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INTERIOR NOISE REDUCTION IN COMPOSITE AIRFRAME STRUCTURES

BY

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Abstract

In the soundproofing process of any helicopter, it is necessary to optimise the interior trim in order to meet the noise and weight requirements. By application of new measurement techniques like sound intensimetry and modern laboratory test facilities, the iterative optimisation progress can be significantly reduced or even avoided.

The paper presents the application of sound intensimetry as a measurement technique to optimise a typical interior trim package for low weight penalty and minimised noise emission. The basic experimentation was made on a composite test structure similar to a realistic helicopter fuselage structure. The effect on the transmission loss for different combinations of various trim panels with absorbing foams between primary structure and the trim panel and the influence of adding damping sheets were tested. The measured sound fields were correlated with modal data of the structure. By scanning the test structure with the intensity measurement probe, it was possible to identify acoustic leakage, to visualise standing waves within the double wall, and to localise resonant frequencies of the structure.

Beside the optimisation of the broadband noise reduction characteristics of the trim panel, it was investigated to increase the transmission loss of the trim panel at discrete frequencies generated by the rotors and the gearbox. By integrating of active means like piezo-ceramic and electrodynamic actuators, the damping properties of the trim panel can be adapted with regard to the critical frequencies without a severe weight increase due to an adaptive control system. The efficiency of the active panel concept is proved on a real helicopter structure.

The results from the passive soundproofing optimisation influenced the development of the interior treatment of the new EUROCOPTER EC 135 helicopter. The layout of the interior trim panels is presented.

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1. Introduction

Cabin noise levels for untreated helicopters are higher than 100 dBA. This level varies between helicopters of different size, performance, gearbox construction, etc. Most standard helicopters with minimum noise requirements have levels of about 90 to 95 dBA. Soundproofed versions for passenger transport show interior noise levels of about 85 dBA, in some cases like VIP helicopters (Ref. 1, 2) even lower. The weight of the additional acoustic treatment is often up to 2% of the helicopter take-off weight. However, despite the effort, a substantial difference can be noticed if compared to the typical noise level in modern airliners (Figure 1).

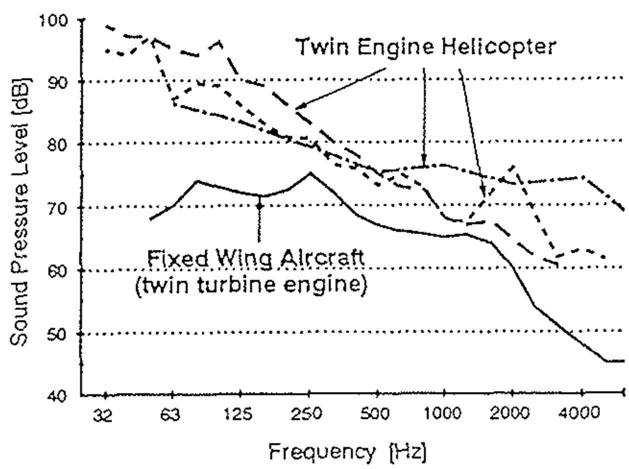

Figure 1: Interior Noise Levels of VIP-soundproofed Helicopters Compared to Fixed Wing Aircraft

With regard to the noise radiating surface area and due to structural considerations, this trim will be a substantial proportion of any noise control strategy. In order to ensure a maximum noise reduction with a minimum of additional weight, it is important to achieve an optimum trim distribution. This is of special importance for modern fuselages made out of reinforced composites since these helicopters are facing severe noise problems compared with conventional aluminium structures. Figure 2 shows transmission loss measurements of a conventional aluminium structure and a honeycomb structure, both in a configuration as used in helicopters. The poor performance of the composite panel is caused by the 20% lower weight of the structure itself and due to the reduced number of stringers and spars necessary to provide the same stiffness. It can be foreseen that new helicopter designs with composite materials will be faced with increased interior noise problems.

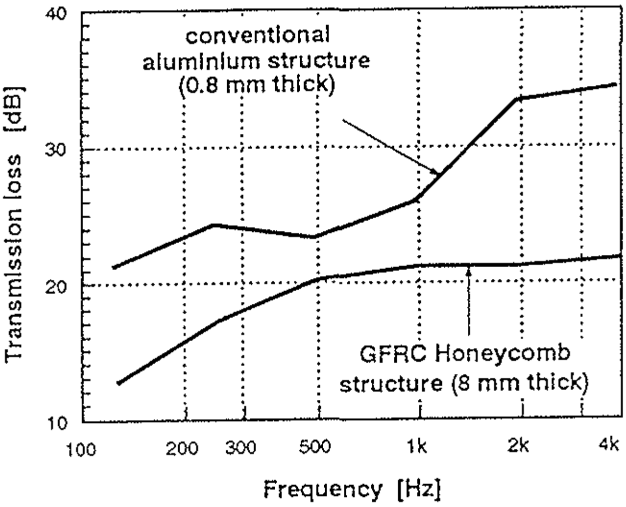

Figure 2: Transmission Loss of Pure Aluminium Structure and Honeycomb Structure (8 mm)

For future helicopter development, the reduction of interior noise is one of the major tasks. There were several interior noise reduction research activities over the last decade. The basic of all advanced noise reduction measures is an effective and economic interior trim which provides maximum noise transmission loss properties. The intention of the acoustic test programme on the composite test structure was to supply specific knowledge for the layout of the acoustic trim of a helicopter fuselage, to investigate the capabilities of the sound intensimetry technique for the design of noise reduction measures, and the evaluation of the feasibility of the active control of the trim panel.

2. Strategy of Interior Noise Reduction

Numerous sources which contributes to the helicopter interior noise. Those which dominate a typical spectrum, are both rotors, the engine and auxiliary equipment, airframe noise, and the main transmission. Generally spoken, the spectrum of helicopter cabin noise comprises a complex series of harmonically related discrete tones, superimposed to broadband noise.

The most annoying noise source is the gear noise of the main transmission which propagates on a structure-borne as well as airborne path into the cabin. The position of the main transmission relative to the passengers is a major factor regarding the magnitude of annoyance. The worst case is if the gearbox is located on top of the cabin above the passengers seats. In small helicopters, effective noise reduction measures are often limited due to the required head clearance of the passengers (see Figure 3). Also the weight of the interior trim panellises especially smaller helicopters which are mainly designed for multipurpose applications and not only oriented to passenger transport tasks.

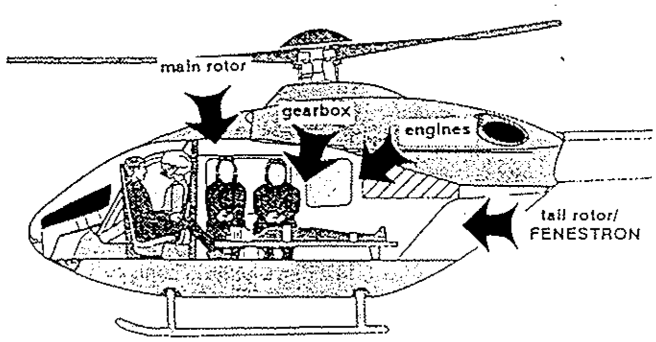

Figure 3: Location of the Helicopter Noise Sources with Relation to the Passengers

Considering the noise generation processes, noise in a wide frequency range is radiated inside the helicopter cabin starting from below 100 Hz and ending by the engine noise with up to 10000 Hz. Figure 4 shows a typical internal noise spectrum typical for a small twin engine helicopter. For a comfortable interior, the noise reduction strategy has to cover the whole frequency range.

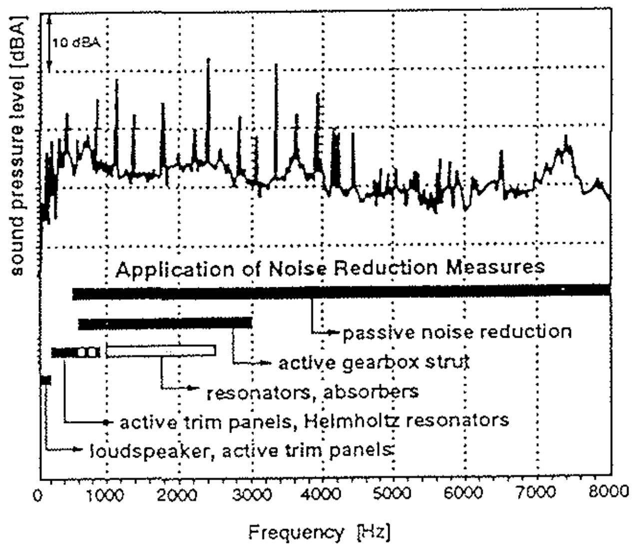

Figure 4: Typical Interior Noise Spectrum in an Untreated Small Size Helicopter and Noise Reduction Measures

For reducing the broadband noise and, of course, in the same amount also the discrete frequency noise, an effective passive sound reduction must be provided by the interior trim. These conventional passive measures often lead to an impairment with respect to other design goals. Especially at low frequencies, passive measures are inadequate to provide the required damping properties for low noise helicopter cabins. Here, active noise control by loudspeakers or active trim panels as secondary sources may take care of the low rotor harmonics. In the upper frequency range, where passive sound reduction is effective, the discrete tones of gearbox and engines deteriorates the passengers comfort. Passive means as resonance absorbers and resonators are able to reduce some of these tones [3]. As most of the noise from the helicopter gearbox is transmitted via the structure-borne path [4], an active gearbox strut concept may be very successful in reducing the gearbox noise.

However, irrespective of the potential benefits of active noise control, these technologies will never replace the need for an effective passive interior trim, especially since many of the active control systems are restricted to certain frequency ranges or to some discrete frequencies.

3. Helicopter Test Structure

A realistic helicopter structure taken directly from the manufacturing process did serve as the test object. The honeycomb shell was made out of glass fibre. The structure was divided by carbon fibre stringers into 4 unequally spaced sections like indicated in Figure 5.

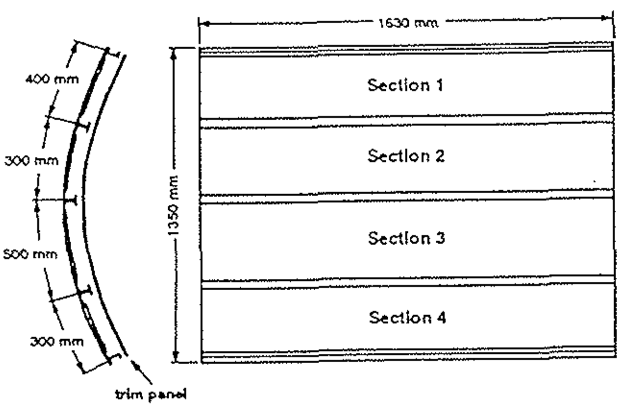

Figure 5: Helicopter Structure for Laboratory Tests

The test structure with the size of 1.65x1.35 m was installed into the test window between a reverberation room and an anechoic room of the Daimler Benz acoustic test facilities (Figure 6). It was excited by a broadband sound source and a shaker located in the reverberation room. The sound intensity radiated by the structure was measured in the anechoic room. A measurement array with an equal spacing of 80 mm was defined consisting of 238 points. In addition to the sound intensity also the global radiated noise was measured.

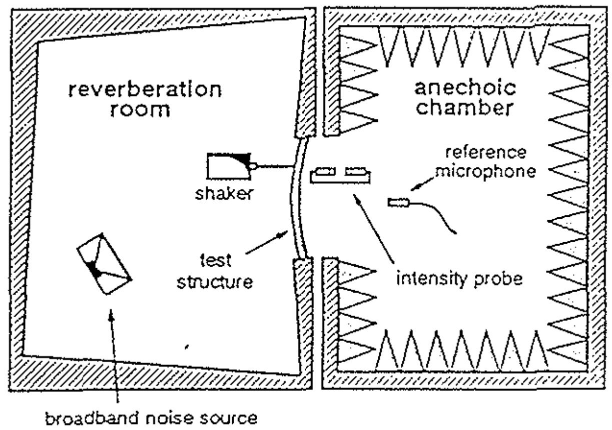

Figure 6: Measurement Arrangement

4. Experimental Test Results

An intensive measurement programme has been performed in order to investigate the feasibility of the application of sound intensimetry to optimise the acoustic trim package and to directly optimise the arrangement of absorbing and damping measures in a double wall system. The measurements covered the frequency range from 80 Hz to 4500 Hz, which is considered to be the most relevant range for an appropriate trim layout. The basic measurement campaign included the investigation of the bare structure and the structure with vibration damping materials. Measurements have been performed with the structure and different trim panels and the double wall system with damping and absorbing materials.

Basic Measurements

The basic investigation started with an detailed description of the acoustical and vibratory behaviour of the test structure. Figure 7 shows a typical example of the measured sound intensity as equal noise contour lines for a 1/3-octave band. It can be seen, that the sound radiation at the stringers is up to 7 dB lower compared to the panel areas between these stiffeners. The three stringers are clearly visible as areas of reduced noise radiation. A rather surprising distribution shows Figure 8 for a frequency range of 160 Hz. Here, the noise radiation between Stringer 2 and 3 was about 15 dB higher than measured in other areas of the structure. The high noise radiation is caused by a local eigen frequency of the structure as confirmed by a modal analysis at 158 Hz.

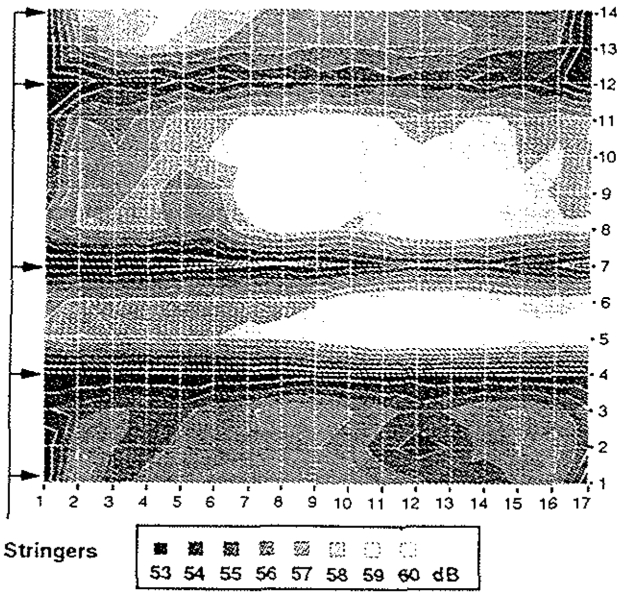

Figure 7: Sound Intensity Mapping of the Test Structure at the 2 kHz-1/3-Octave Band

Vibration Damping Layer

The section was treated by damping layers to reduce the radiated noise. At a first approach, only 50% of the area was covered with stripes close to the stringers and then at the center, respectively, and secondly, the complete area was coated with the same damping material. In Figure 9, the acoustic behaviour is illustrated for the section between stringer 2 and 3. If the damping is applied only close to the stringers, the radiated intensity at 160 Hz remains nearly unchanged, whereas the same amount of absorbing material is applied to the middle section decreases the radiated noise by about 3 dB.

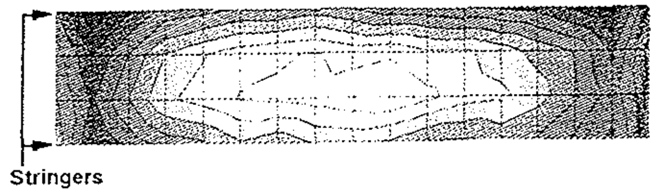

Figure 9a: Damping Layers Positioned Close to the Stringer

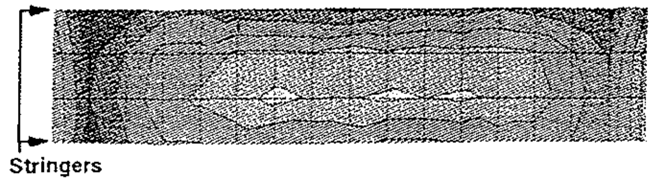

Figure 9b: Damping Layers Positioned in Middle of the Section

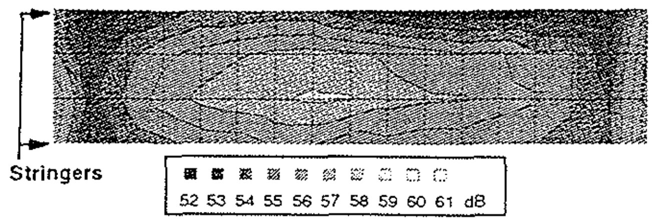

Figure 9c: 100% of the Area Covered by Damping Material

Figure 9: Intensity Mapping of the Area Between 2. and 3. Stringer for the 160 Hz-1/3-Octave Band

Nearly no additional noise reduction was achieved if the full section area is covered by the damping material. The results presented in Figure 9 are restricted only to the 160 Hz 1/3-octave band with the eigen frequency at 158 Hz. Figure 10 shows the overall transmission loss - the difference in transmitted sound power of the

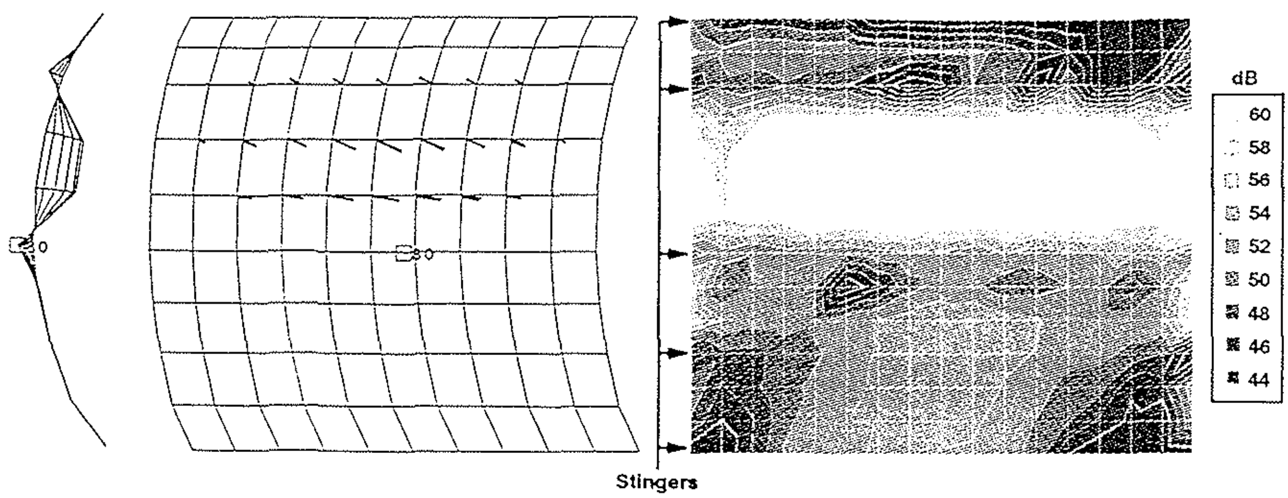

Figure 8: Sound Intensity Mapping of the 160 Hz-1/3-Octave Band and the Modal Analysis at 158 Hz

damped and undamped structure - of the area between the second and the third stringer. Considering the whole frequency range, the different arrangements of damping material does not significantly influence the transmission loss. However, a 100% coating of the structure will increase the transmission loss by about 6 dB mainly due to the increased mass and stiffness provided by the damping material.

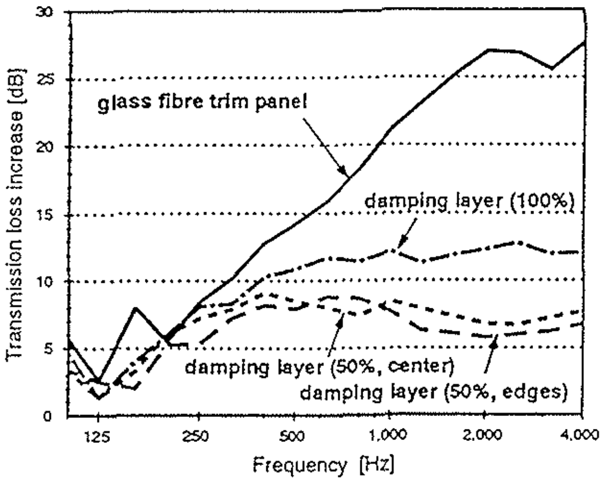

Figure 10: Increase in Transmission Loss of the Test Structure due to Various Damping Layer Configurations Compared to a GFRC Trim Panel (thickness 0.86 mm, weight 1.65 kg/m²)

The increase in transmission loss by adding damping material to the structure is compared in Figure 10 with the increase provided by a second shell. A Carbon fibre reinforced composite panel was mounted to the stringer at 15 locations. In this case, the honeycomb structure is not treated with damping material. Above the resonance frequency of the double wall system (theoretically 238 Hz), the transmission loss increases by about 6 dB per octave. Surprising is the result at 160 Hz, where the trim panel shows a higher efficiency than the damping material. The additional weight for the trim panel is about 1.7 kg/m² (including mounting devices) compared to 0.72 kg/m² or 1.44 kg/m² respectively, if the damping layers cover 50% or 100% of the structure. For a weight optimised standard version of a helicopter without specific noise requirements, emphasis should be laid to an effective interior trim rather than the damping of the structure.

Results of the transmission loss gain for different double wall configuration are shown in Figure 11. The Glass fibre (GFRC) and the Carbon fibre (CFRC) show a very similar behaviour up to 630 Hz, above this frequency the GFRC panel is up to 5 dB better. The honeycomb panel is superior in the lower but poor in the higher frequency range. For the application to the helicopter, the main advantage of a honeycomb panel is its high stiffness, which allows to install the panel at the ceiling with only a small number of mounting points. The poor damping in the upper frequency range can be improved by filling the cores with foam or by use of a sandwich panel with stiff foam instead of a honeycomb core.

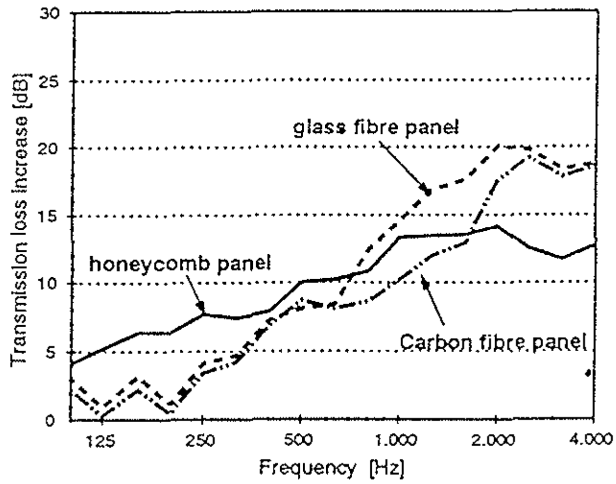

Figure 11: Increase in Global Transmission Loss due to Various Trim Panels Mounted on the Test Structure

Isolation of the Trim Panel

The problem of reducing structure-borne noise transmission to the trim panel may be solved to a certain extent by use of a fully isolated inner shell. For this reason, the trim panel mounts must be designed soft enough to isolate the trim panel from the cabin airframe. However, due to the necessary stiffness and crash requirements which are especially important for the trim panels above the passengers' heads, the softness of the mounts is restricted.

The effect of rubber elements connecting stringer and trim panels can be seen from Figure 12 for a purely structure-borne and a purely airborne noise excitation. For both arrangements, the data give the impression that the tested shock mounts are not suitable for an efficient insulation of the trim panel. Even a reduction of the connection points did not improve the transmission loss. Softer mounts will not be able to adequately fix a helicopter trim panel equipped with the passenger units.

A soft mounting is always necessary for a stiff trim panel where the transmitted structure-borne noise is propagating through the whole panel. In a further test, the trim panel was equipped with a visco-elastic damping material (Figure 12). The noise reduction was only 1.5 dB in maximum and this reduction was caused only by the effect of the added mass of 1.44 kg/m^2. The measurement of the shock mounts and the damping layers on the trim panel indicates that the GFRC panel itself is soft enough to avoid the propagation of structure-borne noise transmitted by the mounting locations to the panel.

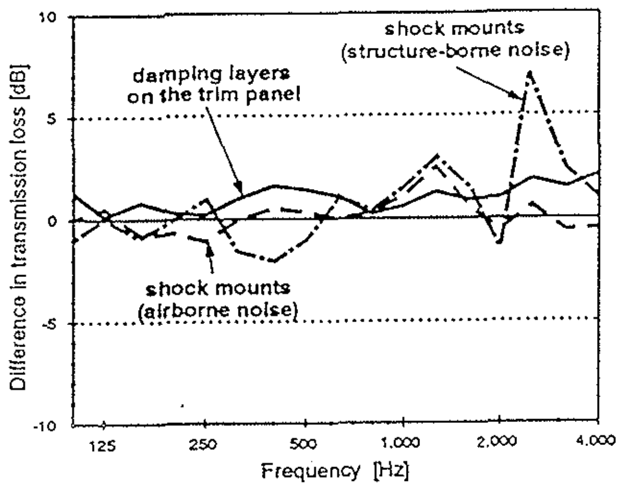

Figure 12: Effect of Shock Mounts and Damping Layers Applied to the Trim Panel

Effect of Foam

Sound absorbing foam within a double wall system considerably increases the transmission loss by avoiding multiple reflections between the walls. The additional gain in transmission loss of the double wall concept by use of absorption material between structure and trim panel is presented in Figure 13. A material for airbome applications with a weight of 11.3 kg/m^3 was used. The tests were performed with layer thicknesses of 30 mm and 50 mm. The data indicate only a minor change for the whole frequency band. The reduced thickness of the absorbing foam results in a weight saving of 0.21 kg/m^2.

In Figure 14, as an example for the effectivity of panel and foam, two intensity maps are plotted for the 500 Hz one-third octave band. The upper plot shows the curved test structure in the basic configuration without any acoustical treatment. The lower plot presents the same structure with trim panel and 50 mm absorption material. Comparing both maps, it should be taken into consideration that the same colour shade varies in level between upper and lower plot by 15 dB. The structural stiffeners are visible in the upper map as regions of lower sound intensity but they disappear when the noise reduction measures are applied. The total

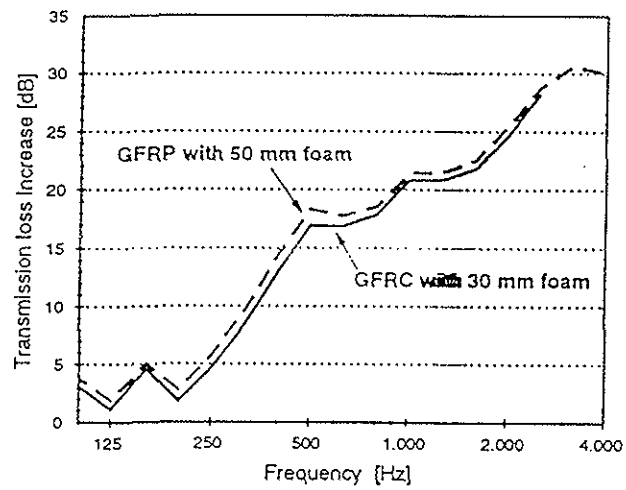

Figure 13: Effect of foam

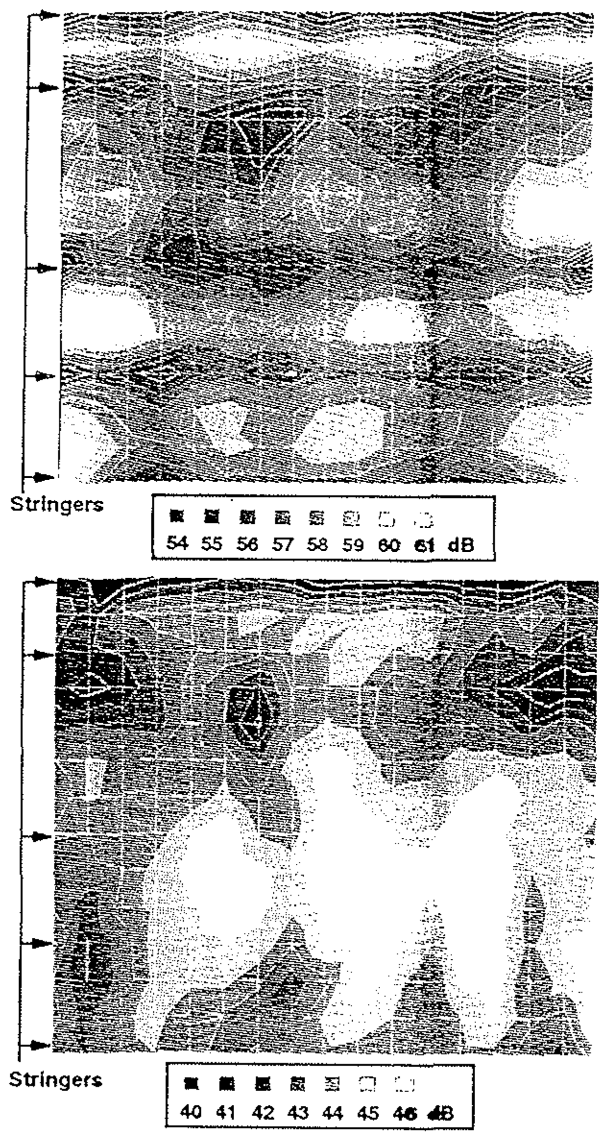

Figure 14: Sound Intensity Map of the Test Structure without (top) and with Noise Reduction Measures at 500 Hz

radiated sound power calculated from the intensity maps was 14 dB lower for the acoustically treated double wall system. This was obtained with an additional mass of 1.67 kg/m^2.

5. Active Control of Trim Panels

By the passive treatment of a helicopter, the noise is reduced in a wide frequency range. However, discrete frequency noise is reduced in the same way like the broadband noise and will still exceed the broadband noise. These discrete noise components are responsible for the annoyance of the passengers even if the overall noise level is considerable low.

The application of active structural acoustic control [5] is a promising approach to reduce some of the discrete frequency tones in the low and mid frequency range. Active structural acoustic control (ASAC) means that the structural vibrations are controlled by actuators in order to reduce the radiated sound. The radiated sound is measured e.g. by using microphones. As actuators simple piezo-electric patches directly glued on the structure can be used. The main advantage of such piezo-electric actuators is that the introduction of significant additional weight can be avoided. A principle set-up of an active panel control system with piezo-electric actuators is shown in Figure 15.

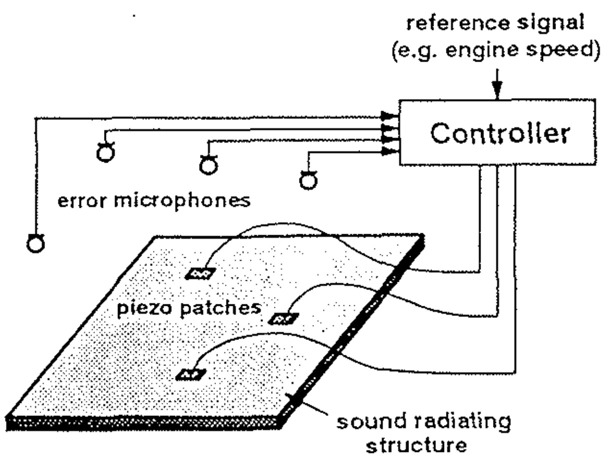

Figure 15: Scheme of an Active Panel Control System

Under normal operating conditions, the sound at arbitrary measurement points generated by the actuators can be described by a linear multiple input (actuator voltage) multiple output (measured sound pressures) system. Therefore, the mean squared sound pressure is a quadratic function with respect to the input voltages of the piezo-electric actuators. This means, that an adaptive multi-channel feedforward controller, as typically used in active noise control systems, is well suited to minimise the mean squared sound pressure which gives usually a rough estimate of the total radiated sound power. As outlined in Figure 15, the adaptive feedforward controller needs a reference signal which is strongly correlated with the noise to be cancelled.

Basic Investigation on a flat panel

As a first step, this technique has been applied to a rectangular plane test panel. For this simply supported test panel, analytical models of the structure with piezo-electric actuators can be derived. Therefore, the test panel is well suited to investigate the principle mechanisms of active structural acoustics and to develop a strategy for defining the necessary number of actuators and their positions.

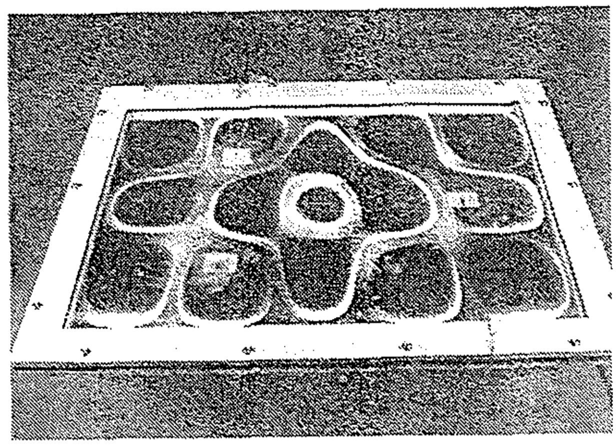

Figure 16: Flat Test Panel for Basic Investigations Excited with 140 Hz (Mode 5,3)

Figure 16 shows a picture of the test panel (aluminium 960x660x1 mm) which was mounted on a wooden box. The panel was stimulated at the center by a shaker at the eigen frequency (140 Hz) of mode (5,3). In the case of resonant excitation, the mechanism of ASAC is simply to reduce the modal velocity of the radiating mode. In the case of off-resonant excitation, more modes are radiating sound. The mechanism of ASAC is therefore much more complicated, since some modal velocities may be also increased in order to minimise the radiated sound. The simulated modal velocities of the test panel for such an off-resonant case are illustrated in Figure 17. Obviously, the velocities of modes (3,1), (3,3) and (3,5) are increased and adequately shifted in their phases by the introduction of optimal control forces (3 actuators).

In principle, one actuator is able to stimulate a single mode, if it is not positioned at the node of a mode. A high efficiency can be achieved by placing an actuator at the antinode of a mode. This means that the maximum number of required actuators is defined by the number of modes which have to be stimulated. Therefore, it is very useful to perform a modal analysis of a given structure to get the information required for adequate actuator positioning. Furthermore, one has to identify those modes which efficiently radiate sound at the frequencies of interest and, therefore, have to be stimulated by the actuators. The actuators should be positioned at the antinodes of these radiating modes. The number of required actuators can be reduced by considering the phase-relationship between the modes. If the structural damping is low, at certain regions of the structure some modes are in phase. By placing an actuator within such a region, all the "in-phase" modes can be suppressed simultaneously with a single actuator. By using optimised positions, usually an actuator can couple into a large number of modes. Therefore, the sound radiation at eigen frequencies of the structure can be reduced by a small number of actuators.

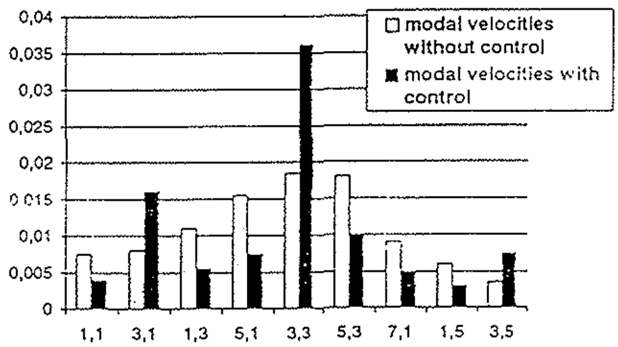

Figure 17: Modal Velocities on the Flat Panel with and without Active Control

For experimental tests, a controller based on the filtered-x-LMS-algorithm [6] has been used. The hardware is based on a Texas Instruments C40 signal processor. The algorithm has been implemented in the time domain, i.e. the controller can be also used for frequency-tracking or broadband applications. Figure 18 shows the noise levels with and without control for an experimental set-up with two piezo-electric actuators and two error microphones used by the control system. The structure was excited by a shaker at the center of the panel. The frequency has been changed very slowly with a sweep rate of 1 Hz/s. To be able to track the frequency, the controller used a broadband identification of the transfer functions between error signals and actuator voltages.

Obviously, rather high reductions of up to 18 dB were achieved. The experimental results show a very similar behaviour compared to the simulation results. The highest reductions can be achieved at the eigen frequencies of the structure.

Similar reductions in the sound pressure level were measured at additional microphones not used by the control system. At low frequencies (100 - 120 Hz), the convergence rate of the controller was very slow. Therefore, the control system was not in a steady state and reductions in the sound pressure levels are poor.

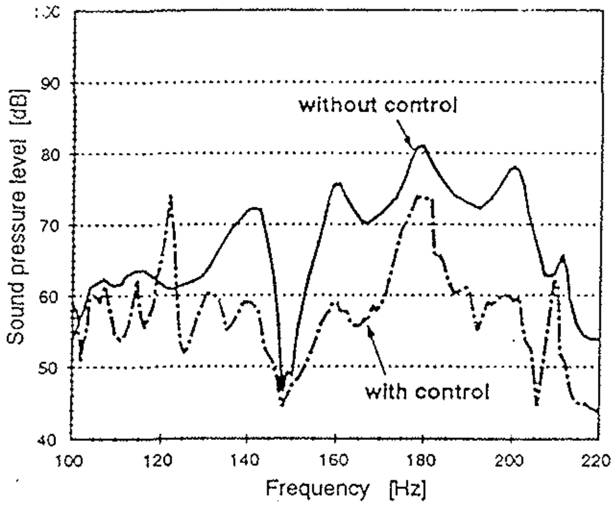

Figure 18: Sound Pressure Radiation of the Flat Panel with and without Active Control

Tests with the helicopter test structure

The test structure as shown in Figure 5 consists of a curved CFRC trim panel mounted on the stringers of the fuselage. For first tests, two piezo-patches (40x60x0.256 mm) on the trim-panel were used. A photograph of the experimental set-up is shown in Figure 19. The test structure was mounted in a window between a reverberant room and an anechoic room as shown in Figure 6. Five error microphones at a distance of about 1.5 m from the trim panel were used.

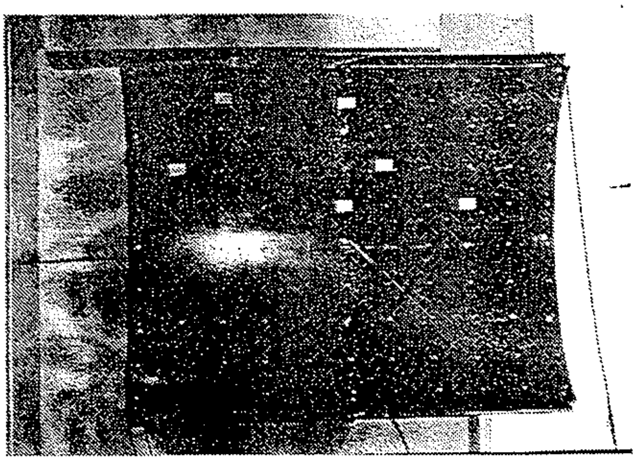

Figure 19: Experimental Test set-up for the Active Panel Control on the Curved Helicopter Trim Panel

Actuators could be also used directly on the fuselage structure which is much stiffer. Therefore, the modal density at a certain frequency is lower compared to the trim panel. This mean that the application of ASAC may be easier with respect to adequate actuator positioning and achieveable sound power reduction. On the other hand, the vibration levels at the fuselage structure are usually higher than at the trim panel. Therefore, the power consumption of actuators on the fuselage and the weight of required amplifiers may be much higher. Furthermore, the trim panel control can be much easier implemented on a real helicopter.

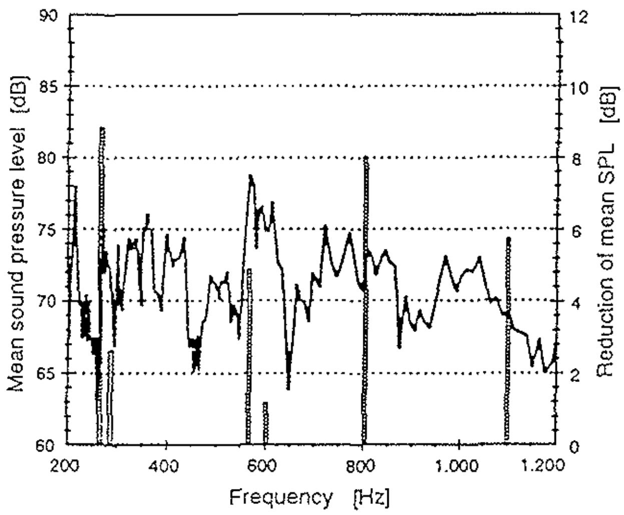

Figure 20: Mean Sound Pressure Level Radiated by the Test Structure and Noise Reduction by Active Control for Discrete Frequency Noise

Noise problems in the helicopter interior are mainly caused by the rotor blade in the low frequency range and the gearbox at higher frequencies up to about 3000 Hz. Figure 20 shows the mean sound pressure level at the microphone locations in the frequency range 200 Hz - 1200 Hz and the reductions achieved for some discrete frequencies. Considerable high reductions up to 8.8 dB have been achieved mainly at resonance frequencies (270 Hz, 560 Hz, 800 Hz). In the off-resonant cases, the reductions are usually much smaller. This is a typical behaviour of an ASAC-system with a small number of actuators. Noise problems mainly occur at those frequencies where resonances of the sound radiating structure coincide with excitation frequencies. Therefore, from a practical point of view this behaviour is very desirable. The first results available up to now are very encouraging. Further work will be directed to experiments with more actuators and simultaneous control of a greater number of frequencies applied to real helicopters.

6. Application to the EC 135

In a first step, the laboratory investigation to optimise the trim panels directly influenced the design of the EUROCOPTER EC 135 interior treatment. In addition to the investigation on the test structure, structure parts of the EC 135 prototype were optimised with respect to a high noise damping. Already in an early stage, a cabin door with its frame was cut out of an EC 135 prototype structure, arranged in the Daimler Benz laboratory /3/, and investigated to minimise acoustic leakage. Furthermore, a full EC 135 prototype fuselage was introduced in the anechoic room (Figure 21). The test should lead to a further improvement of the acoustic trim by a more realistic structure-borne excitation at the transmission deck.

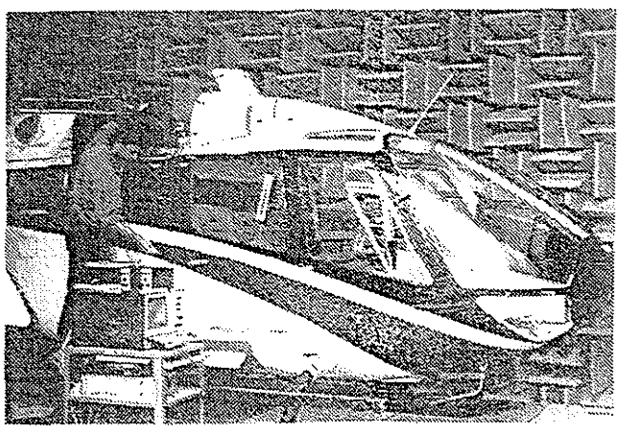

Figure 21: EC 135 Prototype Helicopter in the Anechoic Chamber for Sound Proofing Optimisation

The basic design of the resulting interior trim consists of only four large panels. All utilities necessary for the passengers comfort and safety were integrated in the trim panels to minimise acoustic leakage. Due to the stiffness requirements of the trim panels, especially at the ceiling, a sandwich panel was used with about 2 kg/m^2. All panels were coated with a thin (about 1 cm) layer of soft flexible foam and covered by a thin foil as an additional sound barrier and water-resistant sheet. In addition, the remaining space between structure and panel was filled by foam to cover at least 50% of the available space.

A scheme of the resulting interior trim design and the resulting transmission loss can be seen in Figure 22. The transmission loss measured on the helicopter corresponds well with the laboratory measurements up to a frequency of 600 Hz. In the upper frequency range, the high transmission loss values measured in the optimum laboratory environment could not be reached due to flanking path noise transmission and reverberation effects inside the cabin. The stiffness of the panels allowed to fix it with only a few points to the helicopter fuselage to avoid structure-borne transmission to the trim panels. Especially near the transmission deck, the connecting points to the fuselage were minimised.

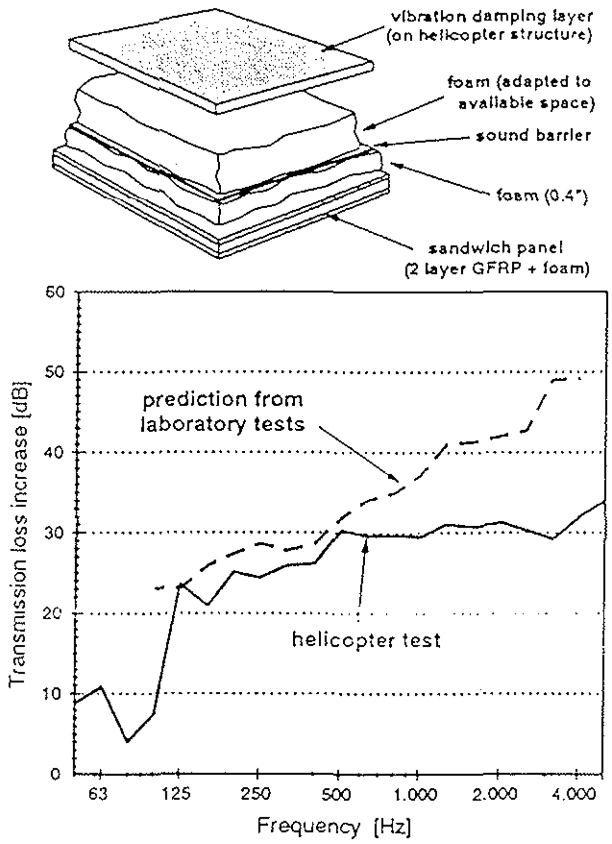

Figure 22: Measurement of the Interior Trim Package Inside the Helicopter Compared to Laboratory Measurements

An impression of the current interior trim of the EC 135 can be seen in Figure 23. Measurements directly taken after the first prototype integration of the panelling and soundproofing confirmed a quite low noise level of 76 to 78 dB(SIL) on all passenger seats. The interior trim for the standard soundproofed version is planned for a total weight which is only about 1% of the helicopters' maximum takeoff weight.

The present interior trim design gives an adequate basis for an low interior noise environment. In a second improvement campaign, main emphasis will now be given to a further improvement of the acoustic treatment for discrete frequency noise components and low frequency noise

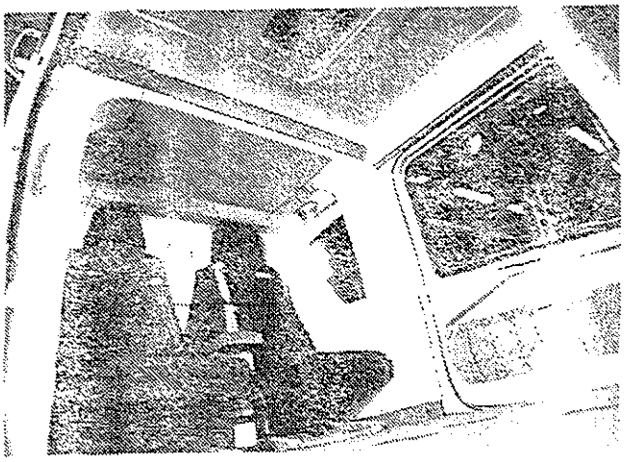

Figure 23: EC 135 Sound Proofing Interior Trim

Conclusions

In an extensive laboratory test campaign, different measures for designing an acoustically effective interior treatment have been tested. The application of optimzed passive measures for the design of the helicopter interior treatment leads to a soundproofing trim with an acceptable weight penalty. The sound intensity mapping technique has been demonstrated to be a valueable tool to identify areas of insufficient soundproofing. However, the application of sound intensimetry under laboratory conditions for interior trim optimisation can only be a first approach. The method has to be adapted for the application to the interior sound field of the helicopter cabin.

Effective passive measures for interior noise reduction like an optimised acoustic trim are required to reduce the overall noise inside the helicopter cabin. In addition to the achieved broadband noise reduction, noise at discrete frequencies can be reduced by the application of active devices like piezo-electric actuators to the trim panel. The tests on the curved structure showed a high efficiency at the vibrational resonance frequencies of the trim panel. For harmonic excitation, noise problems mainly occur if the excitation frequencies coincide with the structural resonances.

At off-resonance frequencies the measured reductions are smaller. The active panel control by the use of small piezo-electrical patches allows to provides to improve the sound transmission loss characteristic of the panel without weight penalty. Whereas the experience gathered by the passive soundproofing investigation can be directly applied to the helicopter trim design, the active panel control demands additional research work mainly for the selection and the optimised positioning of actuators and sensors before the helicopter panels can be successfully equipped with active devices.

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