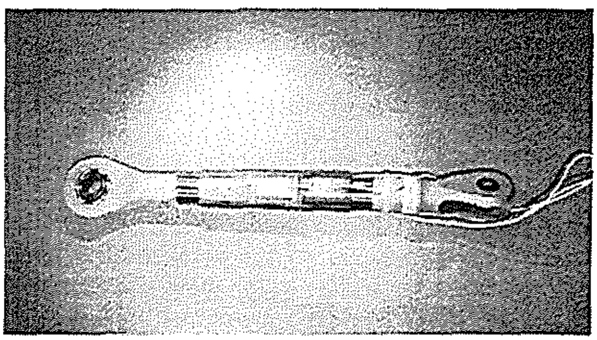

Figure 11: Smart strut for tests in the BK117 helicopter

Both the axial and the circumferential division of the active piezo layer are visible. For the tests in the helicopter the piezo segments were additionally covered with a rubber shrink tube in order to protect the piezo shells against mechanical damage and to isolate the strut electrically.

5. MODELLING AND FREQUENCY RESPONSE

In parallel to the experimental evaluation of the smart strut system, a theoretical analysis of the strut behaviour was conducted.

5.1 Complete Model of the Strut

The spring mass model shown in Figure 8 was used for the layout and for the calculation of the longitudinal motion of the smart strut. However, the first bending frequency of the isolated strut with "free-free" boundary condition is at about 800 Hz, whereas the frequency to be controlled is 1900 Hz. So a spring mass model is not adequate for an overall model featuring both longitudinal and lateral motion of the smart strut. Nevertheless, a complete model (longitudinal and bending) is indispensable for the modelisation of the whole system with controller and strut(s).

Therefore, a more sophisticated model based upon the strut modes in both bending and extension was derived. The integration of this model and its integration into the complete control system was performed by means of a standard control engineering program.

5.2 Verification by Frequency Response

In a first step a frequency response calculation of the isolated BK117 experimental smart strut on the laboratory test stand was performed. The model uses two bending modes in two directions and one longitudinal mode. The output vector contains the lateral accelerations of the fuselage side end of the strut. In this test one piezo row was excited. The result of the calculation and the corresponding measurements are presented in Figure 12. It shows good correspondence between the model calculations and the laboratory measurements. Both the first bending frequency and frequency response of the accelerations at the fuselage-side are well predicted by the model.

Experimental Smart z-Strut for BK117

Lateral Accelerations on Fuselage Side Strut End
Excitation: +/-200V in Piezo Row No. 2

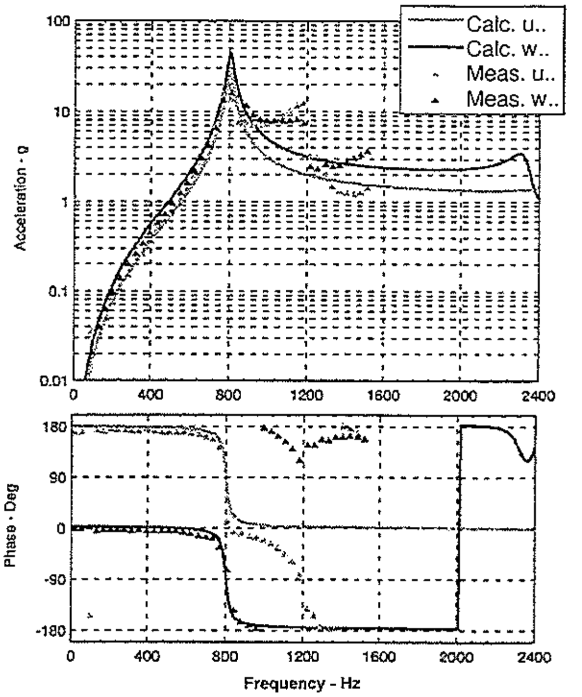

Figure 12: Smart Strut Frequency Response

6. TESTS

This chapter describes some basic laboratory tests with the smart strut and the active control system. Furthermore, details of the measurements of ground runs with a BK117 helicopter equipped with a complete set of smart struts are presented. A more detailed report of the first basic tests with the active strut in the EC135 prototype fuselage can be found in [3]. There are reported also details of the controller system in use.

6.1 Laboratory Tests on a Prototype Helicopter Fuselage

The behaviour of the smart strut in a realistic environment was first investigated on an EC135 prototype test assembly which consists of a complete fuselage and a gearbox housing mounted via four vertical (z-direction) smart struts to the fuselage. Figure 13 shows the experimental setup and Figure 14 shows one of the smart struts mounted between fuselage and gearbox. To generate a primary field, the gearbox housing was excited by a shaker. For the measurements presented here, a frequency control sweep with a sinusoidal signal output was used. A shaker excitation signal which was derived from original BK117 measurements was tested later on, but will not be subject of this paper.

Figure 13: EC135 prototype fuselage in the anechoic room

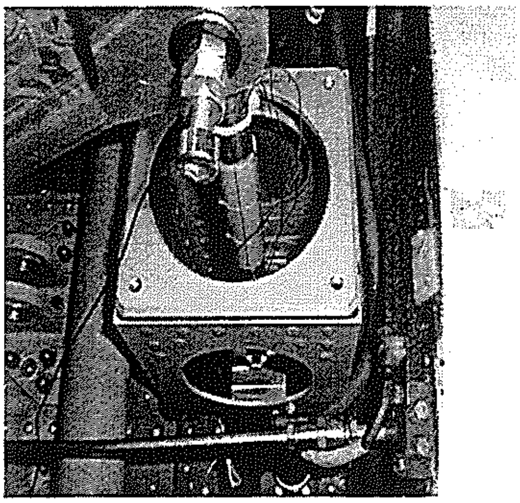

Figure 14: Smart strut mounted in the test assembly

An array of 14 microphones was used to measure the soundfield in the cabin. Four 3-axis accelerometers at the mounting points of the struts to the fuselage were used as error sensors. The active control tests were performed with a controller based on a filtered-x LMS algorithm for tonal noise. The algorithm uses orthogonal reference signals generated from a tachometer signal. The controller minimizes the sum of the squared error signals. In these laboratory investigations the vibrations at the mounting points to the fuselage structure were used as error signals.

As could be measured in flight on a BK117 helicopter, the vibrations in longitudinal direction are dominant, but the vibrations in the other directions are also important (see [3]). First active control tests showed that the reduction in sound power level largely depends on the number of sensed accelerations and also on the number of independent controlled actuators.

6.1.1 Parallel Actuation of the Smart Struts

In the case of parallel actuation of the 4 smart struts, each of the 3 rows of each strut was controlled by the same controller output signal. This resulted in a mainly longitudinal control of the four struts. Figure 15 shows the mean sound pressure level in the cabin with and without control of all 12 accelerations (3 directions at 4 strut mounting points).

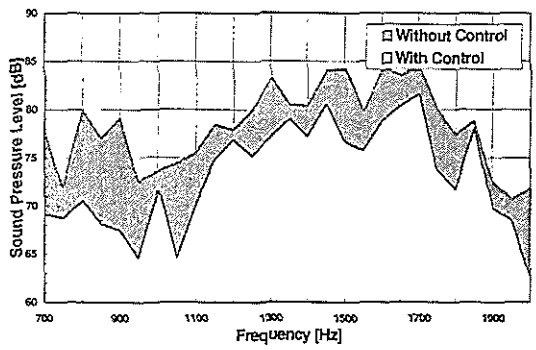

Figure 15: Mean sound pressure level – Laboratory tests with 4 controlled actuators and 12 error sensors

The mean vibration level could be reduced by about 4dB in the frequency range from 700Hz to 2kHz. At nearly all frequencies the reduction of the mean sound power level at the 14 microphone positions is very close to the mean reduction measured at the 12 error sensors (Figure 16). This shows, that the radiated sound is indicated well by the error sensors in the case of parallel actuation of the smart struts.

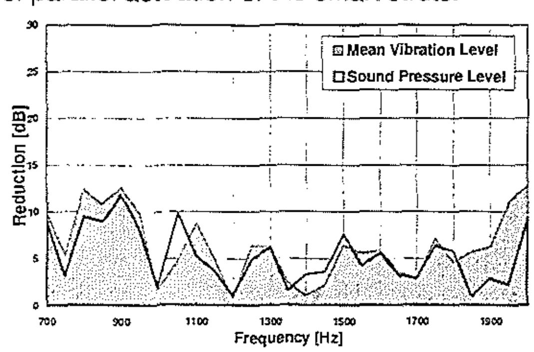

Figure 16: Reduction of sound pressure and vibration levels by active control – Laboratory tests with 4 controlled actuators and 12 error sensors

6.1.2 Independent Actuation of the Smart Struts

Higher reductions of vibration and sound pressure levels can be achieved by controlling all three rows of piezoceramic patches of each strut individually. The results for this test case are shown in Figure 17 and 18. With this configuration we found it possible to achieve about 8 to 12 dB reduction of the mean sound pressure level. Whereas the mean vibration level could be reduced by about 10 to 20 dB in maximum.

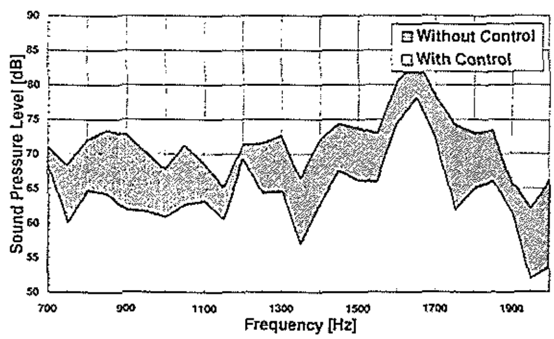

Figure 17: Mean sound pressure level – Laboratory tests with 12 controlled actuators and 12 error sensors

The reason for not reaching this high reduction level for the sound pressure level is due to the flanking airborne noise transmission path.

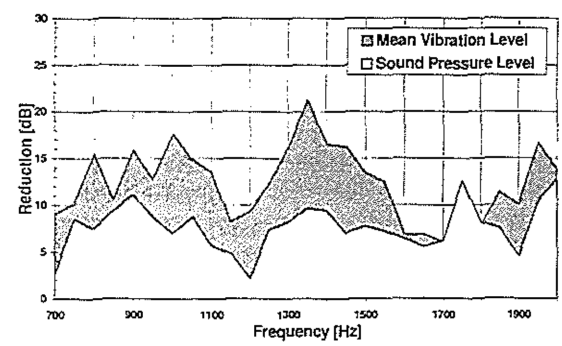

Figure 18: Reduction of sound pressure and vibration levels by active control – Laboratory tests with 12 controlled actuators and 12 error sensors

The tests in the laboratory can only simulate approximately the disturbances in a real helicopter environment. Therefore, the next step in the development of the smart strut system was the evaluation of the system on a BK117 helicopter.

6.3 Ground Tests on a BK117 Helicopter

The EUROCOPTER BK117 helicopter was chosen as testbed (Figure 19).

Figure 19: BK117 test helicopter for smart strut

The BK117 gearbox strut system comprises seven struts, four vertical struts (z-struts), two torque struts (x-struts) and one lateral strut (y-strut) (see Figure 20)

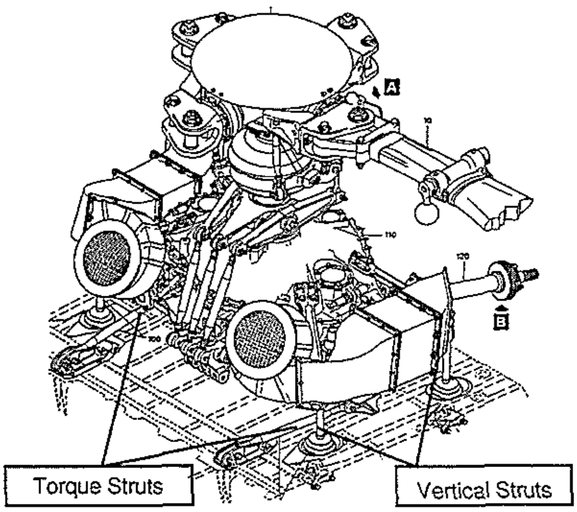

Figure 20: BK117 transmission system

A complete set of series gearbox struts was equipped at the DaimlerChrysler laboratory with the piezoceramic material. All seven series struts shown in Figure 21 were replaced by their corresponding smart strut. Additionally, the helicopter was equipped with ten 3-axis accelerometers (one at each mounting point of the strut to the structure and one for each strut type on the gearbox side), fourteen microphones in the cabin, three 4-channel amplifiers and a 50 channel storage tape recording system.

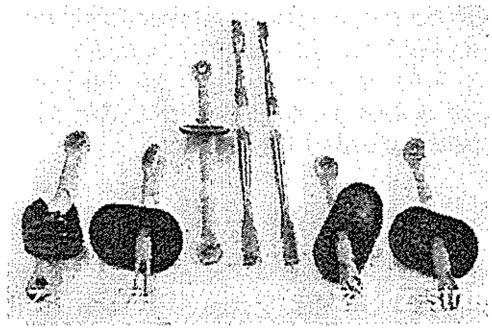

Figure 21: Complete set of BK117 gearbox struts (with covers on the four z-struts and the y-strut).

Special care was taken to reduce the flanking transmission paths for airborne noise as far as possible. Therefore a thick layer of sound absorbing foam for reducing the airborne noise transmission path was introduced between the structure and the interior panelling of the helicopter.

6.2.1 Tests with Shaker Excitation on a BK117 Helicopter

In a first step, again a shaker was used to generate the primary sound field. The tests showed that in this test case it is sufficient to restrict the control to the z-struts. Twelve actuators, that means 12 piezo patches at the 4 z-struts, were used. Error signals were generated by the 21 accelerations at the mounting points to the fuselage of all seven struts. Figure 22 shows the results at the 14 cabin mounted microphones for a single tone at 1900Hz. This tone corresponds to a strong tone usually generated by the BK117 gearbox at 100% rotor speed. The sound pressure level was reduced by about 13dB (mean value).

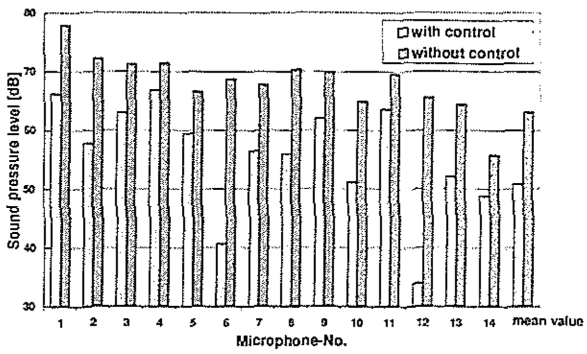

Figure 22: Reduction of sound pressure level - excitation by shaker

6.2.2 Ground Run Tests on BK117 Helicopter

Furthermore, ground tests with the helicopter operating at 100% rotor speed and about 20% torque were performed. Due to large amplitude variations of the tones generated at the gear meshing frequencies, it is rather difficult to determine exactly the effect of the active control system. Nevertheless, for the same configuration as described above mean reductions in the sound power level of up to 5dB (mean value) were found. (Figure 23).

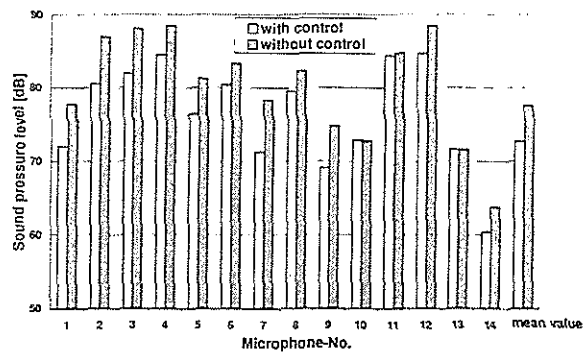

Figure 23: Reduction of sound pressure level - ground run on BK117 helicopter

Figure 24 gives a closer view on the reached reduction of the single gear meshing frequency at 1900Hz for microphone 3. A reduction of 8 dB at this frequency is visible.

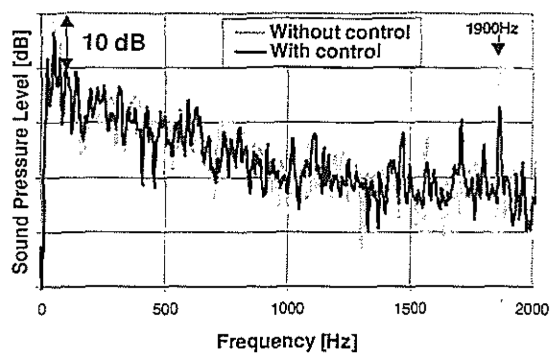

Figure 24: Frequency spectrum with reduction of e.g. the single 1900Hz tone

With respect to the difficult test conditions at these ground runs a substantial reduction of the noise levels in the cabin could be reached. Moreover, these reductions could be found at all microphones. That means a global noise reduction inside the whole cabin can be reached by applying the smart gearbox strut system.

7. FUTURE APPLICATION OF THE SMART STRUT SYSTEM

For the application of the smart strut system to a production helicopter some aspects have to be looked at more closely.

7.1 Serialisation aspects

The integration of the smart strut system into a production helicopter still requires some improvement. At the moment it is planned to introduce the smart strut system as a retrofit kit, which can be ordered by the customer as an add-on.

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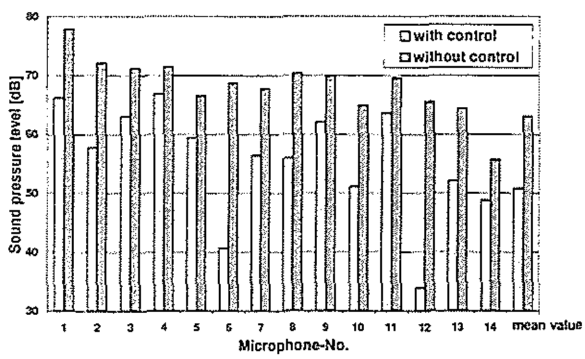

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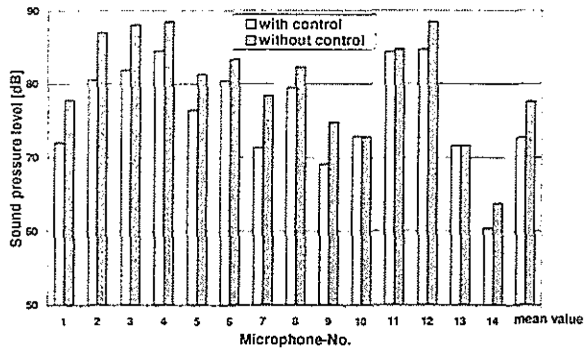

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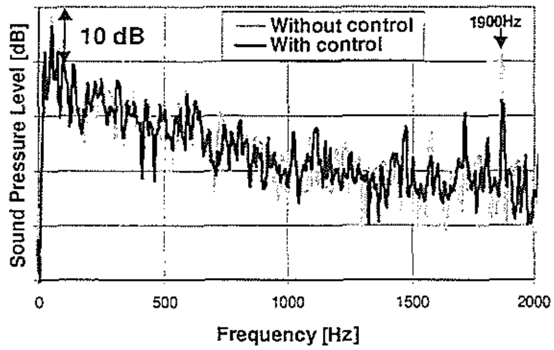

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For the application of the smart strut system to a production helicopter some aspects have to be looked at more closely.

7.1 Serialisation aspects

The integration of the smart strut system into a production helicopter still requires some improvement. At the moment it is planned to introduce the smart strut system as a retrofit kit, which can be ordered by the customer as an add-on.

First of all the smart strut system has to be mechanically satisfactory. In order to guarantee this, lifetime examinations must be carried out, which have to show a sufficient lifetime. The bonding of the smart strut to the strut surface has to withstand the operational conditions.

Today, the smart struts fly in the BK117 helicopter (without the active part, the sensors and the controller). This is done for investigating whether the piezoceramics and the bonding withstand the operational conditions as they occur in normal flight operations.

Some electric problems also have to be solved. The smart strut voltage must not introduce a danger. Another key point in the serialisation is a "smart" power supply. This can be solved by using internal power recovery capability.

7.2 System data

Another crucial point for a reasonable application of the smart strut is the improvement of the basic system data. Although the experimental system works as designed, it still is "too big, too heavy, too expensive, and needs too much power". The following Table gives a comparison of the data for the experimental system and for those envisioned for a production system.

	Experimental System	Production System
Required Power [kW] (For 7 struts with 3 actuators each)	1.2 *)	0.3 **)
Weights [kg]		
- Sensors and Amplifiers	48	< 5
- Filters (Antialiasing)	4	2
- Controller (DSP)	5	3
Sum of Weights	57	< 10

*) with conventional analogue power supply

**) with power recovery capability

Table 1: Comparison of system data for experimental and production smart strut

The table shows that the experimental system has a weight of about 60 kg. The future application as a production system should reach the data listed in Table 1.

8. CONCLUSION

The smart strut system is a very challenging solution to reduce the noise level in a helicopter cabin by acting on the most annoying high tonal gear meshing noise.

The development of the smart strut system was carried out in a step-by-step approach. As a basis, a great deal of experience was gathered with the active system in the EC135 prototype helicopter structure. Theoretical investigations were carried out in parallel to crosscheck the laboratory results. Next the evaluation of the active strut in the BK117 helicopter was done.

The high noise reduction capability of the system could be demonstrated in the BK117 helicopter ground runs. A significant reduction of the tonal noise components in the interior sound field could be demonstrated. The next development step is to prove the concept in flight. It is planned to offer the system after an optimization and serialisation phase as an optional equipment to the customer.

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Appendix A

The character of the indicial response functions calculated for a step increase in Mach number is similar to that obtained for a step increase in incidence[18]. It should therefore be possible to represent the response in the approximate form,

$$C_N = \frac{dC_N}{dM}\overline{M}\left(1 - \sum_n A_n e^{-t/T_n}\right) \tag{A1}$$

where $\overline{M}$ is the step change in Mach number and A_n and T_n are constants which must be determined. The constants A_n are subject to the constraint $\sum_n A_n = 1$.

Using this assumed form the transfer function can be obtained by transformation to the Laplace domain thus,

$$\frac{C_N(s)}{M(s)} = \frac{dC_N}{dM}\left(1 - \sum_n A_n + \sum_n \frac{A_n}{(1+sT_n)}\right) \tag{A2}$$

and the normal force for an arbitrary variation of Mach number can be found from,

$$C_N(s) = \frac{dC_N}{dM}\left(\sum_n \frac{A_n}{(1+sT_n)}\right)M(s) \tag{A3}$$

For a sinusoidal variation of Mach number about a mean value M_o the forcing function in the Laplace domain is,

$$M(s) = M_o\left(\frac{1}{s} + \frac{\mu\omega}{s^2+\omega^2}\right) \tag{A4}$$

and the normal force is given by,

$$C_N(s) = M_o \frac{dC_N}{dM}\left(\sum_n \frac{A_n}{(1+sT_n)}\right)\left(\frac{s^2+\omega^2+\mu\omega s}{s(s^2+\omega^2)}\right) \tag{A5}$$

which can be written in terms of partial fractions as,

$$C_N = M_o \frac{dC_N}{dM}\left(\sum_n \frac{A_n}{s} + \frac{\pi_{1,n}+\pi_{2,n}s}{s^2+\omega^2} + \frac{\pi_{3,n}}{1+sT_n}\right) \tag{A6}$$

Taking the inverse transform and $t \to \infty$ we obtain the following form for the unsteady normal force due to the prescribed motion,

$$C_N(t) = M_o \frac{dC_N}{dM}\left(1 + \sum_n \frac{\pi_{1,n}}{\omega}\sin(\omega t) + \pi_{2,n}\cos(\omega t)\right)$$

with,

$$\pi_{1,n} = \frac{1}{T_n}\frac{\mu\omega A_n}{(T_n^2+\omega^2)} \quad \text{and} \quad \pi_{2,n} = -\frac{\mu\omega A_n}{(T_n^2+\omega^2)}$$

This expression can be simplified to obtain the following expression for the unsteady normal force coefficient,

$$C_N(t) = M_o \frac{dC_N}{dM}\left(1 + \sum_n B_n \sin(\omega t + \phi_n)\right) \tag{A7}$$

where the phase angle ϕ_n is obtained from the ratio of the constants $\pi_{1,n}$ $\pi_{2,n}$ using,

$$\tan(\phi_n) = \frac{\pi_{1,n}}{\omega\pi_{2,n}} = -\frac{1}{\omega T_n} \tag{A8}$$