APPLICATION OF MODERN VIBRATION CONTROL TECHNIQUES ON EC135 AND FUTURE TRENDS

H. Rottmayr, W. Popp, R. Mehlhose
Eurocopter Deutschland GmbH
München, Germany

Abstract

Based on various research activities in the past the new EC135 helicopter is designed and equipped with efficient means for vibration control in order to achieve adequate low cabin vibrations under all operational conditions.

In this paper the applied vibration control techniques are presented in some detail: a passive rotor isolation system with four hydromechanical isolator elements, an auto-tuned cabin absorber and provisions for structural dynamic tuning of both the rotor and the airframe. The resulting vibration levels including the comfort assessment according to ADS-27 are discussed, too. The presented results are typical for the performance of current vibration control technology.

Furthermore this report contains an overview of future vibration reduction activities at ECD by means of active systems. Current research is mainly concentrated on a new generation of actuators based on strain induced piezoelectric actuation materials. The influence of multi-axis isolation for improving the vibration comfort is also investigated under consideration of complexity and costs. The potential of active systems for vibration reduction also depends on the controller design. Following modern trends in disturbance rejection control theory, optimal output vector feedback control in the time domain is applied.

The results in this paper demonstrate how current vibration technology can be further improved by new actuation concepts in the future.

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1 Introduction

The EC135 as shown in Fig.1 is a newly developed, twin engine light helicopter certified and serialized in 1996. The main features of this aircraft which is one of the most progressive in its class, are a bearingless main rotor system (BMR), a very safe capsuled tail rotor (FENESTRON), a high performance anti-resonant isolation system (ARIS), two engines with a full authority digital engine control (FADEC) and modern MMI technologies ("New Avionics"). A detailed description is given in [1], [2].

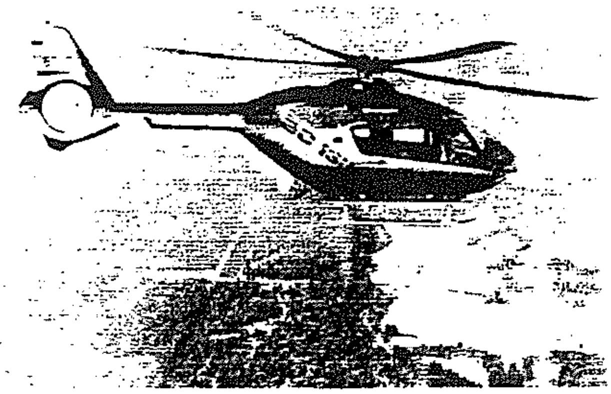


Fig. 1: EC135 Helicopter In Flight

In this paper the vibration control techniques of the EC135 are discussed in some detail with emphasis on the aforementioned passive rotor isolation system and on a lateral cabin absorber. It will be shown that these means –combined with careful structural tuning of both rotor and fuselage modes– are able to provide adequately low cabin vibration levels of about 0.07g at level flight.

The important role of vibration control in the development of helicopters can be judged from Fig.2, which is based on [3].

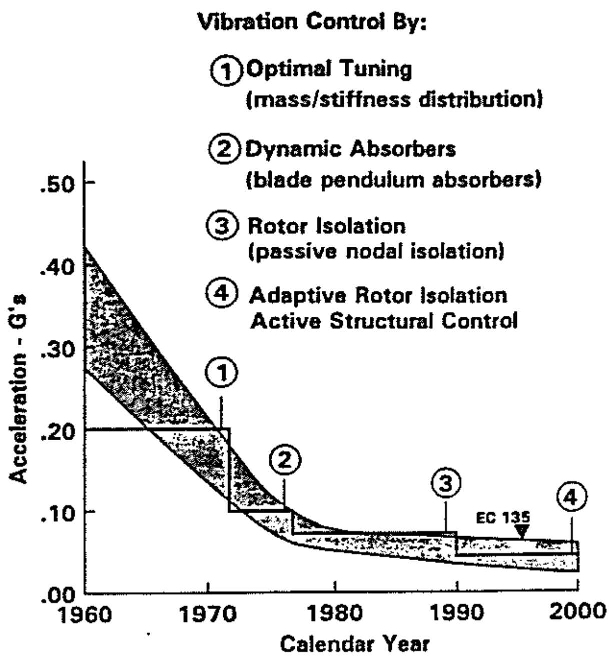


Fig. 2: Efficiency of Helicopter Vibration Control Technology

According to this graph, the EC135 acceleration levels are in the predicted trend. The EC135 vibration comfort is mainly achieved by using consequently ECD's long term research activities on passive nodal isolation systems. It should be mentioned that the EC135 belongs to the first commercial helicopters equipped with this advanced technology.

Based on various theoretical and experimental investigations at Eurocopter (see [4], [5] and [6]), it can be concluded that further improvements with respect to helicopter vibration comfort are difficult to obtain without the support of active means.

It is commonly accepted that the application of adaptive rotor isolation and active structural control is one promising technology in order to fulfill the stringent vibration requirements of the customers in the future.

Alternative active technologies which are applied in the rotating system (e.g. Individual Blade Control) are currently investigated, too. The discussion of these techniques is beyond the scope of this paper.

2 EC135 Vibration Control

Generally the airframe blade-number-harmonic vibrations are caused by the transmitted vibratory main rotor hub loads. These loads strongly depend on the type of the rotor system and the blade structural dynamic tuning. ECD's hingeless (BO105, BK117) and bearingless (EC135) main rotors transmit both inplane and out-of-plane vibratory forces and shaft bending moments. According to these general facts the reasoning for the selected EC135 vibration control means, the various development steps and the validation tests are presented in the following sections.

2.1 Applied Vibration Control Technology

In the past various designs of rotor isolation systems have been investigated at ECD. For ECD's four-bladed main rotors the isolation system has to prevent mainly the transfer of the 4/rev vibratory rotor excitations to the airframe structure. A very effective solution is the passive rotor nodal isolation approach.

The selection of the EC135 vibration control techniques (Fig.3) is based on the successful flight testing of different anti-resonant nodal isolation systems at ECD and analogue experience with cabin absorbers at ECF.

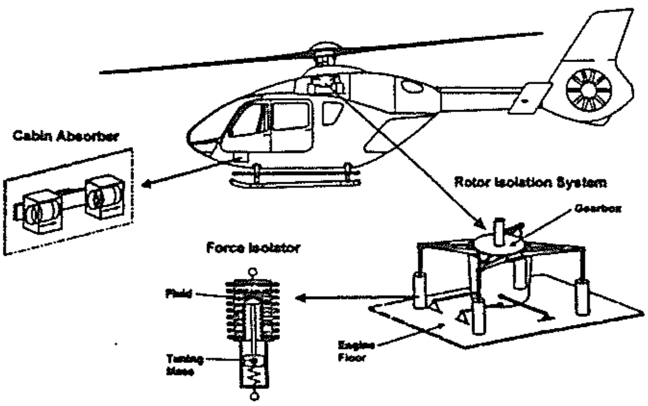


Fig. 3: EC135 Vibration Control Means

Two rotor isolation systems were investigated in detail (see [7] and [8]):

⇒ BK117 with 4z and 1y isolators and

⇒ BO108 with 4z isolators (the BO108 was the predecessor of the EC135).

From the analysis of these tests the following conclusions could be drawn:

⇒ Efficient overall airframe vibration reduction can be achieved by using four vertical force actuators.

⇒ High lateral cabin vibrations due to lateral bending and warping deflections which are typical for light helicopters, can be rejected by a lateral underfloor auto-tuned absorber.

It should be mentioned that the vibration control concept illustrated in Fig.3 takes into consideration the design restrictions for light helicopters:

⇒ Small gearbox/isolator geometry, as a result from the demand for interior dimensions as large as possible (e.g. cabin height).

⇒ Uniaxial isolators which can replace conventional z-struts.

⇒ Lateral absorber as "alternative" to the lateral isolator (design constraints).

A short technical description of the applied vibration control means is given next.

Anti-Resonant Rotor Isolation System (ARIS): The EC135 ARIS system consists of four vertical uniaxial hydro-mechanical isolators, which substitute the vertical gearbox struts. The very compact arrangement is illustrated in Fig.4.

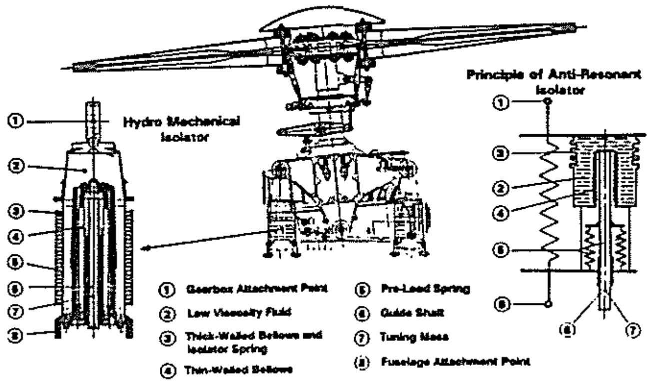


Fig. 4: EC135 Anti-Resonant Rotor Isolation System (ARIS)

The mechanical principle of the hydro-mechanical isolator (Fig.4, right) is similar to the well known isolator with mechanical pendulum, with the exception of a pre-load spring for avoiding cavitation. According to [7] the method of operation is as follows: The stroke of the primary thick-walled bellows –caused by a periodical movement between gearbox and fuselage– generates an enlarged stroke of both the secondary thin-walled bellows and the tuning masses. The resulting inertia forces produce a pressure change in the low viscosity fluid, resulting in dynamic forces upon the fuselage and gearbox attachment points, respectively.

A photo of the complete ARIS isolator and the bellows is shown in Fig.5. The most important isolator data are gathered in the table below:

ARIS Force Isolator Data	
total length - mm	389
max. diameter - mm	118
max. stroke[1)] - mm	5
dyn. displacement ampl.[2)] - mm	0.5
support stiffness - kN/mm	5.0
hydr. amplification ratio -	8.3
total mass - kg	9.5
anti-resonant frequency - Hz	26.3

[1)] limited by hard-over stops
[2)] required for isolation

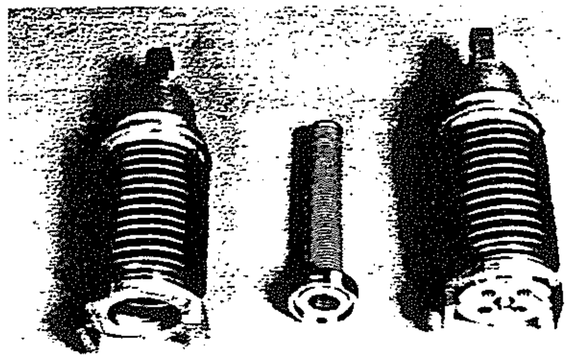


Fig. 5: EC135 Isolator and Bellows

Auto-Tuned Cabin Absorber: The lateral dual-leaf absorber is installed under the copilot seat. Each absorber mass consists of a housing and a movable mass driven by a stepper motor for automatic tuning and rpm-adaption (see Fig.6). The design concept is based on [9].

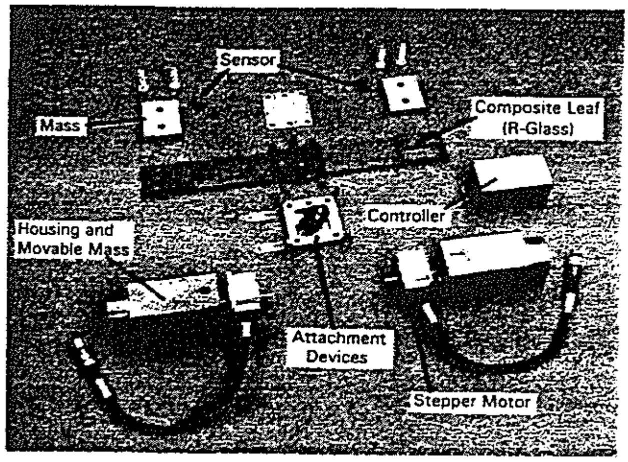


Fig. 6: EC135 Auto-Tuned Cabin Absorber

The housings are attached to a composite spring (R-Glass). The controller adapts the acceleration phase angles between the absorber attachment point and the absorber masses (phase-lock-loop-filter-type control). Some absorber data are shown in the following table:

Auto-Tuned Absorber Data	
total length - mm	500
total mass - kg	10
effective absorber mass - kg	2 x 4.4
movable mass - kg	2 x 1.2
leaf stiffness (R-glass) - kN/mm	0.19
max. counteracting force - kN	1.0
tuning frequency range - Hz	26.3 ± 1.8

2.2 Bench and Shake Tests

Due to the complexity of the vibration reduction task, the validation of theoretical concepts by comprehensive bench and shake testing is a necessity for success.

Bench Testing: Since the beginning of rotor isolation development at ECD, the test rig of Fig.7 is used for experimental studies on passive as well as active nodal force isolators. The test rig consists of a rigid two-body helicopter mass model representing rotor/gearbox and fuselage, the isolator itself connecting both masses, a very soft air spring attachment for generating the "rigid-body-mode" and an electrodynamic shaker simulating vertical rotor force excitation. This arrangement turned out to be best suitable for the assessment of isolation performance. Besides research activities this test rig is also used for tuning purposes of the EC135 production isolators.

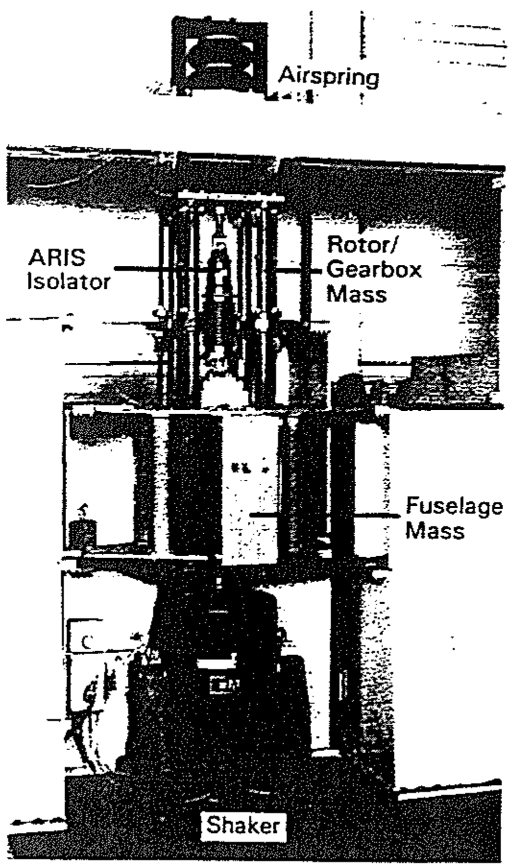


Fig. 7: Test Rig for Pasive and Active Isolator

The EC135 anti-resonant isolator element consists of the following two general components:

⇒ The passive force generator realized by a hydro-mechanically driven mass.

⇒ The support spring realized by a metal bellow.

At a certain excitation frequency of this device, the dynamic spring force is counteracted by the inertia force. Thus, complete harmonic disturbance compensation can be realized assuming absence of damping and linear behaviour of the components. The isolator performance is demonstrated by the plots of Fig.8, showing typical force transmissibilities.

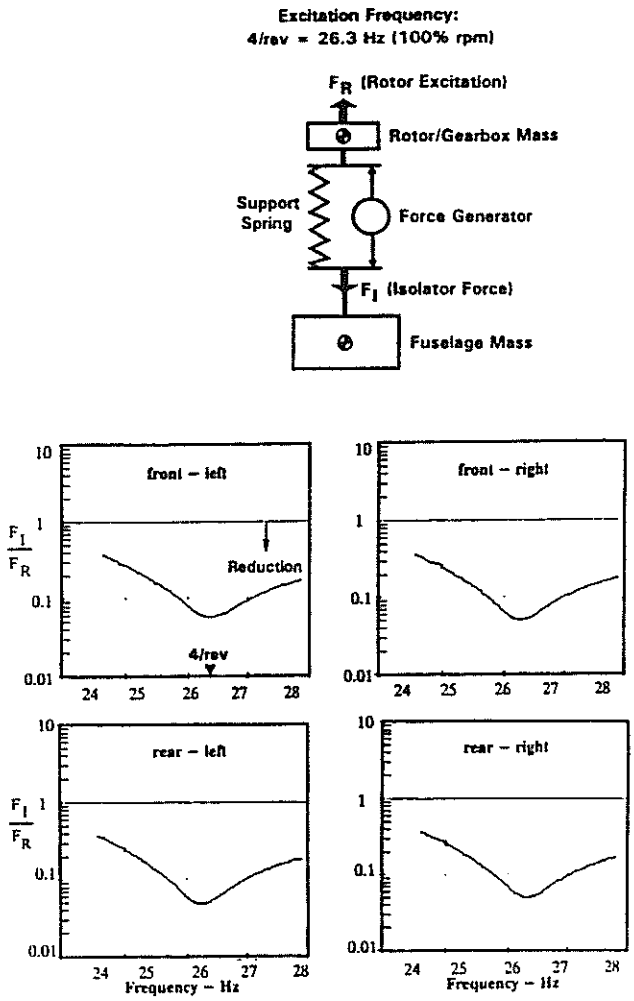


Fig. 8: EC135 Isolator Transmissibilities (Test Rig Results)

The required isolator tuning (anti-resonant frequency equals 4/rev) is checked by those bench tests. The test results show that at the anti-resonant frequency a force transmissibility of 0.05 is achieved, i.e. only 5% of the disturbance is transmitted to the fuselage. The above discussion of the EC135 hydro-mechanical isolator reveals that a "force node" is generated at the anti-resonant frequency.

Shake Testing: The structural dynamic characteristics of the helicopter airframe including all vibration reduction devices are evaluated by finite-element modelling and validated by shake testing. The setup of the EC135 shake test with soft hub suspension is presented in Fig.9.

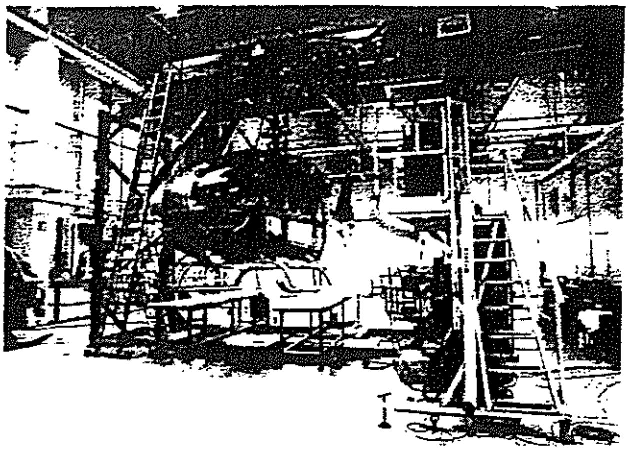


Fig. 9: EC135 Shake Test Configuration

The dynamic tests were performed at ECD in cooperation with the DLR, Göttingen [10]. Both modal data and frequency response curves were measured and analyzed.

The applied finite-element model (NASTRAN) of the EC135 is shown in Fig.10.

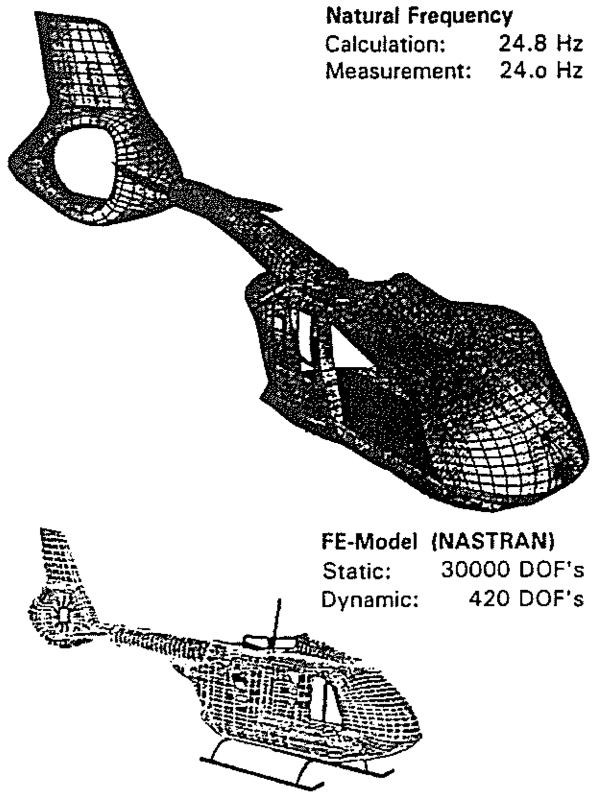


Fig. 10: EC135 Lateral Mode Shape in the Neighbourhood of 4/rev

The knowledge of the airframe mode shapes and the corresponding natural frequencies is of fundamental importance for the interpretation of frequency response data and for the structural dynamic tuning.

The plot of Fig.10 shows the lateral bending/warping mode shape of the EC135 in the neighbourhood of 4/rev. This mode could be verified reasonably well by the shake test. The natural frequency is about 24 Hz, which is adequately separated from the 4/rev vibration excitation. As already mentioned, this type of mode determines mainly the cabin vibration levels in lateral direction. The dynamic calculations indicate that a similar mode is located at about 29 Hz. Thus the current tuning of these modes is a satisfactory compromise.

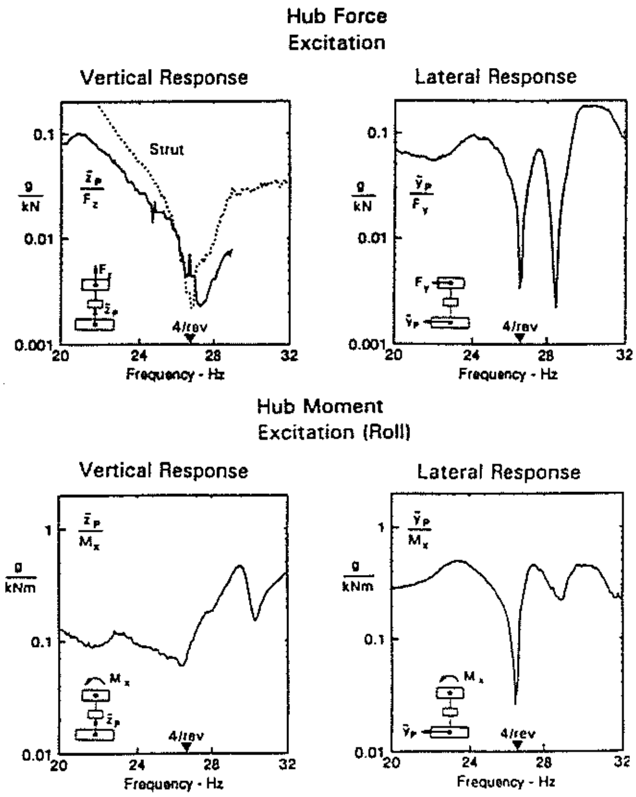


Fig. 11: EC135 Acceleration Transmissibilities at Pilot Seat (Shake Test Results)

For checking the efficiency of the anti-vibration devices (ARIS and cabin absorber) different hub force and moment excitations were applied to the EC135 by electrodynamic shakers. In Fig.11 selected results at the pilot seat are presented in the interesting frequency range of (20÷32) Hz. These measurements demonstrate the complexity of the cabin acceleration response and the efficiency of the chosen vibration control means at 4/rev:

⇒ The ARIS generates a broad notch in the vertical acceleration response and reduces the overall vibration level.

⇒ The lateral cabin absorber produces a pronounced but "small" notch in the lateral acceleration response. The auto-tuning capability of the absorber is required for "stabilizing" the absorber effect at different rotor speeds.

The flight test results to be discussed in the next section will show whether the selected vibration control devices are sufficient for achieving low vibration levels as demanded by the customers.

2.3 Flight Tests and Calculations

During the development and verification of the EC135 helicopter comprehensive vibration measurements were conducted, accompanied by calculations. The succeeding results are selected to highlight the main vibration characteristics with emphasis on forward flight conditions.

4/rev Hub Loads: The vibratory hub loads and moments strongly depend on the tuning of the higher blade bending modes. Therefore the bearingless rotor of the EC135 was carefully tuned in order to minimize vibration excitation, see [11]. The 4/rev hub load amplitudes are presented in Fig.12. These data are derived from strain gauge signals using advanced load estimation techniques.

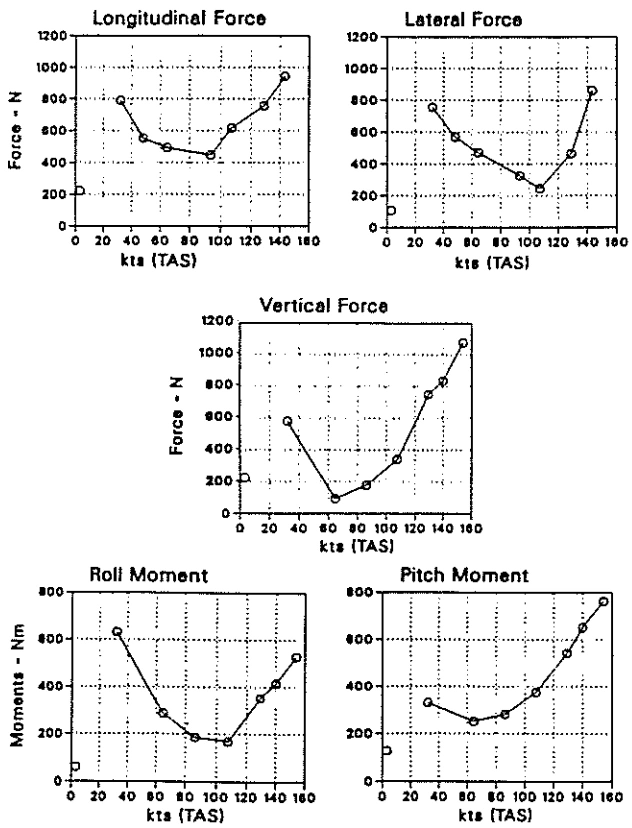


Fig. 12: EC135 Vibratory 4/rev Hub Loads (Level Flight)

4/rev ARIS Displacements and Attachment Vibrations: The four vertical ARIS elements were designed for 4/rev amplitudes of ±0.5 mm. In Fig.13 the measured displacements of the four isolators are plotted showing the different dynamic loadings. In level flight the displacements remain well below the design values; this result corresponds with finite-element predictions.

Typical 4/rev gearbox/fuselage accelerations at the ARIS attachment points are also presented in Fig.13. The vibrations are reduced to a "constant" level of about 0.1g independent of the strongly varying load situations (compare Fig.12). The attachment accelerations are reduced by a factor up to seven.

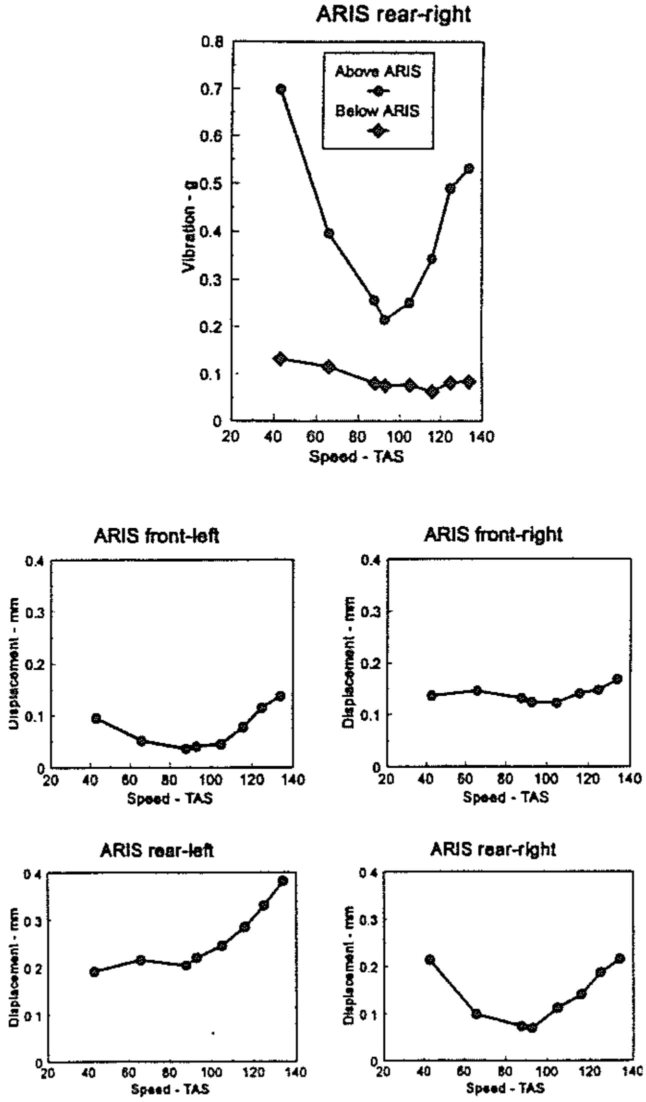


Fig. 13: EC135 ARIS Measurements (Level Flight) 4/rev Displacements and Attachment Vibrations

Pilot Seat Vibrations: The 4/rev and 8/rev pilot seat vibrations in x,y and z-directions are shown in Fig.14 for forward flight speeds up to 140 kts. On the left side of the figure the measured and calculated 4/rev vibrations are compared. The calculations are based on the finite element model of Fig.10 and the hub loads of Fig.12. The predicted vibration levels are in reasonable agreement with the flight test data.

demonstrated in Fig.15. While the vibration levels in x and z direction are mainly determined by the broad ARIS notch, the lateral vibrations depend strongly on the tuning of the lateral cabin absorber. The benefits of the auto-tuned absorber are clearly shown by the processed lateral vibration data.

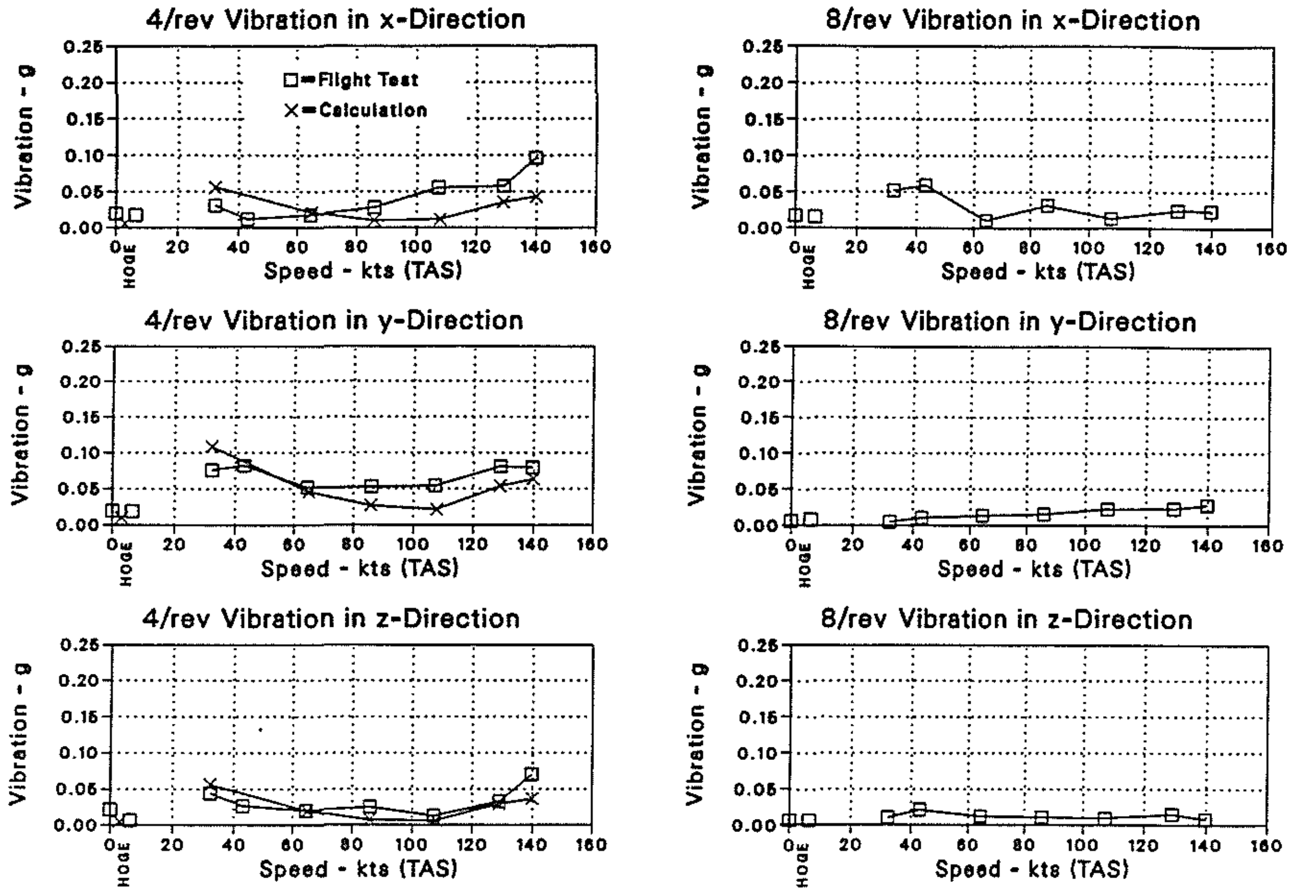


Fig. 14: EC135 Vibrations at Pilot Seat (Level Flight)

From Fig.14 the following g-levels at v_H (140 kts) can be extracted:

	4/rev	8/rev
x-direction	0.10g	0.03g
y-direction	0.08g	0.03g
z-direction	0.07g	0.02g

Both the 4/rev and 8/rev values demonstrate the good vibration characteristics of the EC135 helicopter.

4/rev Pilot Seat Vibrations at Different Rotor Speeds: The rotor speed of the EC135 varies in the range of (98÷104)% nominal rotor speed. The influence of rpm variations at 120 kts is

Vibration Comfort Assessment: In order to complete the EC135 vibration overview, the 4/rev vertical cabin vibrations at different stations are presented in Fig.16 (left). The measured vibration levels are compared again with the calculated data. Obviously the copilot vibrations are underpredicted. The plots confirm that the applied anti-vibration technology is adequate to keep the 4/rev vibrations below 0.1g.

Modern assessment of vibration comfort is expressed by the intrusion index, defined in the US Army ADS-27 standard, see [12]. The intrusion index judges the comfort by taking into account human factors in dependence of frequency and direction. Adopting this approach to the EC135, the values for the intrusion index are between 0.5 and 1.0, see Fig.16 (right). The ADS-27 limit is defined by an intrusion index of 1.0, values of 0.5 are assessed as excellent due to ECD's experience.

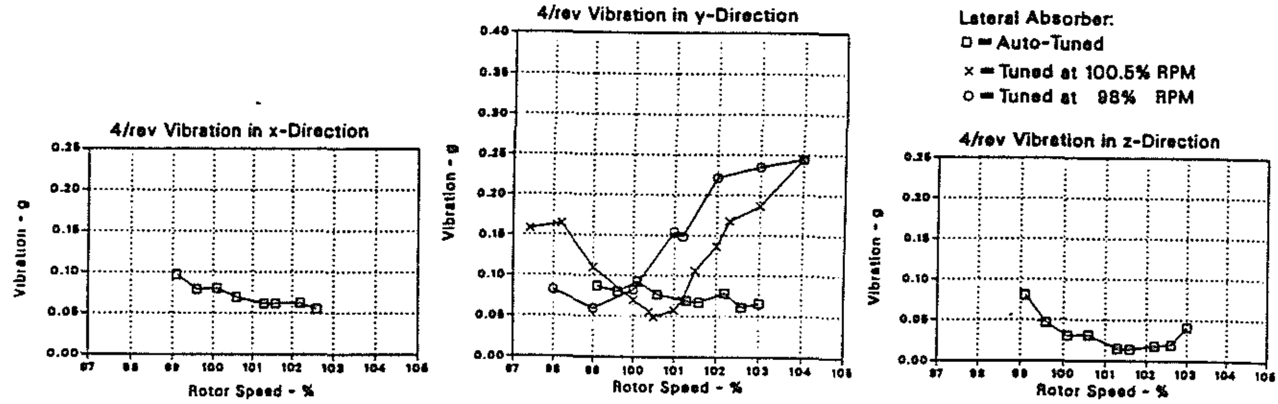


Fig. 15: EC135 Vibration at Pilot Seat (RPM Range at 120 KIAS Level Flight)

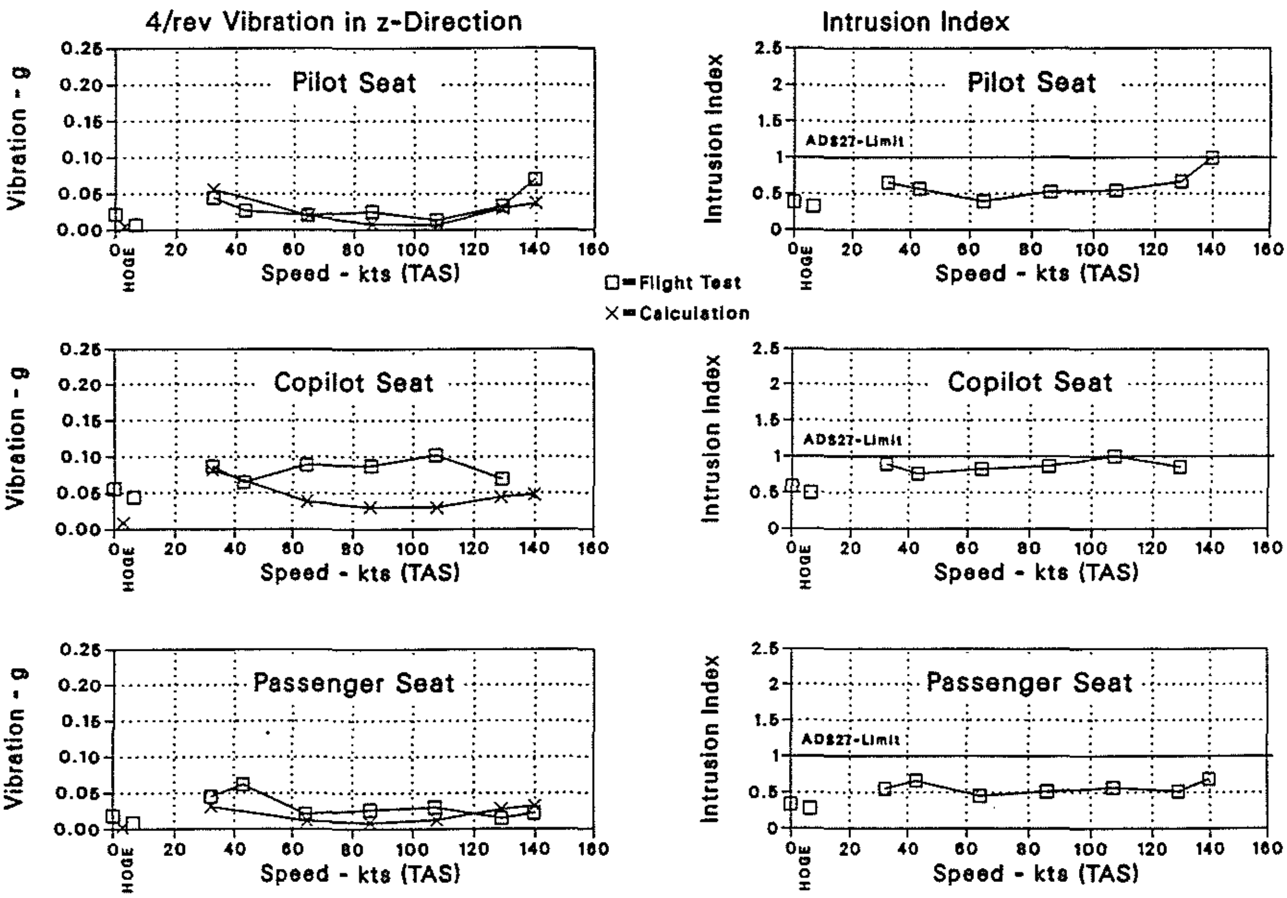


Fig. 16: EC135 Vibration Characteristics (Level Flight)

3 Improved Vibration Control by Active Means

With the adoption of the ADS-27 stringent vibration control requirements for the next generation of helicopters, vibration levels have to be further reduced in order to achieve an intrusion index well below 1.0 for good comfort assessment. Obviously this is a demanding goal requiring further improvements of vibration control techniques. At the helicopter industry two concepts in the non-rotating frame are forwarded:

⇒ Improving current passive rotor isolation systems with respect to multi-axis vibration reduction and adaptive tuning capability.

⇒ Application of active vibration control technology using advanced force actuators interfacing gearbox unit and airframe.

As already mentioned in the introduction, the application of active force isolators seems to have the potential to realize "jet-smooth" helicopters in the future.

3.1 Active Control Concepts

Force actuators replacing conventional gearbox struts are used for the realisation of the following two control concepts (see Fig.17):

⇒ Active Rotor Nodal Isolation with collocated isolator/force sensor constellation.

⇒ Active Control of Structural Response (ACSR) with remote acceleration sensors.

At a first view both concepts seem to be very similar, but they have quite different applications and advantages. This is explained best by the indicated control goals and the function of the active devices: isolator vs. actuator

Active Nodal Isolation: With the nodal isolation concept the rotor disturbances are completely compensated by the rotor/gearbox inertia loads accompanied by zeroing the transmitted isolator forces. Nodal force isolation leads to overall fuselage vibration cancellation in case of replacing all gearbox struts by isolators. This concept was investigated in some detail at ECD in the late seventies (see [13], [14]).

Active Structural Control: The ACSR concept applies "secondary" forces for minimizing the airframe accelerations at specific locations. These secondary forces are generated by the actuator using the rotor/gearbox unit partly as inertial mass ("inertial actuator"). The ACSR approach has proven to be beneficial in case of using a limited number of actuators. This concept was initially developed by Westland in the eighties and proposed for the EH101 (see [15], [16]).

Time Domain Feedback Controller: Both active vibration control systems (nodal isolation and ACSR) can be solved by the "Internal Model Principle" [17] using appropriate servo-compensators in the output feedback. For harmonic (sinusoidal) disturbances, the servo-compensator represents simple oscillators in the open loop. The resulting multi-frequency notches in the closed loop system depend on the applied gains. (High gains may require special control effort for stabilization). Thus the servo-compensator (with rpm-adaption) establishes transmission zeros in the closed loop at the blade number harmonic frequencies. The theoretical background for this robust disturbance rejection controller in the time domain is outlined in [18] and [19]. This type of controller was used for the experimental investigations on nodal isolation in [14] and for the analytical studies on ACSR in [20].

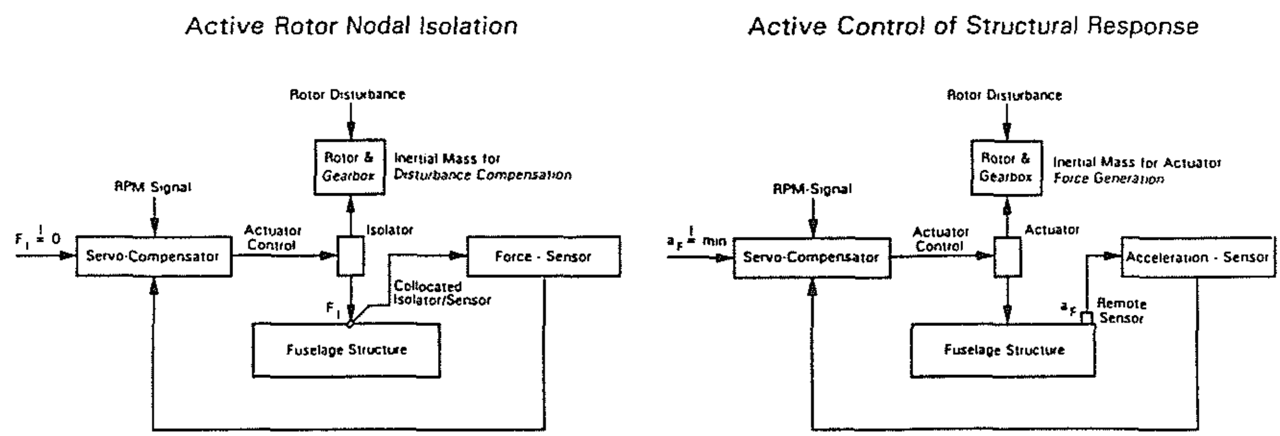


Fig. 17: Active Vibration Control Concepts - Nodal Isolation vs. ACSR

Force Generators: The following passive and active force generators with co-axial support springs are illustrated in Fig.18:

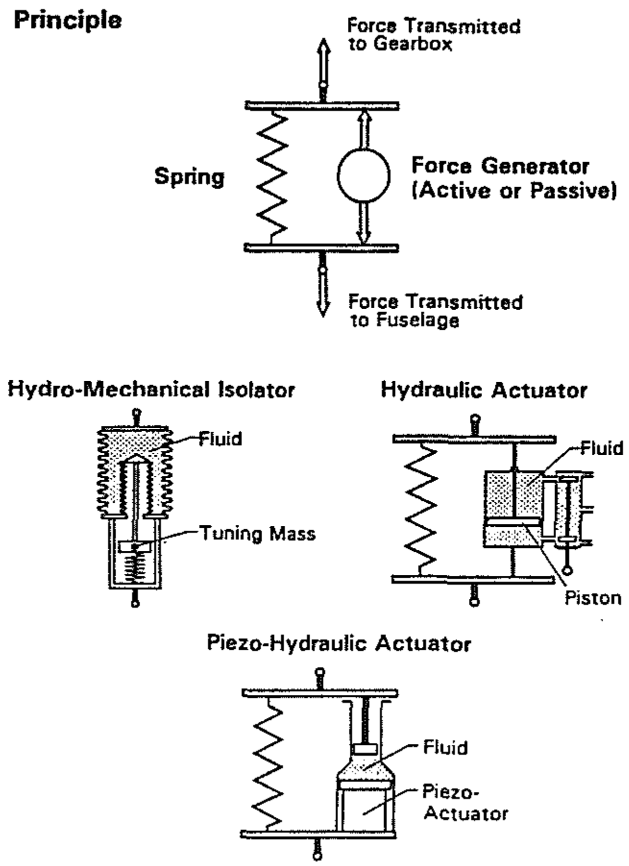


Fig. 18: Passive and Active Force Generators

⇒ Hydro-Mechanical Isolator (EC135)
- passive device requiring linearity and low damping
- single-frequency tuning

⇒ Hydraulic Actuator
- flow-controlled servo requiring special provisions for force control
- highly nonlinear characteristics
- multi-frequency capability up to 50 Hz
- sensitive with respect to sealings and shear forces

⇒ Piezo-Hydraulic Actuator
- inherently force-controlled by strain-induced piezo actuation
- hydraulic displacement amplification provides required ±0.5 mm amplitudes
- approximately linear characteristics
- multi-frequency capability for both vibration and noise control
- capsuled design with no sealing problems
- low power consumption due to load path separation (static/dynamic) and energy recovery capability

The technical features of these three force generators indicate that piezo-hydraulic actuators have the potential to be applied successfully in the future as active vibration control systems. Especially the superiority of piezo-active force control –compared to current force-controlled hydraulic actuators– cannot be overseen. First estimates for the three technologies in Fig.18 show clear advantages of the piezo actuator with respect to performance and weight. If the promising energy recovery concept (smart power supply) can be realized, the piezo based system would need only a fraction of energy, required to drive the hydraulic based active system [21]. For the investigated configurations a power consumption between 0.9 kW and 1.2 kW is estimated. Thus a system weight below 1% of the maximum gross weight seems to be feasible, maintaining the costs of passive systems. Therefore intensive research work is currently performed in order to develop an intelligent and efficient energy recovery power supply.

3.2 Configuration Studies for EC135

In order to check the potential of modern active control techniques for the EC135 a study was started. The investigations concentrate on using new piezo-hydraulic actuators and remote airframe acceleration sensors with the aim of reducing hardware effort. Besides, this research activity was motivated by recent successful flight demonstrations of the ACSR approach on a Dauphin helicopter by EC [22] and a BK117 helicopter by Kawasaki [23].

Configurations: The ACSR configurations studied for the EC135 are outlined in Fig.19:

⇒ 4z-piezo actuators

⇒ 2z + 1y-piezo actuators

⇒ 2z-piezo actuators (rear)

The basic actuator data are:

⇒ effective stiffness: 13 kN/mm

⇒ max. dyn. displacement: ± 0.5 mm

⇒ max. active force: ± 7.6 kN

Seven fuselage acceleration sensors were selected according to general observability criteria:

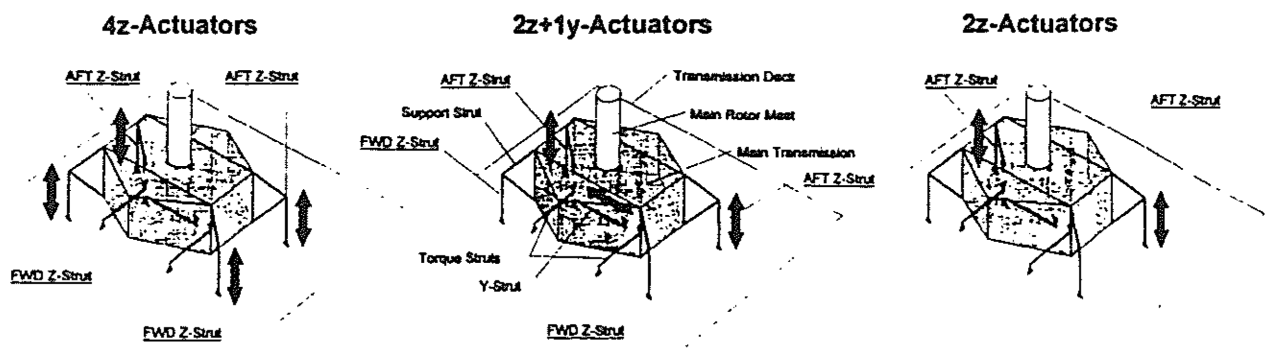
⇒ pilot seat in x, y, z-directions

⇒ copilot seat in z-direction

⇒ passenger seat (right) in y,z-direction

⇒ passenger seat (left) in z-direction

It should be mentioned that other configurations and sensor locations have been studied as well, but the presented systems are the most interesting ones.



Piezo-Actuator

Eff. Support Stiffness = 13 kN/mm
Max. Dyn. Displacement = ±0.5 mm
Max. Actuator Force = ± 7.6 kN

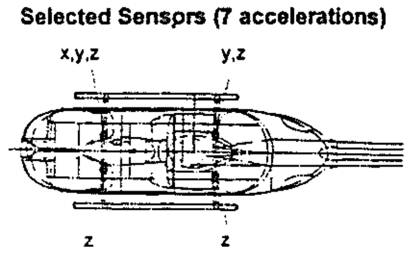


Fig. 19: Study of ACSR Configurations (EC135)

Potential of ACSR: The numerical investigations concentrate on the 4/rev vibration reduction potential by ACSR in level flight. The calculations were carried out with the structural dynamic model of Fig.10, using the vibratory hub loads of Fig.12 as approximation. The results of the fuselage vibration minimization procedure are plotted in Fig.20 for the most interesting lateral and vertical vibrations at the pilot seat and passenger seat. The calculated ARIS data are plotted for convenience, too.

The calculations demonstrate the strong potential of active means for vibration control also for the EC135 helicopter. The 4/rev vibration levels are of the order of ±0.1g or less for all configurations. In particular, the study leads to the following results:

⇒ The 4z-actuator configuration is superior to the 2z-actuator configuration, as expected.

⇒ The 2z + 1y-actuator configuration has the effect to reduce further the lateral vibrations, which was expected by controllability aspects.

The similar vibration behaviour of the active 4z-ACSR system and the passive 4z-ARIS system is surprising and may not be representative. The ACSR calculations were not optimized with respect to feedback gain and sensor locations; thus better vibration reductions can be expected in further loops.

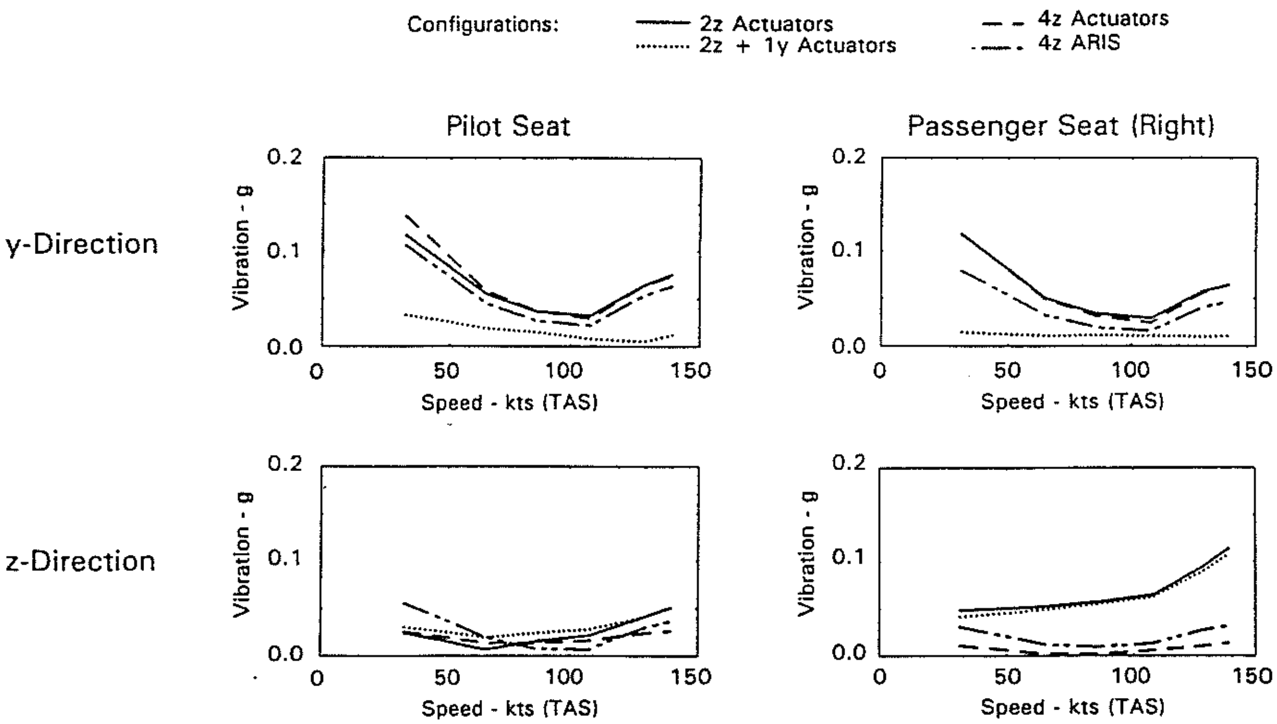


Fig. 20: Potential of ACSR Configurations for Vibration Reduction (EC135): 4/rev Cabin Vibrations

Piezo Actuator Requirements: One of the key issues for applying piezo actuation for ACSR is the establishment of 4/rev displacement and force amplitudes. The required piezo actuator data (level flight) are plotted in Fig.21 for the selected ACSR configuration. These plots reveal that the requirements for the "simple" 2z-system cannot be fulfilled by the present piezo actuator design. But piezo actuation is an appropriate solution for the other two configurations (4z- and 2z + 1y-actuators) where the calculated values correspond to the ±0.5 mm and ±7.6kN actuator design data.

Lesson from the Study: The performed study proves the feasibility of active control technology for the EC135 helicopter with a limited number of actuators and sensors. The most favourable results are derived for the 2z + 1y-configuration. It has to be evaluated, whether the lateral actuator can be replaced by a smart active underfloor absorber (tuned inertial actuator). It is expected that such an active vibration control system can economically be realized by using 2nd generation piezo actuators in combination with time domain disturbance rejection control for improved vibration reduction.

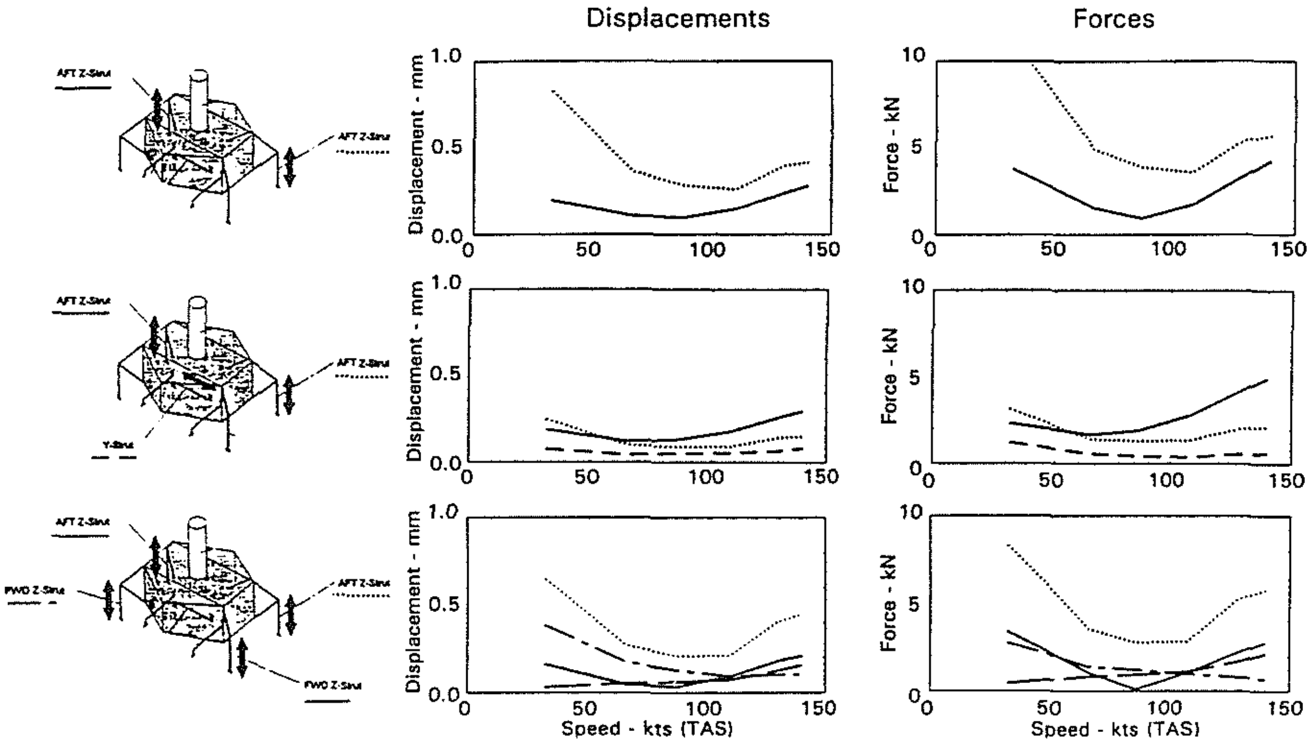


Fig. 21: Requirements of ACSR Configuratios for Piezo Actuators (EC135)
(4/rev Actuator Displacements and Forces)

4 Application of Piezo Actuators in the Future

It was demonstrated in the last chapter that there is a need for a new type of force actuation to overcome well-known problems of conventional actuators. Therefore current research at ECD is mainly concentrated on a "2nd generation" of actuators based on strain induced piezoelectric actuation materials.

4.1 2nd Generation Force Actuators

For helicopter active vibration reduction force actuators are required with adequate high displacement and force capabilities. Common piezo actuators (stack) provide a maximum active strain of about 2‰ and should be sufficiently prestressed under all operational conditions. Intensive research activities were started in 1995 at ECD in cooperation with Daimler Benz Forschung (DB) and Liebherr Aerospace Lindenberg (LLI) in order to work out an appropriate force isolator concept. The actuator concept finally designed by LLI has the following features:

⇒ Hydraulic displacement amplification

⇒ Load path separation

⇒ Preload by gas spring.

A simple model of the actuator (load path separation not shown) is presented in Fig.22; the computational model used in the ACSR study is shown, too, based on an equivalent mechanical model.

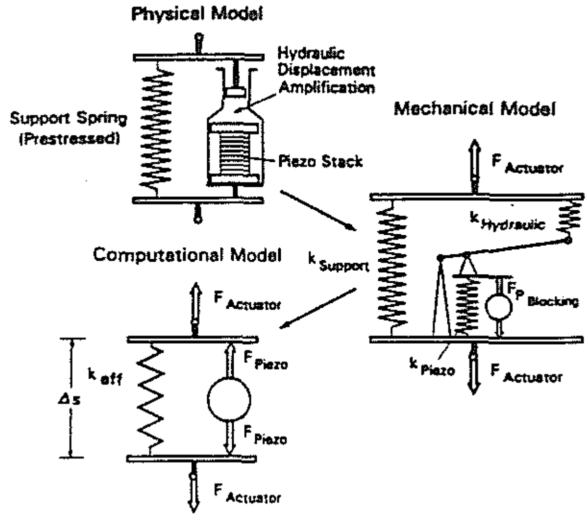


Fig. 22: Piezo Actuator with Hydraulic Displacement Amplification

In order to check this piezo-hydraulic actuator concept a "Laboratory Model" was built and tested.

The design and manufacture of the metal parts, the assembly of the isolator and the basic testing on an existing rig was done at LLI. A view of the isolator cross section, one of the selected piezo stacks and the assembled lab model on the test rig is shown in Fig.23.

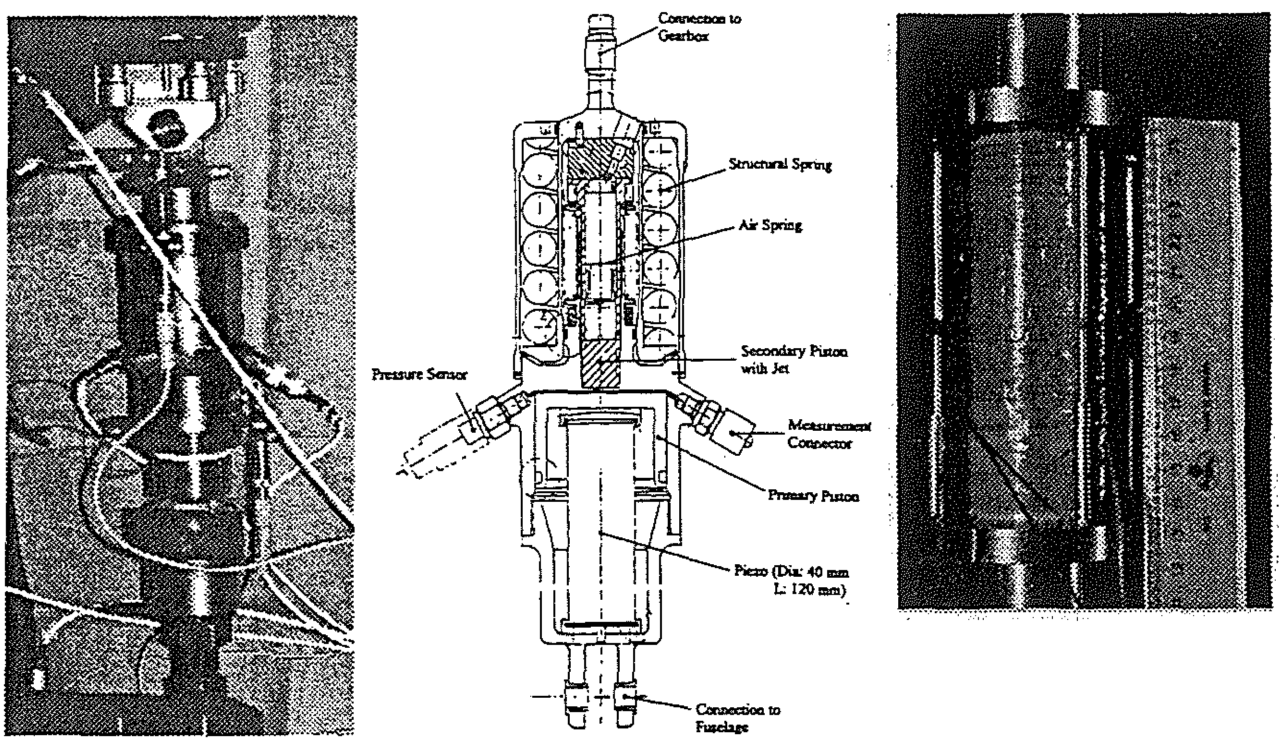


Fig. 23: Piezo Actuator with Displacement Amplification and Load Path Separation (Lab Model Bench Test)

Piezos of the size required for this application are not readily available nor reliable material data for design. A lot of basic investigation had to be done. Different piezo materials were tested with respect to stiffness, active strain and loss factor; preloads equivalent to 90 MPa, electric field strength up to 2000 V/mm and frequencies up to 100 Hz were applied. The final actuator data of the lab model are summarized in the table below.

Piezo Hydraulic Actuator Data

	Lab. Model	Demonstrator
total actuator length - mm	385	292
piezo stack length - mm	120	120
piezo diameter - mm	40/45	60
max. active strain - ‰	2.4	2.4
max. piezo blocking force - kN	112	256
piezo stiffness - kN/mm	390	890
support stiffness - kN/mm	2	7.5
hydraulic stiffness - kN/mm	100	100
eff. dyn. support stiffness - kN/mm	4.8	12.9
max. active power - W	170	400
hydr. amplification ratio -	11.9	11.9
max. dyn. displ. ampl. - mm	0.5	0.5
max. dyn. force amplitude - kN	3.5	7.6
total mass - kg	11.0	6.5

Basic testing of the lab model included active and passive, static and dynamic functionality, frequency response with respect to input signal and disturbance (i.e. dynamic rotor load), response of piezo and isolator to step and harmonic inputs and endurance at the relevant frequency (i.e. 4/rev) as a function of the input amplitude. Fig.24 shows the achievement of two important design goals, i.e. dynamic displacement amplitude of 0.5 mm and load path separation. The prediction agrees quite well with test results.

Finally the most important features of the new piezo-actuator are summarized:

⇒ High resolution, high control accuracy

⇒ Low power consumption due to the possibility of energy recovery concept for the reactive energy

⇒ Large active forces

⇒ No friction within the piezo

⇒ No wear within the piezo

⇒ Fast response time, high bandwidth

⇒ Direct conversion of electric into mechanical energy

⇒ Self sensing capability

Together with a suitable hydraulic amplification the isolator shows the following features:

⇒ Dynamic displacement amplitudes up to 0.5 mm

⇒ Highly precise (linear) force actuator

⇒ Compact, weight and volume optimised isolator

⇒ Separation of high static flight loads from the piezo stack by using a by-pass-jet

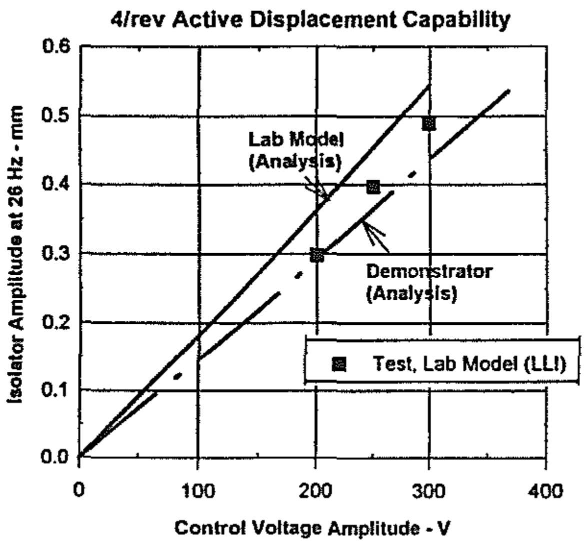
⇒ Maintenance free due to hermetically sealed gas and fluid volumes

⇒ Inherent preloading of the piezo stack and temperature compensation by a pressurised air storage

⇒ Parallel passive load path (fail safe)

⇒ Simple actuator set up resulting in cost effective manufacturing of parts

The background of piezo actuation is found in [24], [25].



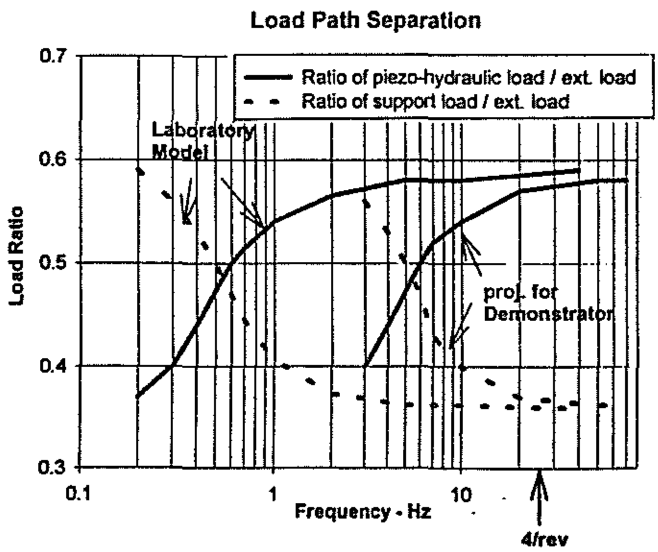


Fig. 24: Development of Piezo Force Actuator (2nd Generation)

4.2 Research Activities (MARI)

In 1995 the research program Multi-Axis Rotor Isolation (MARI) was started at ECD in collaboration with selected partners from German industry and universities.

The envisaged project plan is given below:

⇒ Testing of Lab Model and Controller →12/97

⇒ Testing of 2nd Generation Piezo Actuator →12/98

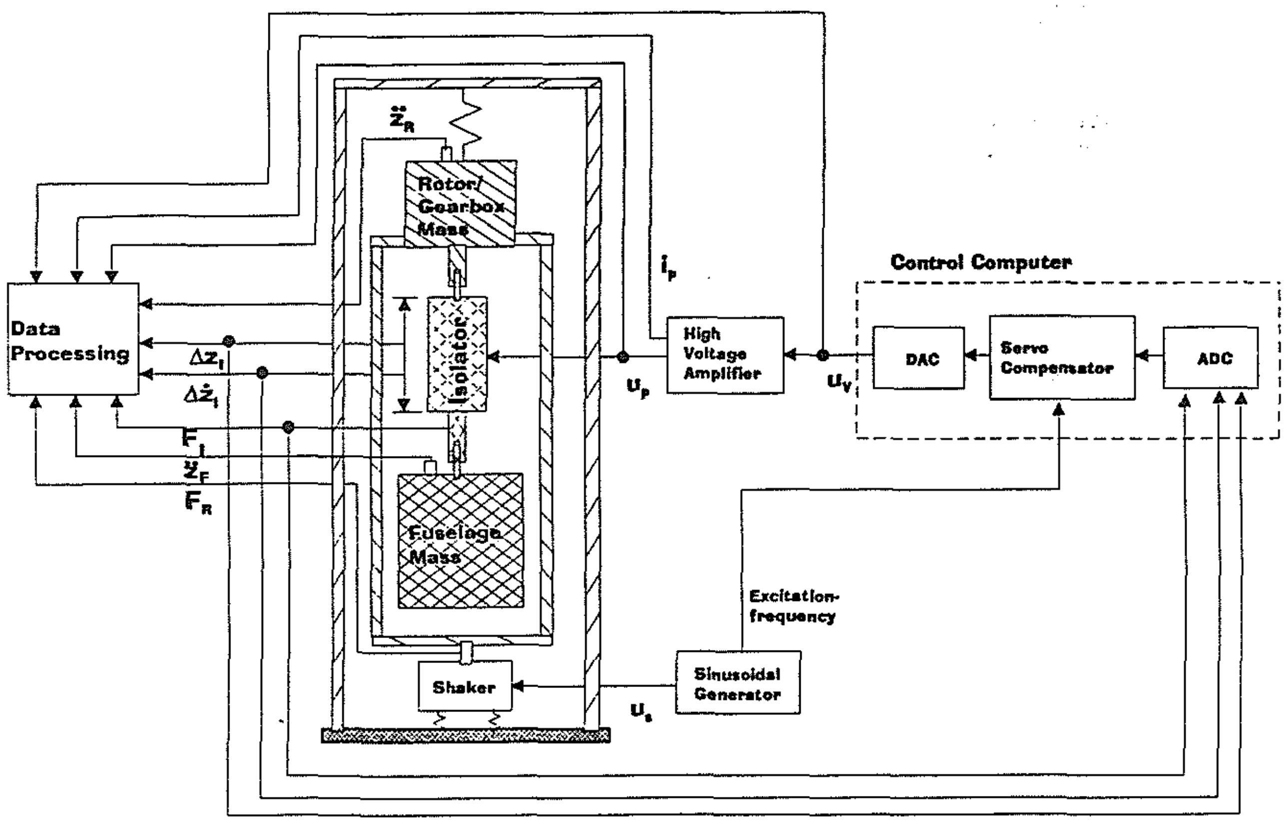
- on Test Rig
- on Multi-Axis Test Bench

⇒ Flight Testing of Active Isolation System →12/99

The lab model will be tested on ECD's functional test rig (Fig.7) in order to confirm the dynamic behaviour and to proof the envisaged control concept in open and closed loop. The principal arrangement is shown in Fig.25.

The control concept is based on disturbance rejection control in the time domain. Either the force of the isolator or the acceleration of the fuselage are fed back through an rpm-adaptable two frequency notch (4/rev and 8/rev). Additionally the actuator displacement and/or velocity can be fed back. The control laws are already designed using optimal output feedback theory [26], and will be realised on a digital control computer. Sample rate of the control computer will be about 500 Hz. Simulation results are given in Fig.26 for the single frequency excitation case. Note the faster time response and the broader notch characteristics for the high gain controller.

Based on the results with the lab model flightworthy isolators for the demonstrator are being designed. Prior to flight trials which are planned for early 1999 the complete isolation system will be tested on a multi-axis test rig. After these tests the flight trials will be performed.



Note: Isolator force F_I measured by load cell or fuselage accelerometer (indirect)

Fig. 25: Nodal Isolation by Piezo Isolator (Test Rig)

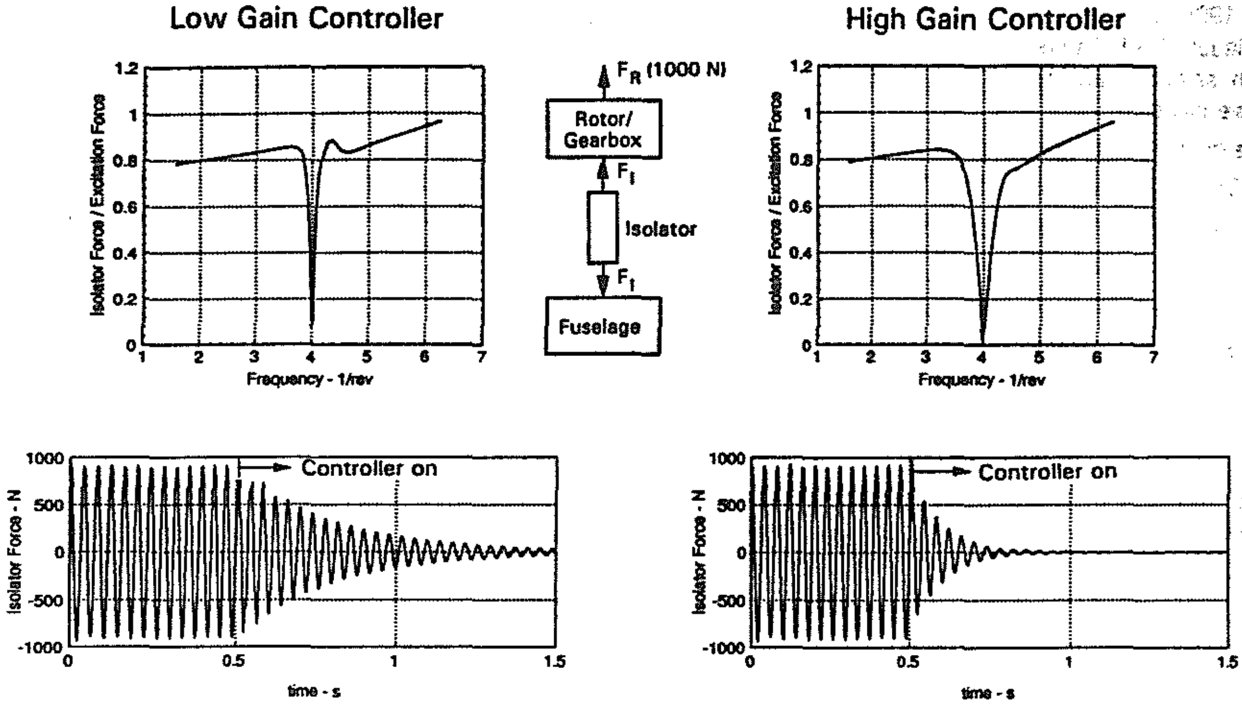


Fig. 26: Active Rotor Nodal Isolation by Disturbance Rejection Control
Force Transmissibility and Time History

5 Concluding Remarks

The new commercial EC135 helicopter is equipped with an efficient passive vibration control system. The technology used on the EC135 is presented in some detail. In addition recent research activities on active vibration control in the fixed system are presented, showing that piezo-hydraulic force actuators have the potential for establishing active vibration control technology in future helicopters.

The following conclusions can be drawn from the paper:

⇒ The EC135 helicopter equipped with a nodal isolation system achieves vibration levels less than 0.1g with a corresponding intrusion index between 0.5÷1.0.

⇒ Active vibration control based on piezo actuators is a feasible solution to reduce weight penalties, power consumption and complexity.

⇒ 2nd generation force actuators using strain induced piezo actuation materials, hydraulic displacement amplification and load path separation fulfill the requirements for helicopter vibration control.

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