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GROUND AND FLIGHT TESTS OF A PASSIVE ROTOR ISOLATION SYSTEM FOR HELICOPTER VIBRATION REDUCTION

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Abstract

One method of reduction of the rotor induced cabin vibrations consists of separating the helicopter fuselage dynamically from the rotor-transmission unit by use of convenient isolator elements. This paper deals with the development of a passive nodal rotor isolation system for the BK 117 helicopter. It consists essentially of five local uniaxial force isolators which operate according to the well known antiresonance principle and which are tuned to the 4/rev main excitation frequency. Initially, the effectiveness of the rotor isolation system is proved by a shake test. For that, the test vehicle, which is suspended by the rotor hub, is loaded by realistic rotor excitation forces and moments by use of suitably arranged electrodynamic shakers. Secondly, the vibration isolation system is tested in flight for different configurations. Detailed ground and flight test results are presented. An excellent isolation efficiency is obtained.

1. Introduction

During the last ten years, remarkable progress with regard to performance, in particular of light and medium weight helicopters, has been obtained. Novel rotor systems, which not only permit higher speeds but also considerably improve maneuverability, have contributed to essentially extend the range of mission of such helicopters. The increasing usage for accident rescue and passenger transportation, the demand for installation of highly sensitive instruments, and last but not least the requirements of the UTTAS draft RFQ of 1971 (.05 g limit; revised, in 1976, upward to 0.1 g), have motivated the industry to intensify working on helicopter vibration reduction.

The major helicopter vibration source is the rotor. The excitation is conditional upon the flight principle itself. The nonuniform air flow through the main rotor in forward flight causes periodically variable air loads on the rotor blades leading to fixed-system n/rev excitation forces and moments at the rotor hub, where n is an integer multiple of the number of rotor blades. In general, the first "number-of-blades" harmonic is the dominant helicopter excitation.

A method of reducing rotor induced cabin vibration is rotor isolation by connecting the rotor-transmission unit and fuselage by specific isolator elements. The passive antiresonance force isolator represents an attractive compromise between effectiveness and technical resources (Ref. 1). Several embodiments of such isolator elements have been applied to helicopters up to now (Ref. 2-7). Based on Ref. 8, the present paper outlines the development and testing stage of an effective nodal vibration isolation system for hingeless rotor helicopters.

2. The Isolation System

The MBB concept of a passive rotor isolation system for helicopters is as follows: The helicopter fuselage is dynamically separated from the rotor-transmission unit by use of uniaxial isolator elements which operate according to the antiresonance principle. The isolators are arranged at several points, in different operating directions, as connecting members between main gearbox and fuselage to obtain multi-degree-of-freedom vibration isolation. The number of isolator elements depends on the number of the required degrees of freedom of isolation. The use of uniaxial force isolators offers several advantages:

- mechanically simple design of the isolators
- well-defined separation of the load paths
- universal applicability to different types of helicopters
- mechanical assembly technique for realizing one or more degrees of freedom of isolation.

The single isolator is essentially formed by the parallel arrangement of a spring and a passive force generator. The method of operation is such, that for a certain frequency the dynamic part of the spring force and the dynamic force, produced in the force generator by the relative movement between fuselage and rotor-transmission unit as a result of rotor excitation forces and moments, are opposite and equal at the fuselage side attachment point of the particular isolator element. The dynamic rotor forces and moments are compensated for the most part by inertia loads of the rotor-transmission unit itself.

Such a rotor isolation system has been developed in the MBB ARIS program (ARIS = Anti-Resonance Isolation System). The isolation system which is schematicly shown in Fig. 1, has been adapted to the installation conditions

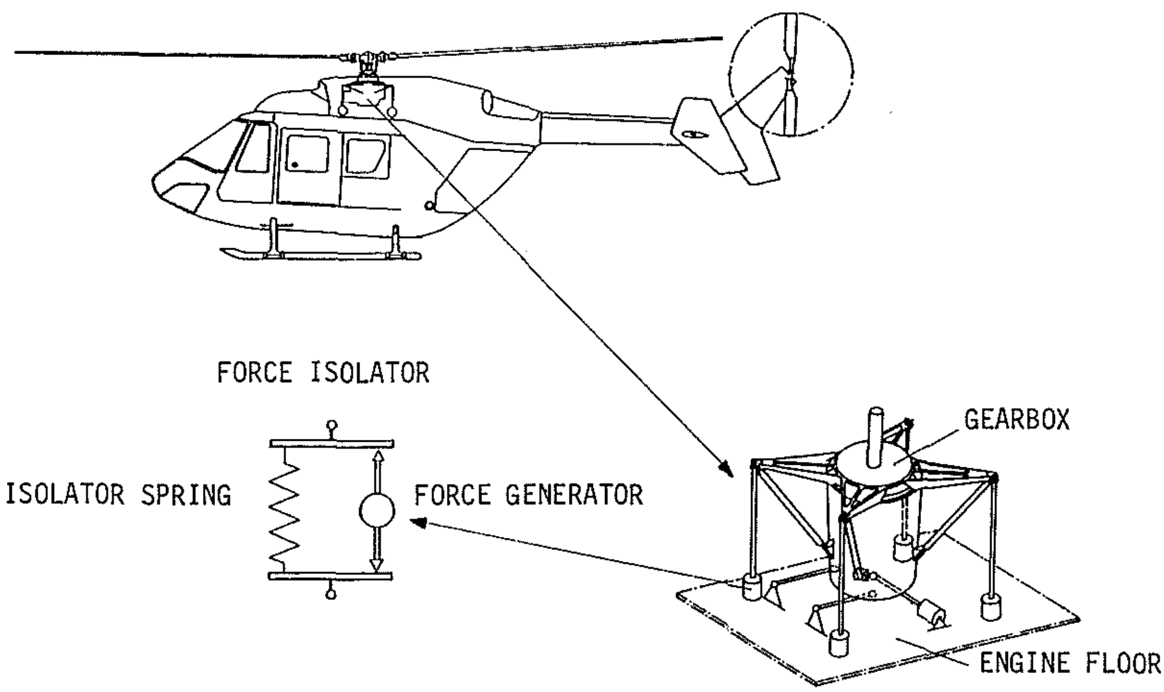

Figure 1: Schematic view of the BK 117 rotor isolation system

of the BK 117 helicopter serving as test vehicle. It consists of four vertical isolators and one lateral isolator and permits the specific isolation of lateral and vertical excitation forces and of roll excitation moments. Due to the longitudinally aligned rotor control rods and due to the engine and tail rotor drive shafts, isolation of the longitudinal axis would not be possible without performing greater modifications at the helicopter. Therefore, two struts which serve to transmit longitudinal forces and rotor torque, are arranged in the longitudinal direction. Since these struts could only be mounted underneath the main gearbox and not at the level of the center of gravity of the rotor-transmission unit which lies approximately at the height of the swash plate, the isolation of excitation moments about the pitch axis is only partially achieved.

To guarantee freedom of movement of the rotor-transmission unit normal to the operating axes of the particular isolator elements, they are joined to the fuselage and the gearbox respectively by so-called quasi-hinges which are "soft" compared with the axial stiffness of the isolator springs and approach the behaviour of ideal spherical bearings. In this way, any play and any friction is avoided in the transmission suspension. The total stiffness of the secondary springs in the transmission suspension which are caused by the quasi-hinges, amounts to about ten percent of the axial stiffness of one isolator element.

As a preliminary investigation, a theoretical functional analysis of this rotor isolation system has been conducted by use of a simple three-dimensional dynamical model idealizing fuselage and rotor-transmission unit by rigid bodies. In between, several uniaxial force isolators can be arranged

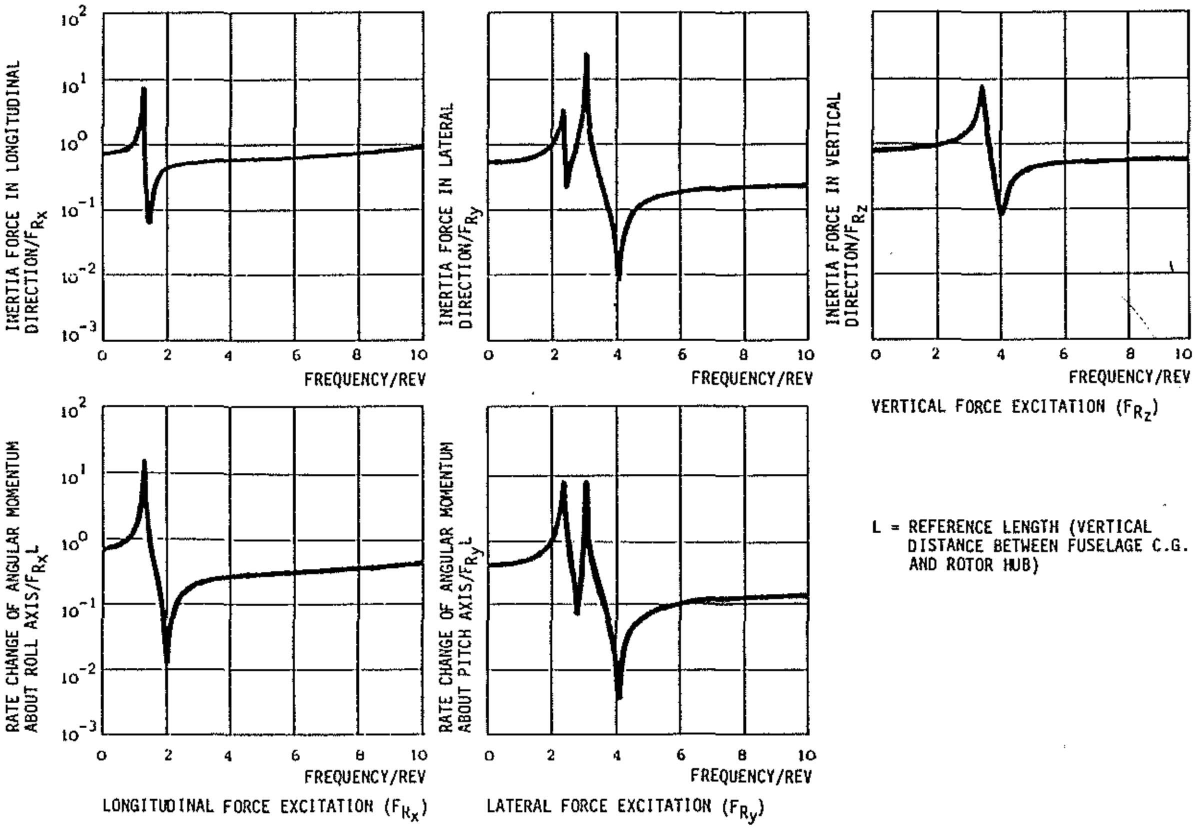

Figure 2: Calculated transmissibilities for force excitation

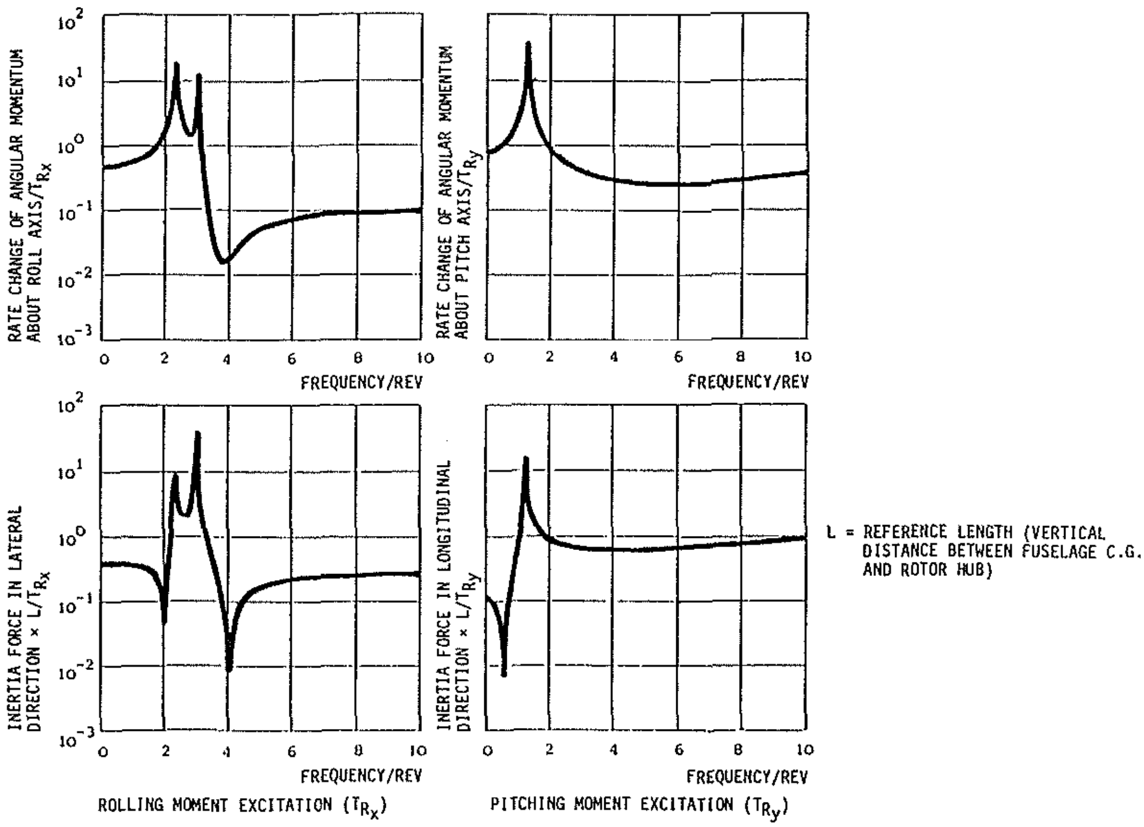

Figure 3: Calculated transmissibilities for moment excitation

in arbitrary operating directions. Secondary stiffnesses which are conditioned by the hingeless transmission suspension, can be simulated by corresponding translational and torsional springs. To consider friction losses in the transmission suspension, parallel dampers have been added to all springs. In quantifying the operating quality of the rotor isolation system, it is useful to compare the inertia loads reacting on the fuselage mass with the particular rotor excitation forces and moments. In Figs. 2 and 3 the calculated amplitude characteristics of the most important transmissibilities are shown. As was to be expected, good isolation efficiency is obtained in case of a lateral, vertical, or roll excitation. Isolation of longitudinal forces and pitching moments is insufficient as a result of the two longitudinally aligned torque struts.

3. The Isolator Elements

Two different types of uniaxial antiresonance force isolators have been developed in the ARIS program (Ref. 8). One of these isolator elements is fitted with a mechanically driven pendulum as force generator. The assembly which is shown in Fig. 4, is intended for installation as one of four vertical isolator elements in the BK 117 helicopter. Two parallel glass fiber composite ring-type springs serve as the isolator spring. The single oval-shaped spring is composed of nine layers. The required stiffness is primarily produced by four layers which are wound of unidirectional glass fiber rovings. To prevent resin bonding damage of the single glass fibers, in particular in the curved

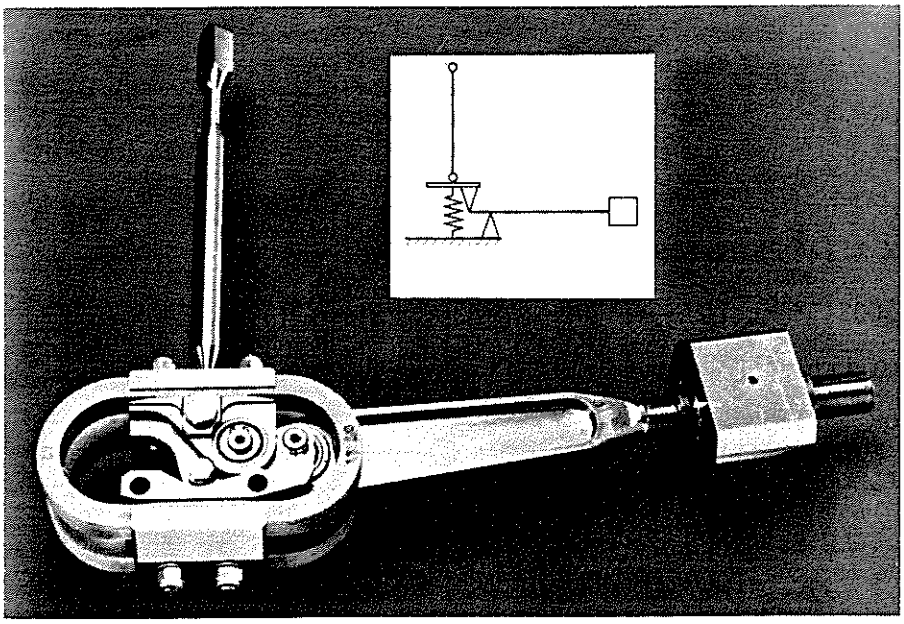

Figure 4: Design of the antiresonance force isolator with mechanical pendulum

zones of the spring, the unidirectional layers are alternately bonded with fabric layers each consisting of 0^{o}, 45^{o}, and 90^{o} oriented glass fibers. The pendulum bar is hinged to the fuselage and gearbox side mountings of the isolator spring by laminated elastomeric bearings. Static rotor loads are transmitted by the isolator springs. As connecting elements between isolator and gearbox, titanium pinned joints with flexible segments at both ends, are used. For fine tuning, the pendulum mass can be shifted on the pendulum bar.

The other isolator version is in principle similar to the isolator described in the preceding section. Fundamentally, it also consists of a parallel connection of a spring and a pendulum possessing, however, an hydraulic transmission. The isolator model with hydraulic force generator which is illustrated in Fig. 5, is designed for application as a lateral isolator in the BK 117 helicopter. The main components are two metal bellows, a tunable pendulum mass, and a supplementary spring. The bellows form a self-contained unit which is completely filled with a water-alcohol mixture. The outer bellows has a wall thickness of 1.6 mm and serves not only for sealing the fluid volume but also as isolator spring and due to its angular flexibility, as isolator-gearbox connecting hinge. The fuselage connection is made by a titanium flexible element screwed on to the isolator. The pendulum weight is fastened to the free end of the inner bellows which has a wall thickness of .25 mm and allows high axial deformations. It is guided in the axial direction by two linear ball bearings. The additional coil spring statically pressurizes the fluid in the bellows system to guarantee that the pendulum mass continuously follows the sinusoidal stroke of the outer bellows. The main advantages of this isolator type are the total symmetrical arrangement of all components performing only translational movements and deformations respectively, the good linearity of the isolator springs, and the very low inherent damping of the entire element.

The effectiveness of both isolator models has been proved by use of an uniaxial functional model. In Fig. 6, the measured amplitude and phase characteristics of the force transmissibilities are shown. The dotted curves

1. GEARBOX ATTACHMENT POINT
2. LOW VISCOSITY FLUID
3. THICK-WALLED BELLOWS AND ISOLATOR SPRING
4. THIN-WALLED BELLOWS
5. LINEAR BALL BEARINGS
6. PRE-LOAD SPRING
7. GUIDE SHAFT
8. TUNING MASS
9. FUSELAGE ATTACHMENT POINT

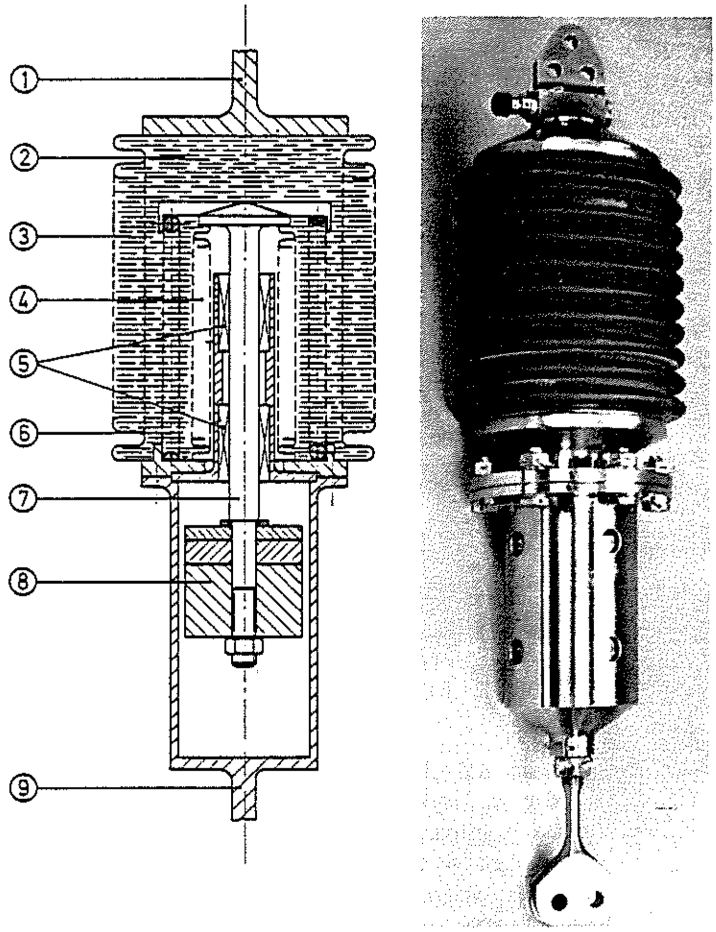

Figure 5: Design of the antiresonance force isolator with hydraulic pendulum

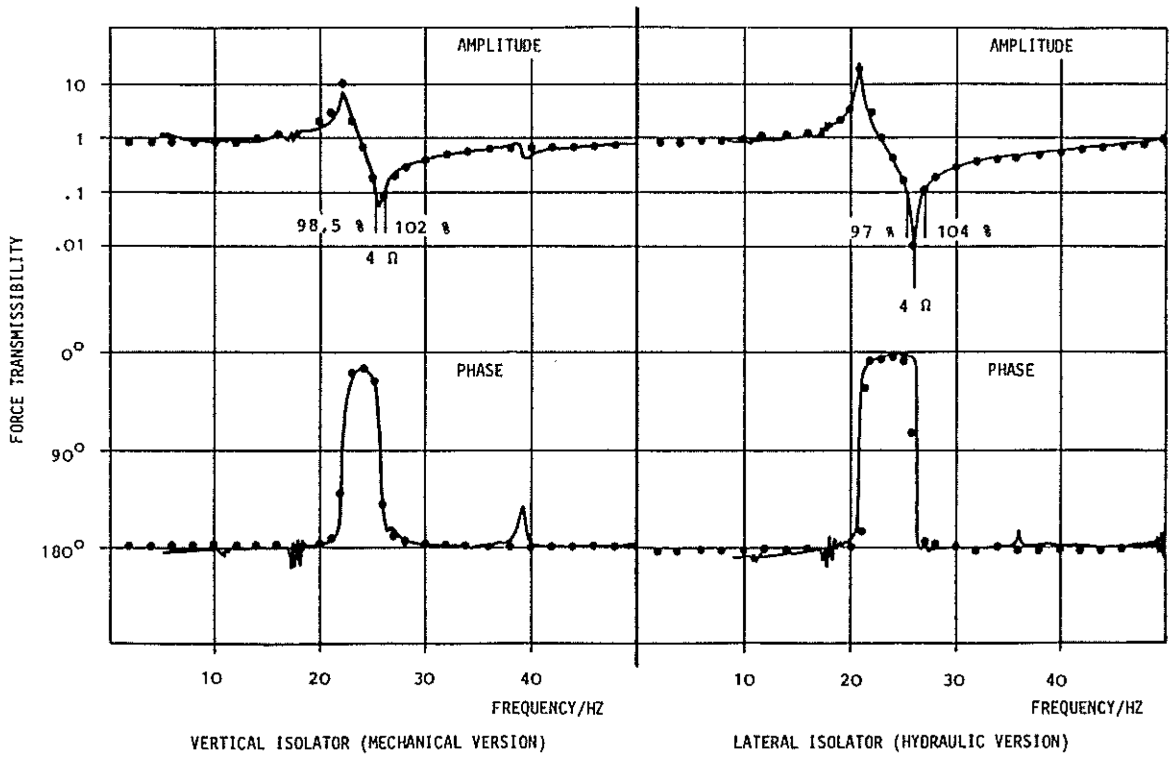

Figure 6: Measured isolator transmissibilities

are theoretical results determined with the aid of suitably idealized equivalent dynamical systems. The essential experimental data are summarized in Table 1. The numerical values which enter the theory, have been determined in separate experiments or taken from manufacturers specifications. Isolation efficiency is particularly excellent with the hydraulic version.

isolator type	mechanical	hydraulic
equivalent fuselage mass /kg	650	
equivalent rotor-transmission mass /kg	135	
total isolator stiffness $/Nm^{-1}$	5.7×10^6	5.5×10^6
static fluid pressure /bar	-	10

Table 1: Isolator bench test data

4. Ground Vibration Test *

The next step in the ARIS program was the ground test of the total system, helicopter plus isolator elements. For that, a set of controlled manufactured components of the rotor isolation system consisting of four vertical isolators with mechanical pendulum (Fig. 7), one lateral isolator with hydraulic pendulum (Fig. 8), and two glass fiber composite longitudinal struts (Fig. 9), has been installed in the BK 117-P2 helicopter. To guarantee the flight safety of the test vehicle, numerous quasi-static and dynamic loading tests have been performed with the isolator assemblies as well as with the critical components (ring-type springs, pendulum bearings, transmission struts, bellows). Before the installation of the isolator elements in the helicopter, they had been separately tuned in the laboratory to the 4/rev rotor excitation frequency (25.5 Hz).

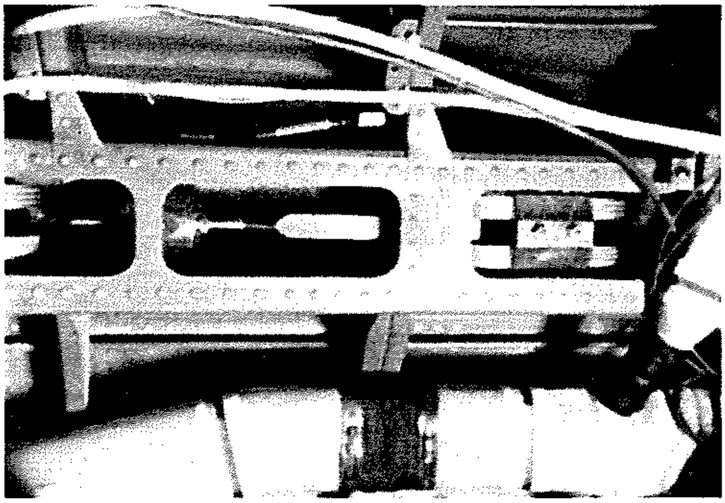

Figure 7: Helicopter installation of vertical isolator (seen from below)

* These experiments have been performed in cooperation with the DFVLR Göttingen.

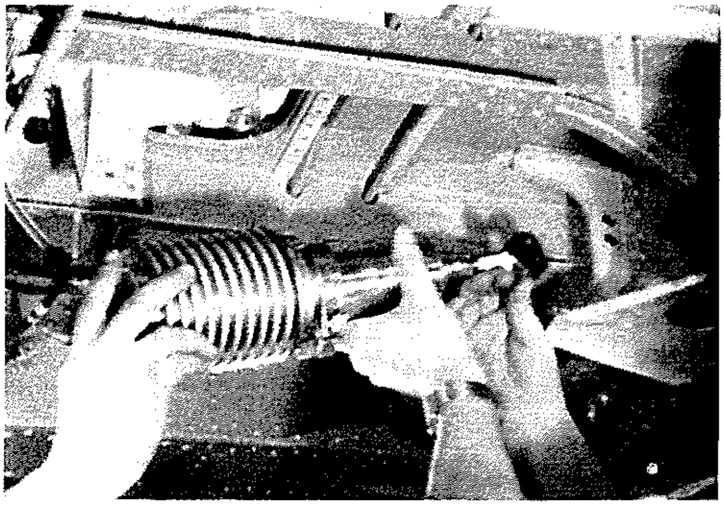

Figure 8: Helicopter installation of lateral isolator

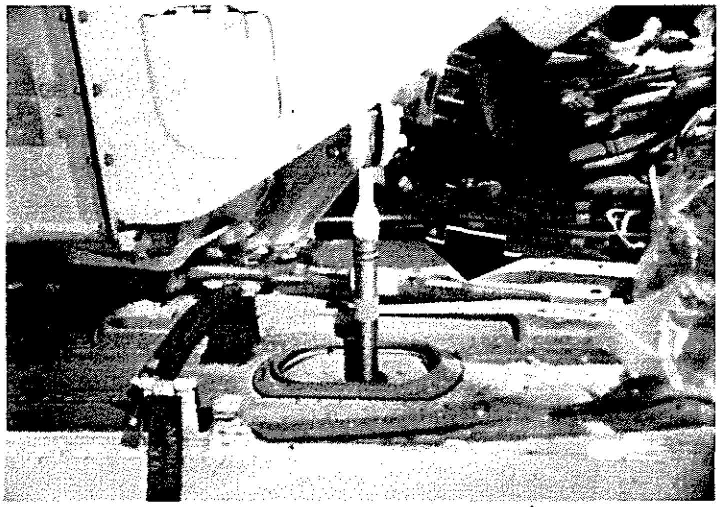

Figure 9: Helicopter installation of longitudinal struts

The function of the vibration isolation system has been proved on the ground by a shake test. The experimental arrangement is shown in Fig. 10. To simulate the free-free condition of the flying helicopter, the test vehicle was suspended by the rotor hub on a weak adjustable air spring (natural frequency below 1 Hz). The rotor excitation was done by use of suitably arranged electrodynamic shakers: two 400 N - exciters each standing on tripods on the right and left hand side of the helicopter to generate a vertical, roll, and pitch excitation respectively (Fig. 11); a 2000 N - exciter hanging on a crane before or beside the helicopter to generate a longitudinal or lateral excitation (Fig. 12). Instead of using the rotor blades for feeding in excitation forces and moments, a I-beam welded cross was mounted on the rotor hub which substitutes at least the weight of the missing blades.

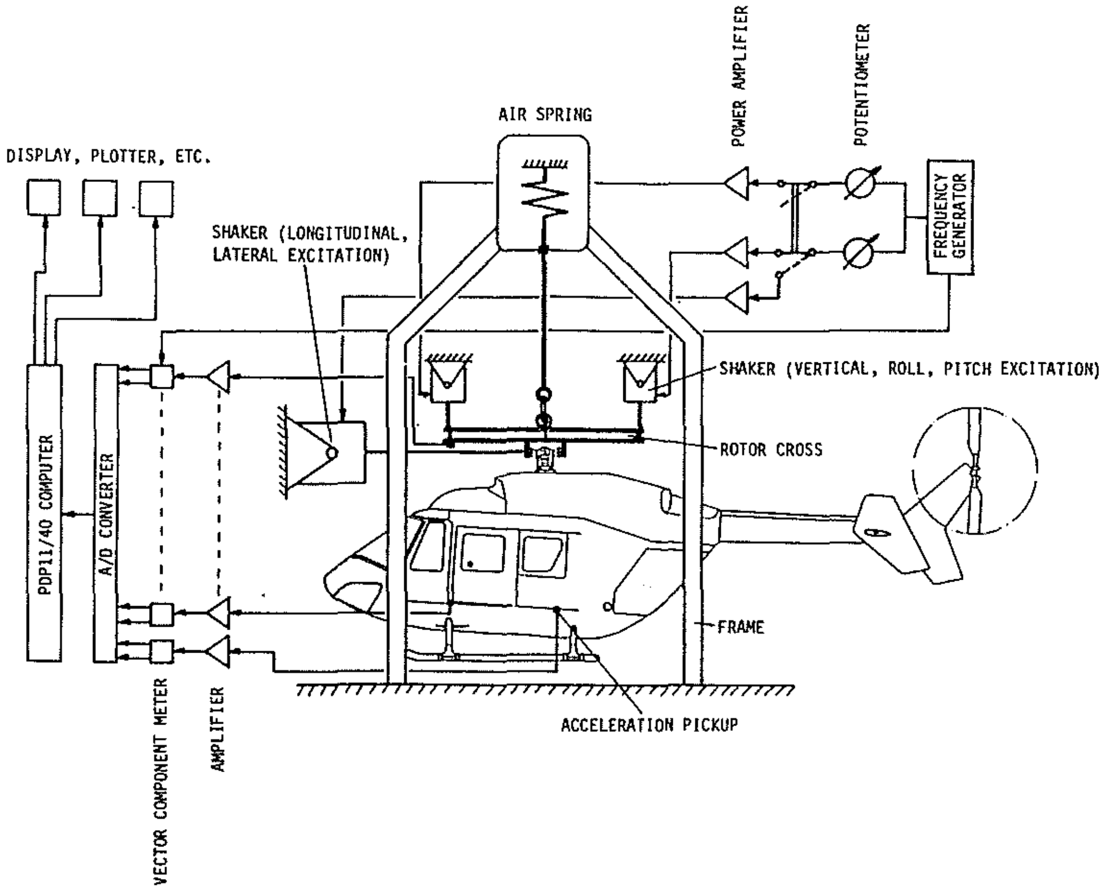

Figure 10: Experimental arrangement of shake test

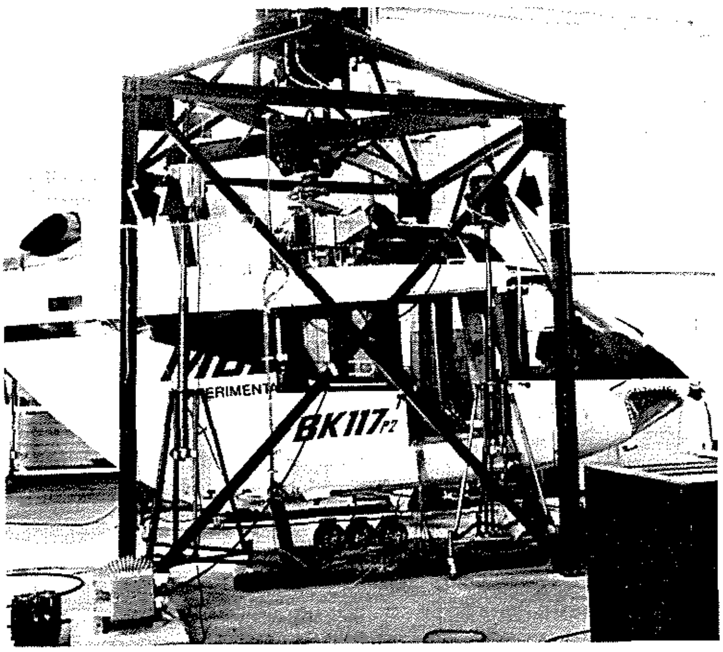

Figure 11: Test setup for vertical, roll, and pitch excitation

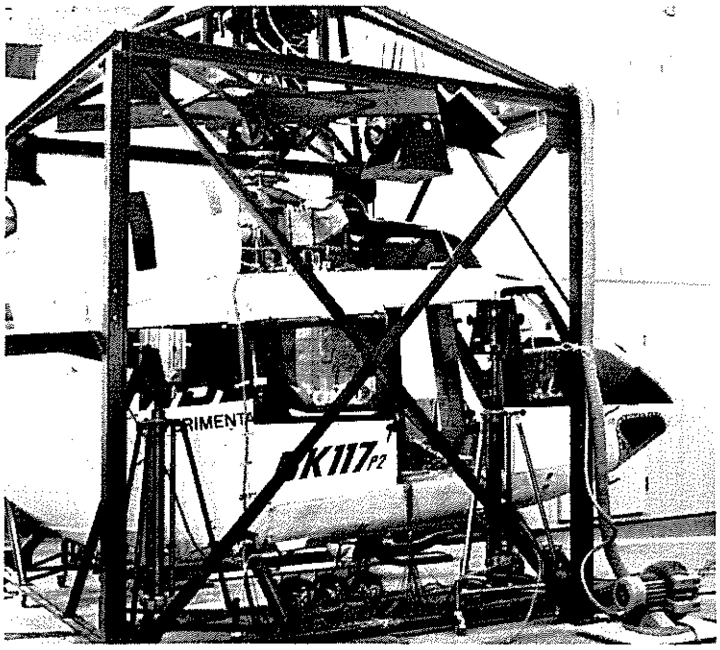

Figure 12: Test setup for longitudinal and lateral excitation

The helicopter was excited successively in the longitudinal, lateral, and vertical direction as well as about the roll and pitch axis at a frequency of 25.5 Hz, equipped with a great number of measuring pickups. The maximum excitation amplitudes were 2000 N longitudinal and lateral, 1300 N vertical, 1400 Nm rolling, and 1000 Nm pitching. The most important results of this shake test are listed below:

- A satisfactory isolation efficiency is obtained for 4/rev lateral, vertical, and roll excitations.

- A 4/rev pitching moment is poorly isolated since the pitching degree of freedom of the rotor-transmission unit against the fuselage is partially restrained by the two longitudinal struts. The fuselage responds relatively sensitively to such excitation.

- The torque struts also restrain the longitudinal motion of the rotor-transmission unit relative to the fuselage, however, the fuselage response to 4/rev longitudinal force excitation is small.

To illustrate these statements, the real and imaginary parts of the accelerations which have been measured at various points of the test vehicle for the different 4/rev excitation forces and moments, are graphically represented in Figs. 13 and 14 (real part: in phase with the excitation; imaginary part: in phase quadrature to the excitation). For the general theoretical understanding of these results, extensive frequency response FEM calculations have been performed to accompany the experiments. Summing up, it may be said that on ground, at idealized test conditions (no elastic rotor blades; non-rotating rotor; separate loading of the rotor hub by the particular excitation components; uni-frequency sinusoidal excitation),

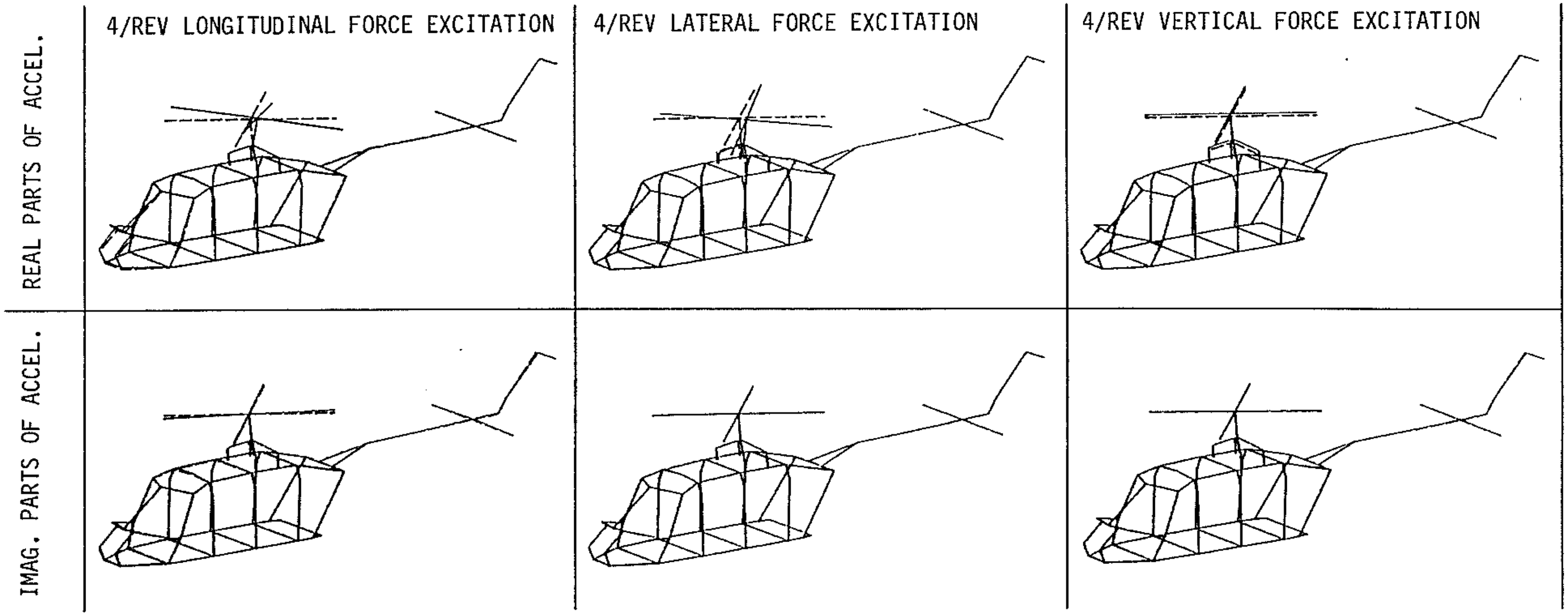

Figure 13: Acceleration response to 4/rev force excitation

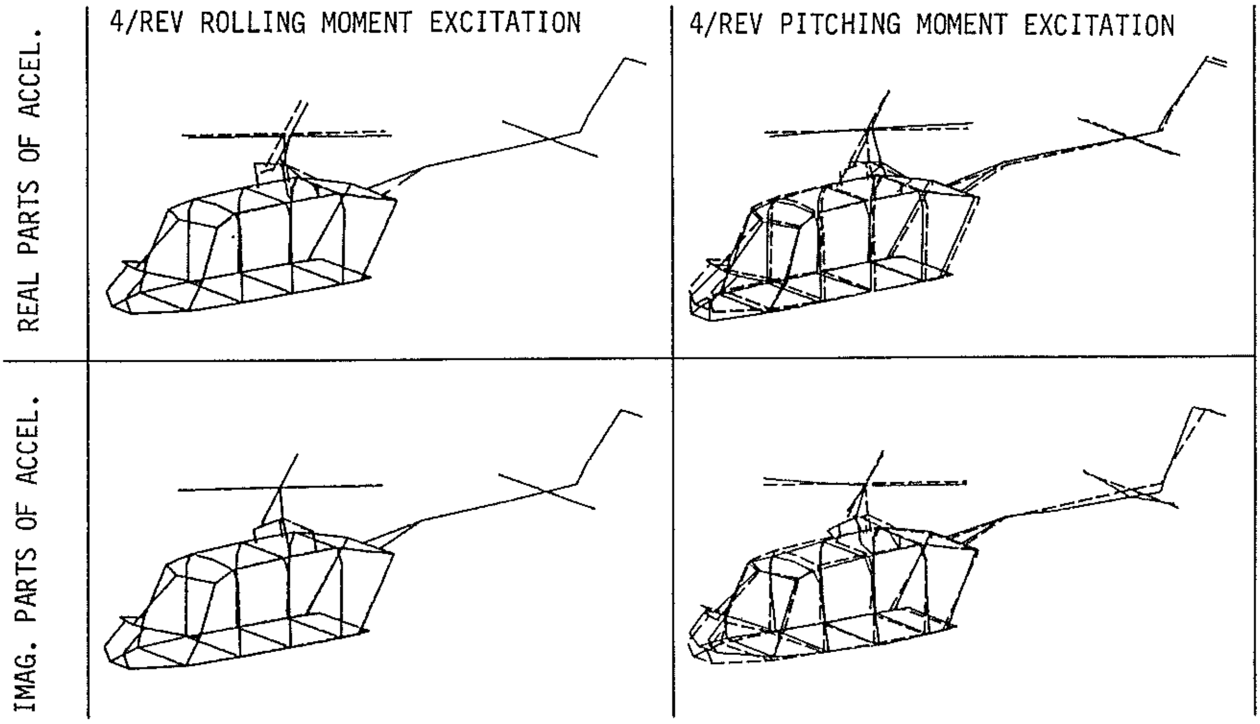

Figure 14: Acceleration response to 4/rev moment excitation

the rotor isolation system has met the requirements. It works well at 4/rev excitations in direction of the built-in degrees of freedom of isolation, and it does not work or it works only moderately - as expected - at excitations in direction of those degrees of freedom which are at least partially blocked by the longitudinal struts.

5. Flight Test Results

Because of the component tests of the essential members and the lack of operational defects during whole helicopter ground vibration test, the safety of the system was confirmed and flight tests with the rotor isolation system were started. They have been done in several configurations:

- vertical isolators active, lateral isolator blocked
- vertical isolators active, lateral isolator active
- vertical isolators blocked, lateral isolator blocked (reference flight).

For these tests, the helicopter was equipped with the following instrumentation:

- acceleration pickups at various points of the fuselage for measuring cabin vibrations
- acceleration pickups at the main gearbox for supervising the gearbox vibrations and for determining the vibrational modes of the gearbox

- resistive wire strain gauges on the connection members between gearbox and fuselage (isolator elements, transmission struts) for measuring the static and dynamic strut forces
- displacement pickups at the isolator elements for measuring and supervising the static and dynamic isolator deflections
- resistive wire strain gauges on the rotor shaft and on the rotor blades for measuring and supervising the rotor loads (rotor excitation).

These measured values have been recorded as a function of the forward flight speed, the load factor, and the collective pitch setting of the rotor blades. In addition, measuring flights with different take-off weights and c.g. positions have been performed. Some representative results of the flight tests reflect the excellent isolation efficiency of the ARIS. In Fig. 15, cabin floor vibrations at the measuring points pilot seat, copilot seat, and aft cabin are plotted versus forward speed. The 4/rev g-levels are shown

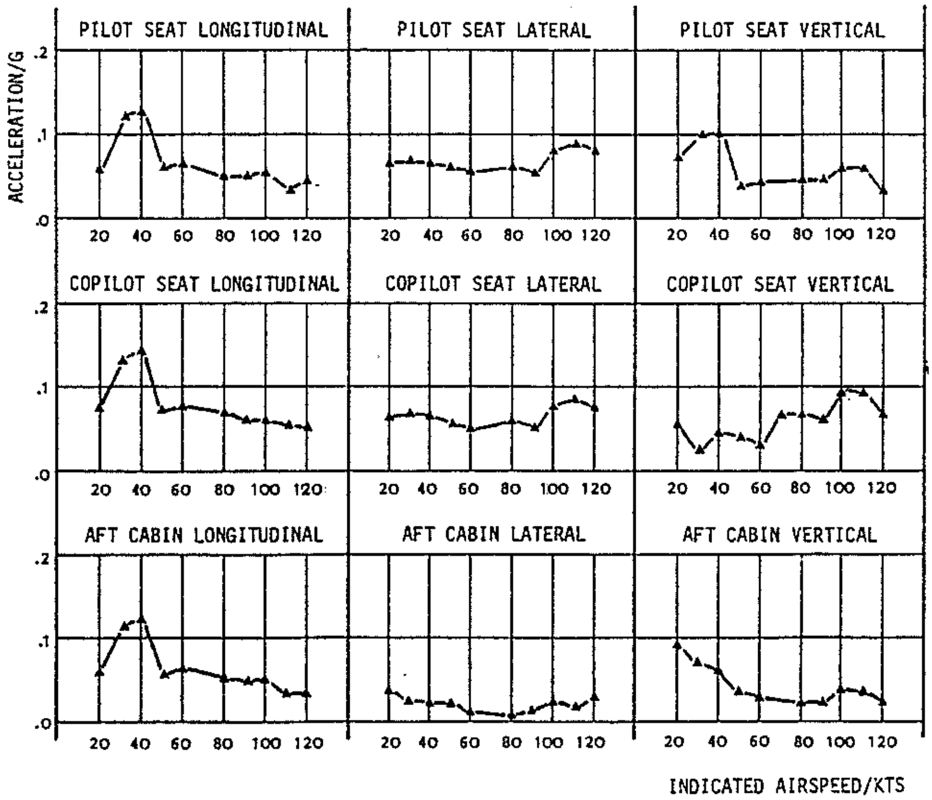

Figure 15: 4/rev cabin vibration versus forward speed

for the longitudinal, lateral, and vertical vibrational components. The results of measurement confirm the subjective impression of the helicopter crews who have characterized the cabin vibration level of the test vehicle in the complete flight envelope (including landing approach) as decidedly low. In the helicopter which was only equipped with four vertical isolator elements, primarily vertical vibrations but also longitudinal vibrations have been reduced. With an additional lateral isolator, also lateral vibrations have been considerably decreased. With the complete isolation system, the 4/rev lateral and vertical vibrations lie below .1 g, the 4/rev longitudinal vibrations lie below .15 g over the whole forward speed range.

In Fig. 16, the 4/rev isolator forces and transmission strut forces respectively with and without rotor isolation system are shown as a function of the forward speed. It becomes obvious that the connecting members between

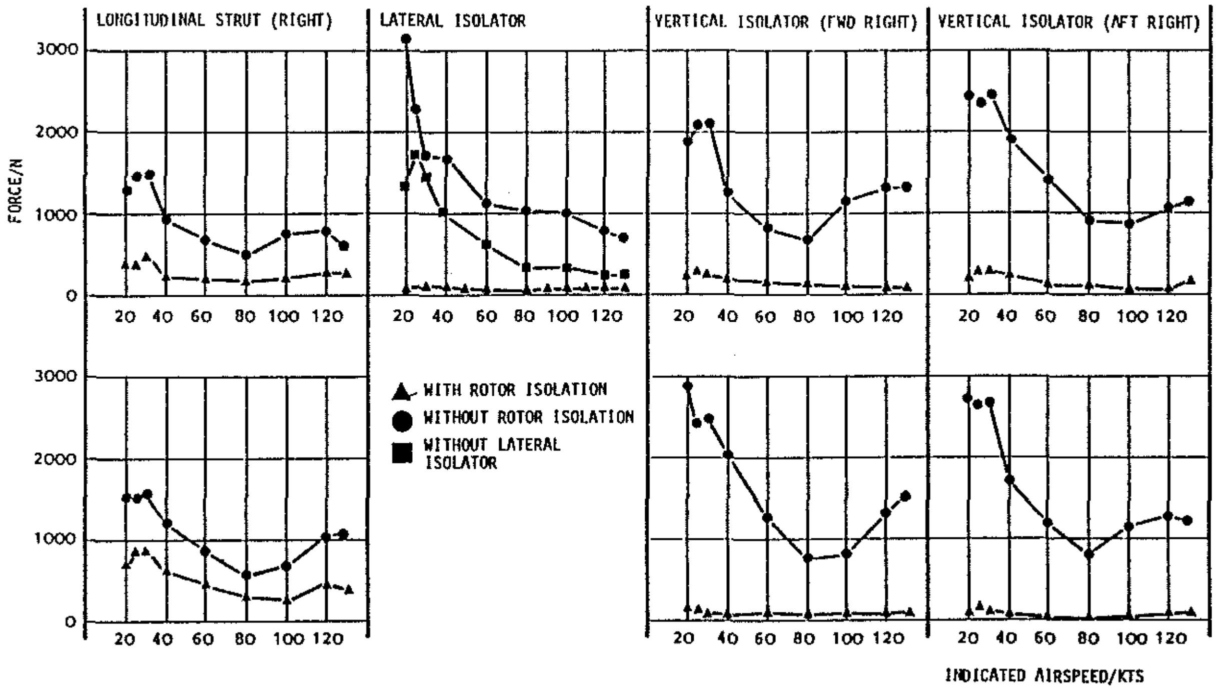

Figure 16: 4/rev transmission strut and isolator forces versus forward speed

gearbox and fuselage which are formed by an isolator element, transmit only extremely low 4/rev forces to the fuselage. But it may also be considered as an advantage of the rotor isolation system that the 4/rev parts of the forces in the two longitudinally arranged torque struts have also been reduced. To demonstrate the operation of the isolators, the 4/rev deflections of the isolator springs are shown in a corresponding manner in Fig. 17. These almost pure 4/rev motions came up to ± .7 mm at the vertical isolators on the right and to ± .5 mm at the lateral isolator in the low speed range. Maximum values of about ± 1.2 mm and ± .9 mm respectively appeared during the landing approach. The isolator deflections for the configuration with lateral isolator lie altogether higher than for the configuration with only vertical isolators.

Fig. 18 gives an impression of the rotor excitation by means of the measuring points flap bending moment (at a radius station of .51 m), lag bending moment (at a radius station of .67 m), and shaft bending moment (.22 m below the hub center) with and without rotor isolation. The given 3/rev, 4/rev, and 5/rev parts all contribute to the 4/rev excitation forces and moments in the non-rotating system. Comparing the results of the two configurations, it is indicated that the excitations are of the same order in consideration of a certain scatter.

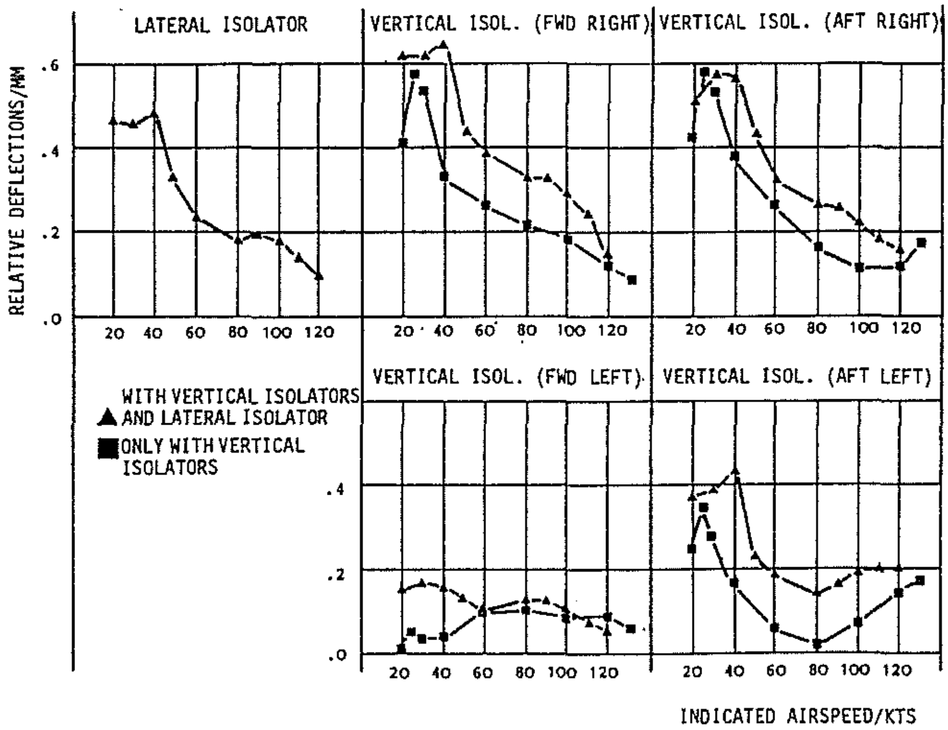

Figure 17: 4/rev isolator relative deflections versus forward speed

6. Conclusions

A passive nodal rotor isolation system which uses uniaxial antiresonance force isolators as connecting members between fuselage and main gearbox for decreasing the rotor induced 4/rev cabin vibrations of a helicopter has been developed to the prototype stage in the MBB ARIS program. With regard to the specific installation conditions in the BK 117 test vehicle, a rotor isolation system has been acquired consisting of four vertical isolators and one lateral isolator for the specific isolation of rolling moments as well as vertical and lateral forces. Two parallel quasi-hinged struts restrain the gearbox in the longitudinal direction. Two different types of uniaxial isolator elements have been applied. One model is equipped with a mechanically driven pendulum and has been designed for vertical installation. The lateral isolator is fitted with a pendulum possessing a hydraulic transmission.

After intensively testing the critical components in the laboratory, the helicopter integrated isolation system has been subjected to a ground operational test, loading the test vehicle by realistic rotor excitation forces and moments by use of suitably arranged electrodynamic shakers. Following, the vibration isolation system has been flight tested. The 4/rev lateral and vertical cabin vibrations are below .1 g in the entire forward speed range. This is also true in case of the longitudinal direction excepting the transition flight region at which a vibration level of .15 g has been measured. The additional weight caused by the rotor isolation system amounts to less than 1% of the maximum take-off weight of the BK 117 helicopter (2850 kg). It is intended to offer the vibration isolation system as an optional equipment for the BK 117 helicopter.

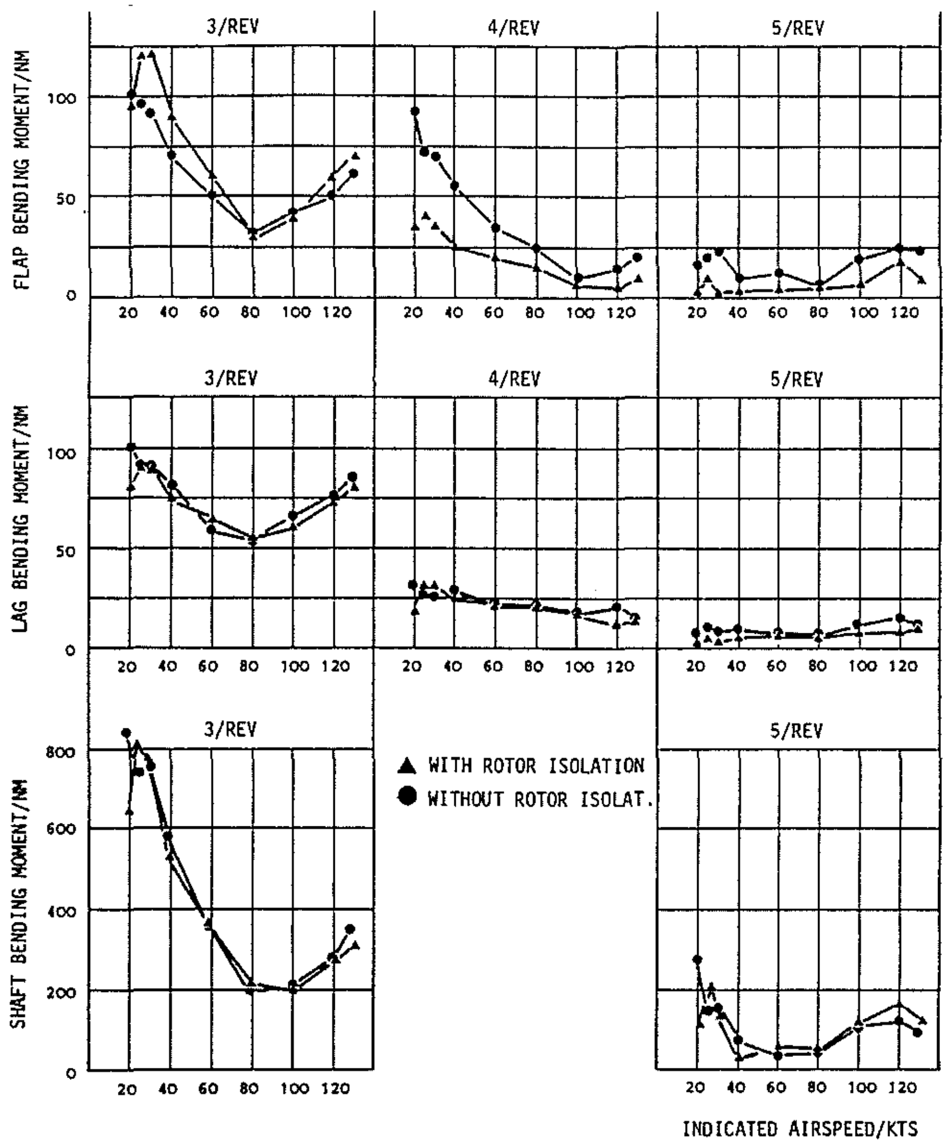

Figure 18: Dynamic rotor loading versus forward speed

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