SIXTH EUROPEAN ROTORCRAFT AND POWERED LIFT AIRCRAFT FORUM

PAPER NO. 10

HELICOPTER VIBRATION CONTROL - A SURVEY

G. Reichert

Messerschmitt-Bölkow-Blohm GmbH
Munich, Germany

September 16 - 19, 1980
Bristol, England

THE UNIVERSITY, BRISTOL, BS8 1HR, ENGLAND

HELICOPTER VIBRATION CONTROL - A SURVEY

G. Reichert

Messerschmitt-Bölkow-Blohm GmbH
Munich, Germany

Abstract

The complexity of the helicopter vibration problem and the procedures necessary for considering vibration throughout the development phase are presented. The stringent vibration requirements of modern helicopters necessiate special methods and devices to control and reduce vibration to an acceptable level.

A review of past, current, and future possibilities and methods for reducing helicopter vibrations is given, including structural optimization of the rotor and the whole helicopter, blade and rotor pendulum absorbers, rotor isolation concepts following the antiresonance principle (nodal isolation), and also the possibilities of active isolation devices. In the whole field, the helicopter industry has obtained a broad experience from special test programs as well as from new development programs with installed antivibration devices.

Vibration will always remain a helicopter problem. There are effective means of reducing the levels, but vibration specifications must be realistically determined to avoid excessive weight penalties and development costs.

1. Introduction

Almost without exception, vibration has been a problem for all helicopters, and vibration will continue to play an important role in the development of the next generation of helicopters. New and more stringent requirements for permissible vibration levels, to which pilots and passengers will be exposed, and the requirement for increased reliability and reduced maintenance costs, have induced helicopter manufacurers all over the world to start extended research and development programmes with the aim of substantially reducing excessive vibration. Because of the great importance of the problem and the many related activities, several survey papers have been presented over the years, reporting research and development programmes, which have been conducted with varying degrees of success, References 1 - 4. This paper will attempt to give an overview of today's situation, with improved methods and procedures to be used during development, and with new or improved means for vibration control; but also with more and more severe requirements and with higher expectations which sometimes seem to be unrealistic.

Figure 1 shows the trend of helicopter cabin vibration levels over the past 25 years. There has been enormous progress with a vibration reduction from 0.3 or 0.6 g to values around 0.1 g. Throughout the years the requirements have been for lower values than could be realized with production helicopters. A special example is the AAH/UTTAS specification which

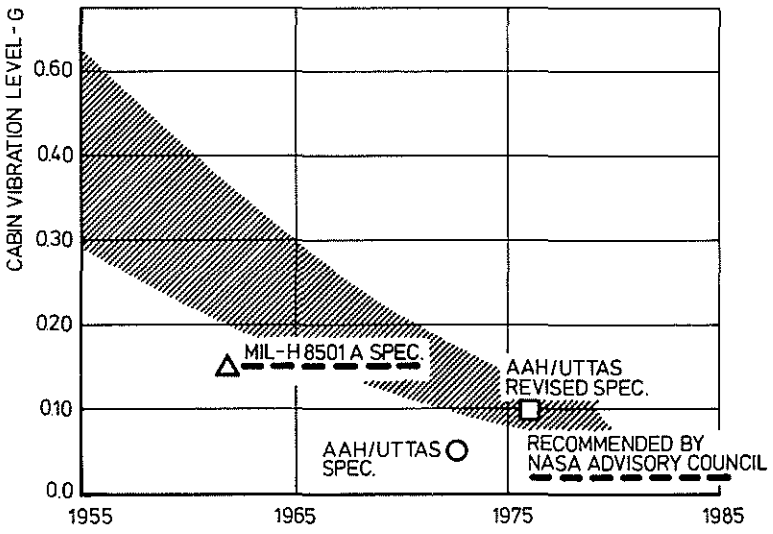


Figure 1 Trend of Helicopter Vibration Levels

originally required vibration levels lower than 0.05 g. None of the competitors could fulfill this specification, and finally the specification had to be raised to 0.1 g, which seems to represent today's technology. The NASA Research and Technology Advisory Council Subpanel on Helicopter Technology recommended in 1976 a desirable level of 0.02 g, but it seems that such levels can be realized only if vibration control techniques achieve a major breakthrough. It is clear, however, that further progress has to be made. Figure 2 shows wellknown Goldman-data, going back to the year 1948,

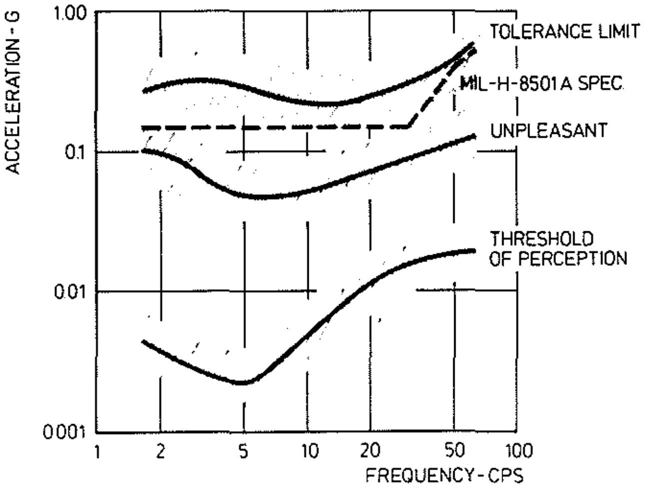


Figure 2 Vibration Tolerance Criteria

D.E. Goldman, H.E.v. Gierke
Effects of Shock and Vibration
on Man
Shock and Vibration Handbook
C.H. Harris / C.E. Crede
McGraw-Hill Book Comp. 1951

about vibration tolerance criteria, Reference 5. In the meantime similar studies have been conducted, but the results did not change very much, Reference 6. Helicopters with vibration levels higher than 0.1 g, are really not comfortable. In the past the helicopter users had to tolerate higher values, but nowadays they are no longer willing to accept high vibration levels. If a level of 0.02 g could be attained there would be no further discussion about helicopter vibration. Today's situation is not satisfactory, neither for the operator nor for the manufacturer of helicopters. Because of the continuing progress of technology there will always be a high expectation on the side of the operators. Perhaps, some manufacturers have raised too high an expectation, with enthusiastic reporting of related research and technology work, which resulted in very low vibration levels - but very often it seems to be extremely difficult or even impossible to recreate such values with production helicopters, without creating new problems. All the manufacturers are optimistic for the future. Their technological forecast promises the "jet smooth helicopter" to become a reality before the turn of the century as their understanding of the fully coupled aeroelastic rotor/fuselage system improves and their isolation techniques achieve perfection, Reference 7.

For the present, it is the discussed human factor criterion, i.e. the sensitivity of the pilots and passengers to the vibration environment, that is the most stringent and difficult to meet. The other part of the vibration problem, which is associated with functional reliability and maintainability requirements, is contributing directly to the cost effectiveness of the whole helicopter, particularly by its effect on structural fatigue and by the influence of the vibration environment on engines and equipment. There is a direct connection in many aspects of the two problem areas, but it would be beyond the scope of this paper to cover them both in combination.

2. The Complexity of the Vibration Problem

With a helicopter in forward flight the non-uniform flow passing through the rotor causes oscillating airloads on the rotor blades which produce excitation forces and moments at the rotating hub. This excitation is periodic. For an ideal rotor with identical blades the remaining major sources of excitation are at frequencies of

$$(n - 1)\ \Omega,\quad n\Omega,\quad (n + 1)\ \Omega,$$

$$(2n - 1)\ \Omega,\ 2n\Omega,\ (2n + 1)\ \Omega,\ \ldots$$

determined by the number of blades n and the rotational frequency of the rotor, Ω. As the forces and moments are transmitted from the rotating hub system to the fixed fuselage system they act as excitation forces and moments on the fuselage with $n\Omega$, $2n\Omega$, ... frequencies. The rotor acts as a filter which only transmits oscillatory moments and shear loads with these frequencies to the fuselage. The oscillatory loading applied to the fuselage depends upon the number of blades. Since the magnitudes of the lower harmonics of blade loading are considerably greater than the magnitudes of the higher, a significant reduction of the vibratory loads can be achieved by a change to a higher number of blades.

The resulting typical vibration characteristics of the fuselage are illustrated in Figure 3 for the example of a fourbladed helicopter in the form of an amplitude spectra. There are pronounced frequencies only. The typical vibration characteristics of a helicopter in its different flight speed regimes are shown in Figure 4. There are two regimes, low speed flight and high speed flight, where the vibration levels are critical. Because of the increase of the nonuniformity of the relative flow field with increasing speed, the increase of vibration with speed is to be expected, whereas the high values in the low speed regime are initially surprising.

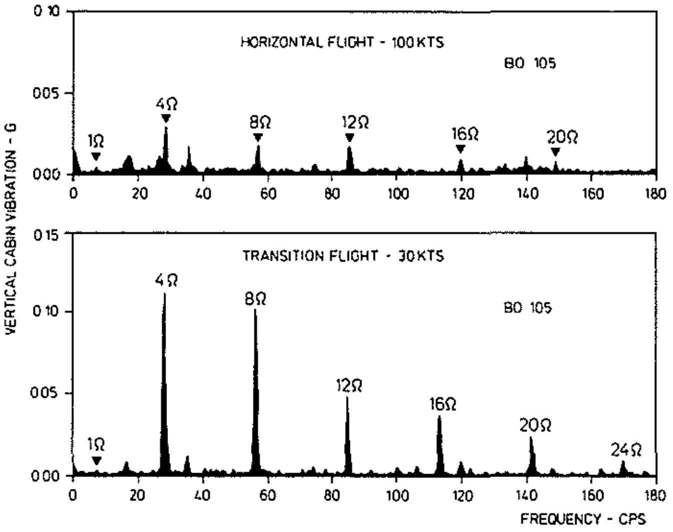


Figure 3 Frequency Characteristics of Helicopter Vibration

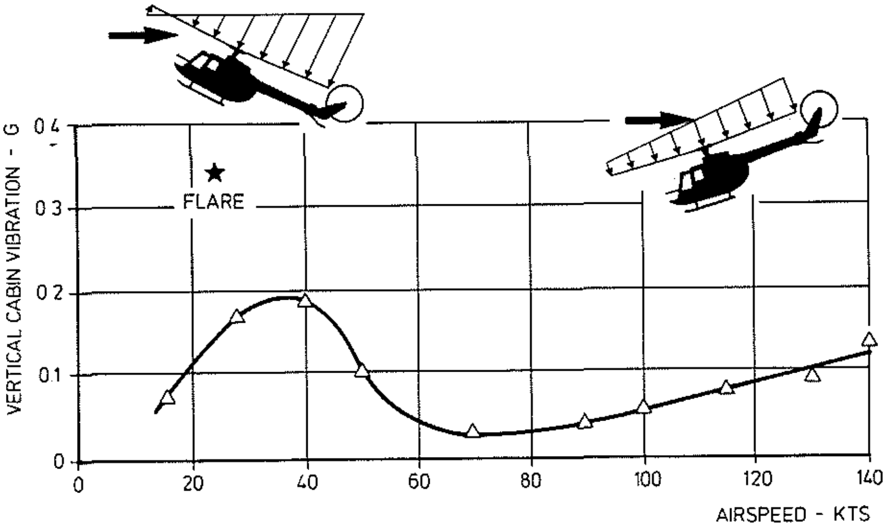


Figure 4 Helicopter Vibration with Increasing Airspeed

The marked increase in vibration levels at low speeds can be attributed to the nonuniformity of the induced velocity field caused by interaction effects of blade vortices. At low speeds these effects are most pronounced as the induced velocities are highest in this regime. Normally, the highest vibration levels will be reached during the flare maneuver, i.e. the transition from slow speed to hover flight with a change of the rotor angle of attack from the normal negative value of forward flight to a positive value. In this situation, an inflow component from the flight direction is working against the induced flow component, so that the mean value of the superimposed velocities will be very small with the effect that the blade vortex interactions are strongly pronounced. Of course, the duration of the extreme flare vibrations is only a few seconds, but they are for many helicopters a real problem because of their severity. Figure 5 tries to illustrate this flare situation showing the flow situation, the vibration level and the exciting moments of the rotating hub of a fourbladed hingeless rotor varying with time. It is quite surprising that the third harmonic of the moment and the fifth do not reach their highest values at the same time. For the fuselage both are acting as fourth harmonic excitation. It is quite clear that the analytical methods used to calculate airloads and resulting moments and shear forces at the hub are most unreliable for such conditions of flight.

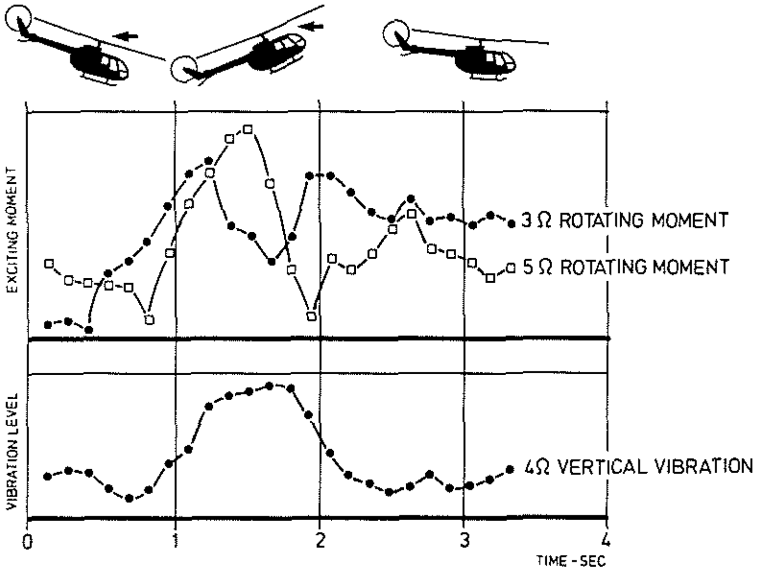


Figure 5 Helicopter Flare Vibration

Also for the high speed regime the available analytical methods are insufficient. While the variable induced velocity field in this regime has only a small effect on the airloads, compressibility, stall effects, and unsteady aerodynamics must be considered, thus complicating the analytical methods. Today's best prediction methods can give some qualitative trends, but their accuracy is not sufficient to calculate exact values, and that is the case for both regimes. Compared to performance or flightmechanical calculation, for which mainly the mean and lower harmonic rotor loads are important, the standards of airload analysis methods with higher harmonic loads, which have to be used for vibration work, are much higher. In future, improved methods will be available, but the question will be, if they can be used for development work. Perhaps, they will be too complex to handle and will consume too much effort and computer time to be used for real development work, for which early and quick answers on the influence of parametric variations are necessary.

The sources of the vibration problem are the excitation loads generated by the rotor. They depend on the airloads generated by the blades and the dynamic characteristics of the whole rotor system. The response of the fuselage to these excitations will finally be responsible for fuselage vibration levels, for instance in the cockpit. It is necessary to ensure that the dynamic characteristics of the fuselage are adequate to maintain minimum vibration levels. And again, that is a very difficult task. The basic shape and therefore, stiffness of the fuselage will be fixed by considerations other than vibrational characteristics, which are influenced mainly by higher bending modes.

3. Vibration Considerations during Development

A very good description of the state-of-the-art and the procedures to be used during development is given in Reference 4, which also covers the experience with AAH and UTTAS developments. The following explanations and comments will partly be based on it.

Figure 6 presents the flow diagram of the complete helicopter vibration problem during all phases of development. Vibration work has to start

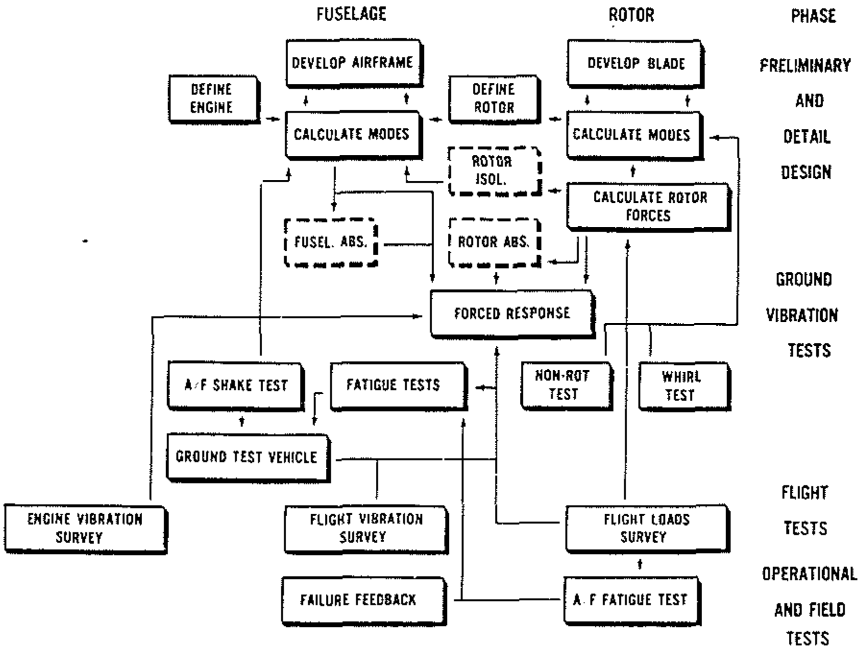


Figure 6 Flow Diagram of the Helicopter Vibration Problem

with preliminary design. Definition of the blades and the rotor is not possible without considering vibration characteristics. As a design will always be a compromise of all the different requirements, it will not always be possible to make it optimal for vibration. Selection of the rotor type and sometimes also of the number of blades is very often determined by the background and the history of the particular manufacturer. Definition of the main parameters like disc loading, rotor tip speed, rotor solidity and blade chord has normally to be done without considering vibration though these parameters will influence the vibration environment. During the final selection of blade twist and tip shape their influence on vibration has to be checked. Most important is the definition of the blade dynamic characteristics. It is necessary to avoid resonance conditions of the coupled blade bending and torsional modes with the exciting rotor harmonics. The normal way is to establish the blade frequency diagram, as shown in Figure 7, in the very early design phase. Blade mass

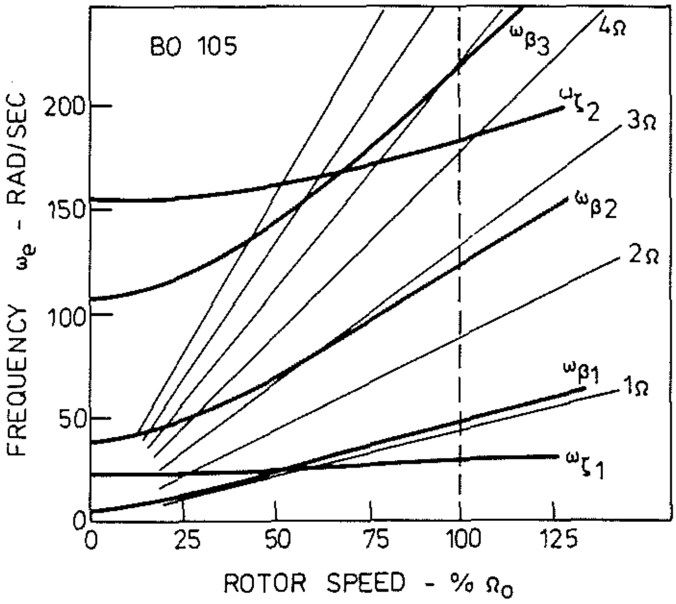


Figure 7 Blade Frequency Diagram

and stiffness distribution are the input for the calculation. Today's analytical methods for blade modes and natural frequencies are reliable with only some minor problems in deciding on the right inputs for the blade attachment area and the dynamic characteristics of the hub itself. Determination of the modes must be accomplished to insure that blade natural frequencies are separeted from each other and from the exciting harmonics within the whole range of rotor speed. This can be done easily by the use of tuning weights with proper placement for effectiveness on one particular mode without influencing the other modes. Figure 8 gives an illustration of the possibilities. Structural optimization of the rotor blades and the rotor is nowadays standard procedure during development, and with the use of fiber-composites for the blade structure, (which seems to be the trend for

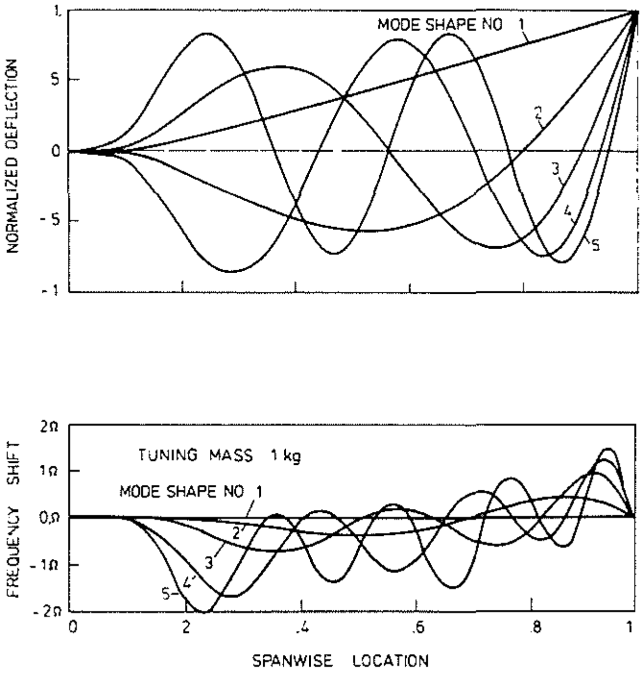


Figure 8 Rotor Blade Frequency Tuning by a Concentrated Mass

future helicopters), there are less manufaturing constraints preventing realisation of the ideal structural properties.

The next step is to ensure that the response of the fuselage to excitation from the rotor is itself maintained at a minimum level. In the early design stage, the fuselage is often represented as an elastic beam, but as the design phase evolves, a more complex finite element model is developed and utilized. It is very important that the engine and the rotor and gearbox system with its mounting structure are properly defined so that the entire airframe is represented by the model. The calculations in the early design stage must show the rough proximity of any major fuselage mode to the nΩ exciting frequency. In addition they should indicate the sensitivity of forced response to changes in the stiffness of structural components, which could be modified or redesigned if it is found to be necessary later on during development. But it seems to be worthwhile to note here, that the troublesome airframe modes are often relatively insensitive to basic stiffness changes, once the outline shape of the fuselage has been fixed. The change in structural mass associated with a stiffness change of this type tends to cancel out the effects of the stiffness, leaving the natural frequencies little changed, Reference 3.

During the detail design phase the finite element model will become more and more refined and the calculations should include frequencies up to the 2nΩ excitation. Detailed finite element models need some detail design information, and then the calculations are lengthy. By the time the results are available it will already be difficult to make structural changes, and this seems to be the practical problem. Structural optimisation methods and usuable finite element methods are available and can be used as has been shown in several papers, e.g. References 8 ÷ 10. Figure 9 shows a typical finite element model of a helicopter, and Figure 10 gives a comparison of calculated and tested data.

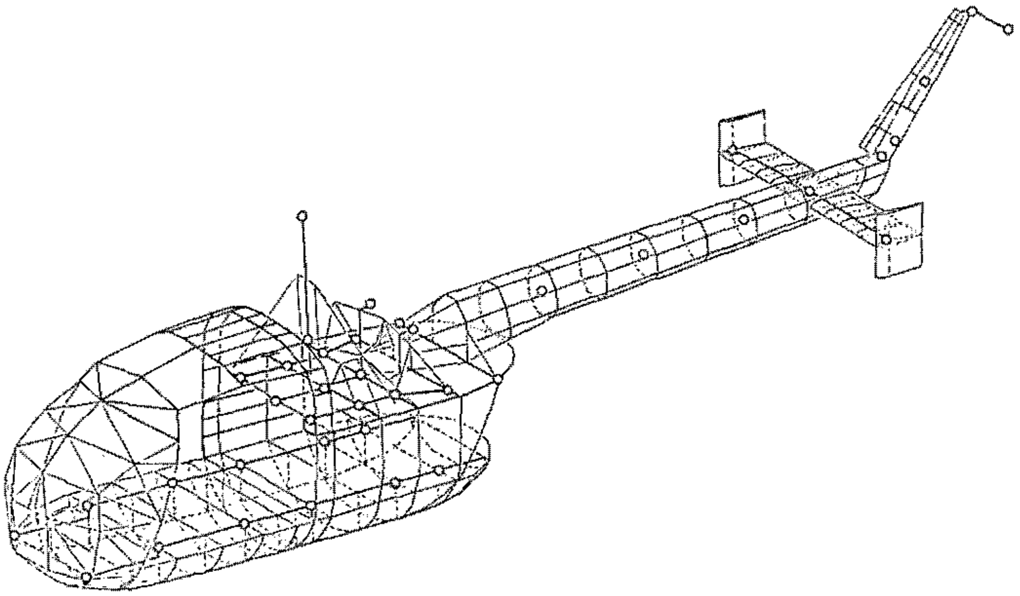


Figure 9   Finite Element Model of BO 105 Helicopter

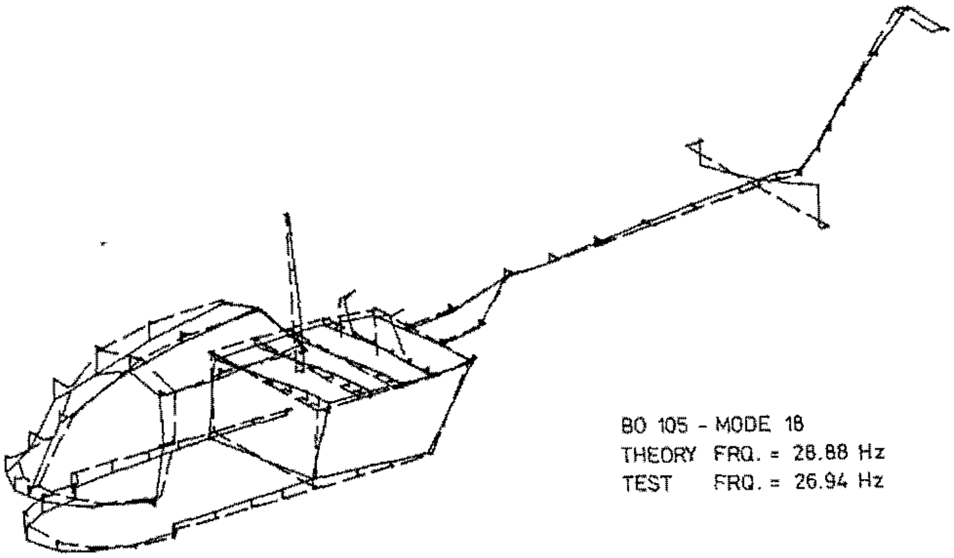
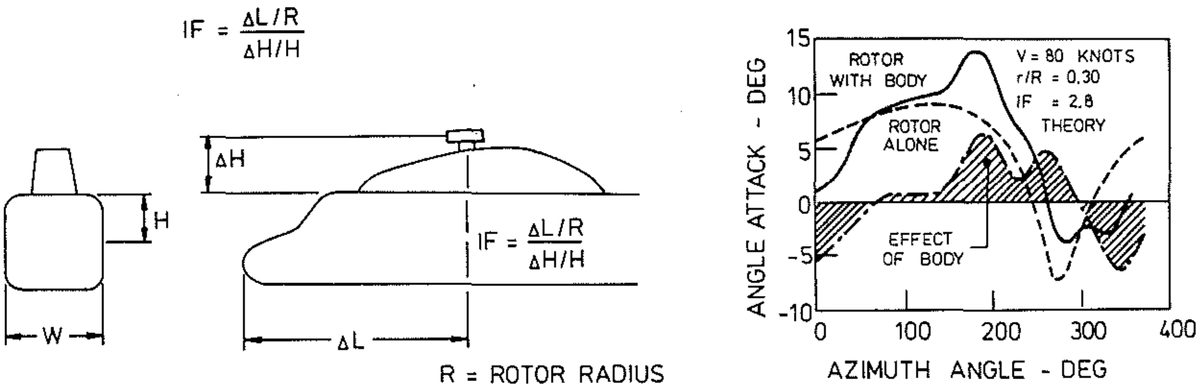


Figure 10   Torsional Fuselage Mode

The characteristics of the rotor/gearbox/engine mounting system strongly influence the transmission of the exciting forces and moments from the rotor to the fuselage. In the early design stage, precautions for structural modifications in this area have to be considered. Very often the suspension system will be designed as an isolation system.

The distance between the rotor and the fuselage will also be defined during preliminary design phase. The effect of this distance on vibration characteristics is very often negligible, but UTTAS/AAH experience has shown, that a considerable contribution to vibration could be the result, if this distance is too short. All four UTTAS/AAH competitors had to raise their rotors for vibration reduction. This vibration was due to rotor downwash effects on oscillatory pressures on top of the fuselage and overhead canopy and their deflection back through the rotor flow field. Such aerodynamic effects are difficult to calculate, but there are some empirical data, Reference 11. Figure 11 tries to define the critical parameters for interference and shows some illustrative results.



INTERFERENCE PARAMETERS

AIRFRAME EFFECT ON BLADE ANGLE OF ATTACK

Figure 11 Aerodynamic Rotor/Fuselage Interference

With the progress of development work the dynamic structural models have to be refined. The described procedure goes through several iterations with changes in blade properties and the fuselage structure. Now, blade and hub forces and moments will be calculated using a sophisticated mathematical description of the dynamic characteristics of the rotor system together with an accurate description of the aerodynamics. Once the hub forces and moments have been predicted they can be combined with the dynamic model of the airframe to obtain the forced response to predict inflight vibrations. Consideration of the flexibility of the rotor support system must be included. The state-of-the-art and the overall possibilities are best described by the following statement of Reference 4:

"The coming of age of the computer during the last decade has greatly improved the analytical tools available to the helicopter design engineer. However, it should be recognized that use of these tools can only increase the probability and confidence that an aircraft will exhibit an acceptable vibration environment in service, because it virtually is impossible (technically and economically) to conduct a design program that would guarantee design goals. It is, therefore, most beneficial to make provisions for vibration control in the design of the aircraft".

There is no doubt that today's more stringent vibration requirements demand some additional resources for vibration control. Improved dynamic rotor design and improved structural design of the fuselage are no longer sufficient. There are several concepts and means available as the next chapter will show. The precautions for such additional systems have to be foreseen in early design stage although it might be not quite clear to what extent they will be finally required. Additional antivibration devices can be effective only if they are integrated into the overall system of the helicopter in the right way requiring, therefore, available space and mounting provisions at special structural points, which will only be available if they have been specially considered. The interaction with the overall dynamic characteristics should also be studied in the early phase. In some cases the final decision as to whether additional systems are neccessary, or not, will not be possible before flight testing.

Once hardware becomes available testing is initiated. Then results of dynamic blade measurements and later on of whirl tower tests as well as of dynamic airframe shake tests will be used to improve the dynamic models. The conclusions will become more and more realistic, but only final flight testing will be able to close the design loop with the airloads.

4. Vibration Reduction Systems for Helicopters

Excellent progress has been made with special vibration reduction systems. The helicopter industry has gained broad experience from special test programmes as well as from new development programmes with installed antivibration devices. Some methods are already applicable to production helicopters, others are still in the research phase with some technical problems to be solved. There are methods which influence directly the exciting forces at the blade or the hub with dynamic absorbers or with multicyclic control of the blades. Other methods try to isolate dynamically the rotor from the airframe, and fuselage absorbers form a third category. The state-of-the-art of such possibilities for vibration control will now be discussed with the following comments.

Vibration Control at the Blades or the Hub

Centrifugal pendulum absorbers mounted on rotorblades have already been in use for a long time, and several companies have good experience, i. e. mainly Boeing-Vertol, Hughes, and MBB, References 12 ÷ 15. This device can be used to reduce the response of particular flapping or inplane modes of the rotorblades with the object of reducing root shear and/or root bending moment. The absorber assembly rotates with the rotor, and the restoring force for the pendulum mass is provided by centrifugal force. Hence the system is self-tuning with respect to changes in rotor speed. Figure 12 shows as an example of this type of absorber a 3Ω-flap pendulum on a MBB-BO 105. The 4Ω exciting moment in the fuselage system can be reduced by this system to about one third, as shown in Figure 13, with a similar reduction in the cabin vibration levels. A problem with this type of absorber is that

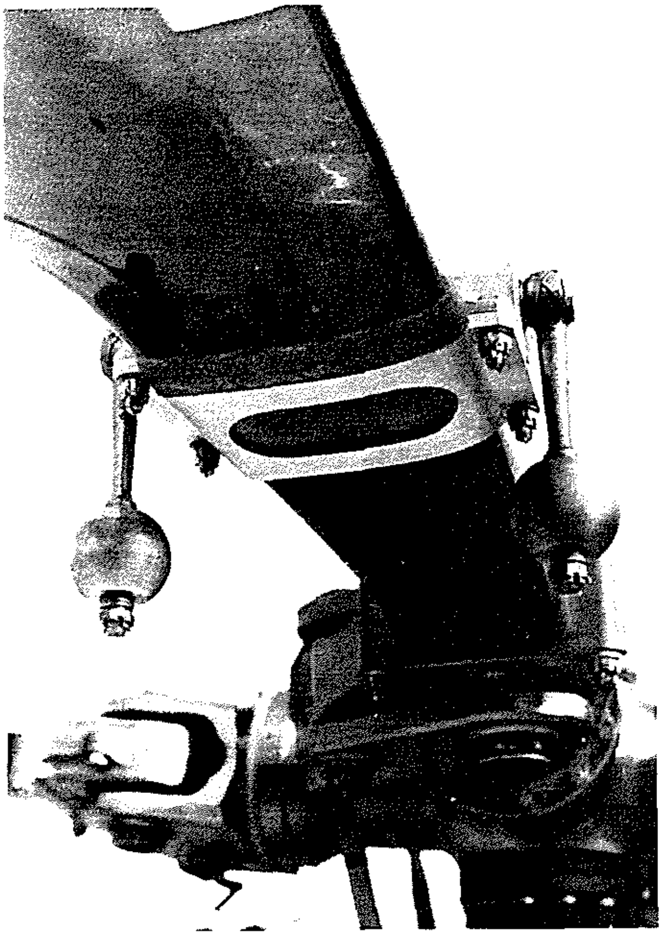


Figure 12 BO 105-Blade with 3Ω Pendulum Absorber

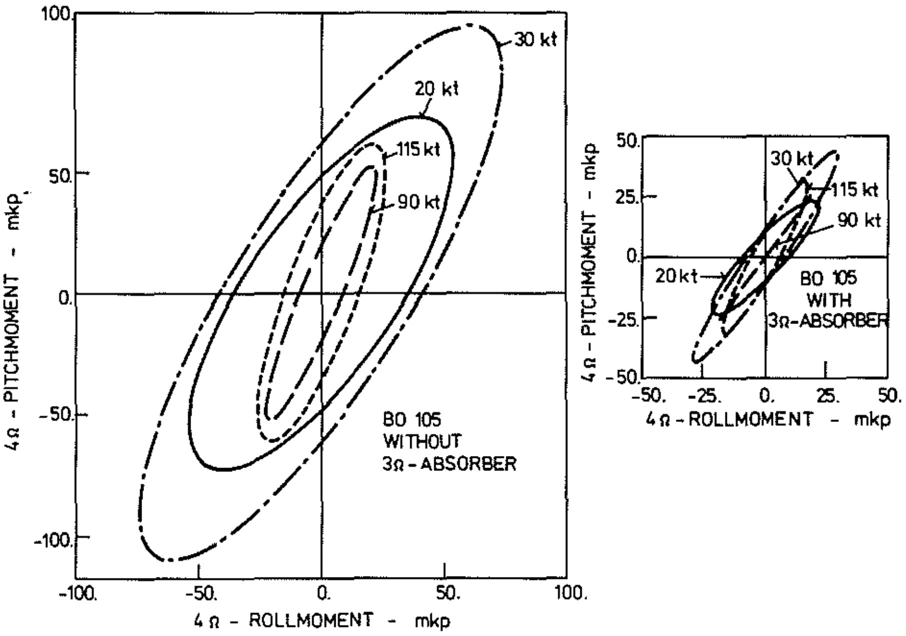
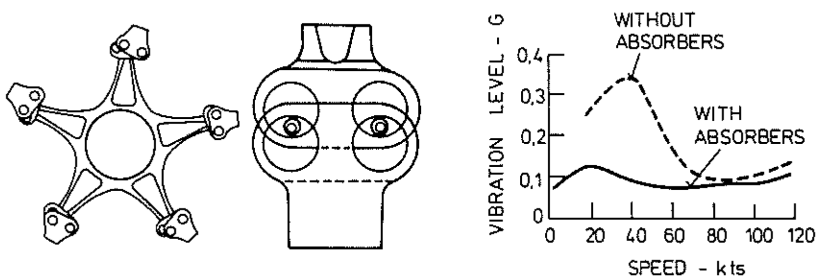


Figure 13 Reduction of Moment Excitation with Pendulum Absorber

each troublesome mode needs a seperate absorber, and this would make a complete, combined system too complex and expensive. Perhaps, this is the reason why blade pendulum absorbers are not used in a broader application.

Another possibility is a centrifugal type of rotor hub absorber, the bifilar absorber as illustrated in Figure 14. The pendulum counteracts the effects of the horizontal vibratory shear forces at the hub. This system is successfully used mainly by Sikorsky with several helicopters, Reference 16.



5-BLADED ROTOR WITH BIFILARABSORBER

Figure 14 Bifilar Pendulum Absorber

Westland is working on a fixed frequency rotor hub vibration absorber based upon fiber-composite springs. The operational characteristics are very similar to the bifilar pendulum, but, of course, it is not self-tuning. The aim is to obtain a device with no maintenance requirement, and this is not possible for centrifugal pendulum absorbers the operation of which relies on sliding or rolling of metal surfaces. A disadvantage is the necessary compromise in tuning for varying rotor speed. Reference 17 reports limited but successful flight testing, and there are plans to productionise the device.

The exciting airloads at the blades are periodic at frequencies equal to the fundamental and higher harmonics of rotor rotational speed. Therefore, it should be possible to influence and minimize them through the use of various orders of harmonic blade pitch control. If the exciting airloads could be directly minimized at the place of their origin, this should be the best solution for solving the vibration problem. The concept is not new, but early attempts seemed not to be feasible because of technological problems. Now, technology has advanced to the point where higher harmonic or multicyclic blade control in open or closed loop should be possible. There is an improved knowledge of the helicopter problem itself, but more pronounced is the overall progress in control theory, in electronics and with high frequency actuator systems. Therefore, it seems to be quite reasonable that most helicopter manufacturers and in addition several research institutes are working in this field with similar but also distinctly different approaches. If the number of published papers is taken as a scale of activity, then most activity in vibration control is with higher harmonic concepts. At the forum of the American Helicopter Society eight papers have been presented this year, References 18 ÷ 25. The last number of Vertica was a special edition for active control systems for rotorcraft with five papers, References 26 ÷ 30. At last year's European Forum two papers were given, References 27, 31. Some systems control the individual rotating blade, while others control net rotor-induced forces acting on the fuselage. It is not yet clear as to which approach will be superior. With some systems outstanding research results with windtunnel tests have already been achieved; others show great promise. Flightworthy active control systems are in the design stage, and soon actual flight testing will give some answers to the still open questions of design applications concerning complexity and costs as well as safety and reliability.

Some of the concepts work with outboard blade lift control devices or individual blade root actuators in the rotating system, both of which can increase the number of control degrees of freedom. Other concepts concentrate on blade root control via high frequency swashplate actuation, which seems to involve less radical hardware development for most helicopter configurations. Figure 15 shows the feedback loop configuration as used in windtunnel tests, Reference 26. The input processor computed vibratory signal levels from the measured blade root flap bending waveforms. (Of course, also other vibration signals could be used). This was a real-time operation. The controller algorithm computed swashplate motions in three degrees of freedom. The actuating system for the windtunnel tests had to go up to about 90 Hz. Precise control was achieved at this frequency using off-the-shelf hydraulic hardware with a novel servoloop design. Oscillatory amplitudes up to 1.3° of blade pitch were obtained. This was sufficient for full suppression of the selected vibratory components in some, but not all, of the test conditions. Figure 16 gives an impression on the possible reduction of vibratory loads in level flight. It can be demonstrated that a good transient response can also be expected. The average harmonic inputs used by the active system to suppress the controlled components in steady trim condition are shown in Figure 17. These results confirm the expectation that both amplitude and phase of the required inputs change greatly with flight condition. For this reason an automatic control system, i.e. the closed loop system can be the only operational solution. For a final evaluation

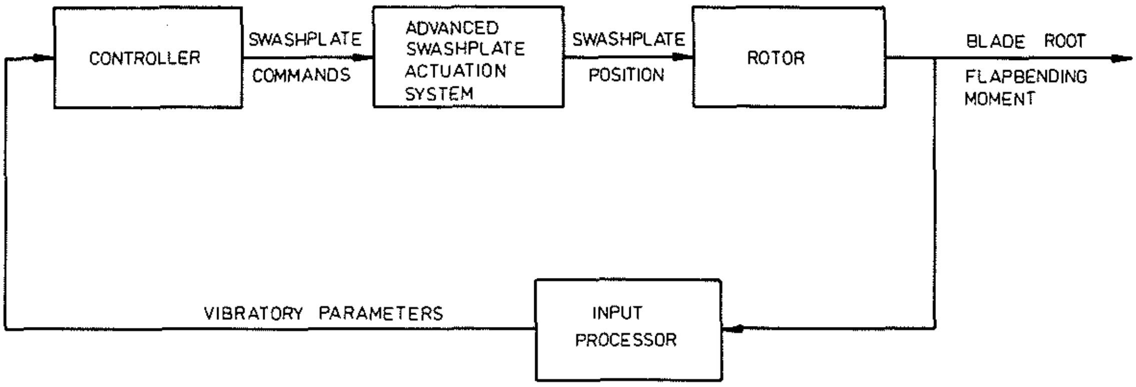


Figure 15 Feedback Loop Configuration of Active Blade Control

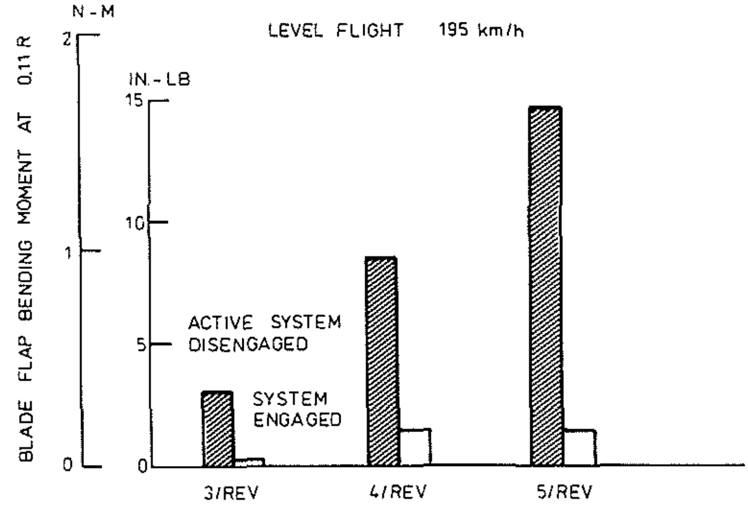


Figure 16 Vibration Reduction with Active Blade Pitch Control

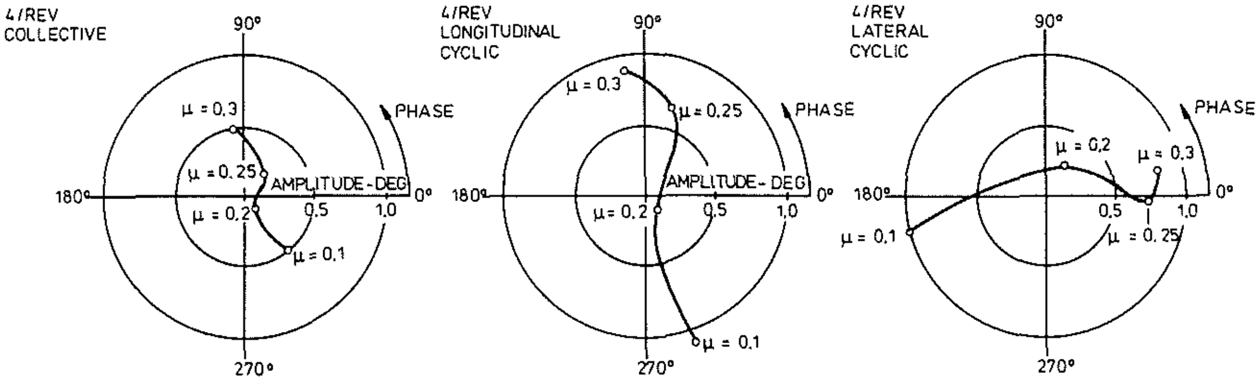


Figure 17 Harmonic Inputs Applied to Suppress Vibratory Loads in Steady Flight

of a system the shortcomings must also be considered. There will not be complete vibration eradication because it is not possible to reduce blade root moments and shear forces to the same degree. Higher harmonic control is combined with an increase in power by some percent. Maximum alternating pitch link loads may increase by more than 60%, also blade fatigue loads will be higher. The necessary structural changes could cost about 1% gross weight.

Vibration Control by Rotor Isolation

Passive isolation with flexible mounting of the rotor and gearbox to the fuselage has been used over the years to minimize the transmission of rotor forces to the fuselage, for instance all Bell helicopters employ flexible mountings. Refinements in analytical methods and development of practical hardware have led to considerable improvement in the effectiveness of passive isolation. Today, simple flexible mounting is no longer used, but more or less direct isolation systems.

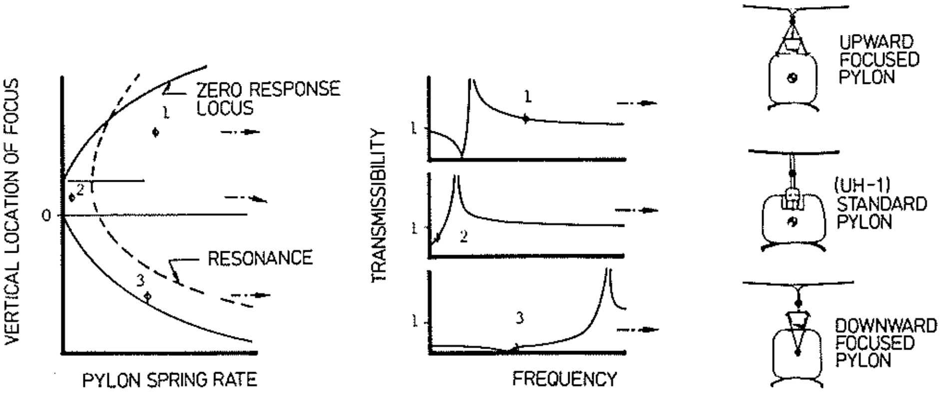


Figure 18 Response Characteristics of Rectilinear and Focused Pylon

Figure 18 illustrates the principle of the focused pylon, Reference 2. Such focusing systems get more and more complex if isolation in more than one axis is required. Good results can be achieved in connection with the twobladed teetering rotor, whereas other rotorsystems producing exciting rotor moments in addition to shear forces would have some difficulties. The problem with such isolation concepts is to provide adequate low-frequency isolation without excessive relative displacement. Isolation of the large vertical lifting forces of a helicopter rotor while maintaining a low relative displacement has precluded effective isolation in the vertical direction by conventional means.

Consequently use of the nodalization concept is the next step. Figure 19 illustrates the basic principle: at the node points no oscillating forces will be transmitted. Bell successfully demonstrated their nodal beam gearbox mounting system. This system interposes a beam mounting arrangement between the gearbox and the airframe, and is configured such that the airframe is suspended from the node points of the beam system when vibrating in response to the rotor hub forcing system, References 32 ÷ 34. The concept is illustrated in Figure 20.

Kaman has developed a system known as DAVI (Dynamic Anti-Resonant Vibration Isolator) with a strong similarity in its mechanism of operation to the Bell system. At first, it was intended to be used for the isolation of crew seats, but in the meantime it has been used successfully to isolate complete rotor systems with flight test programmes on Bell UH 1, MBB BO 105

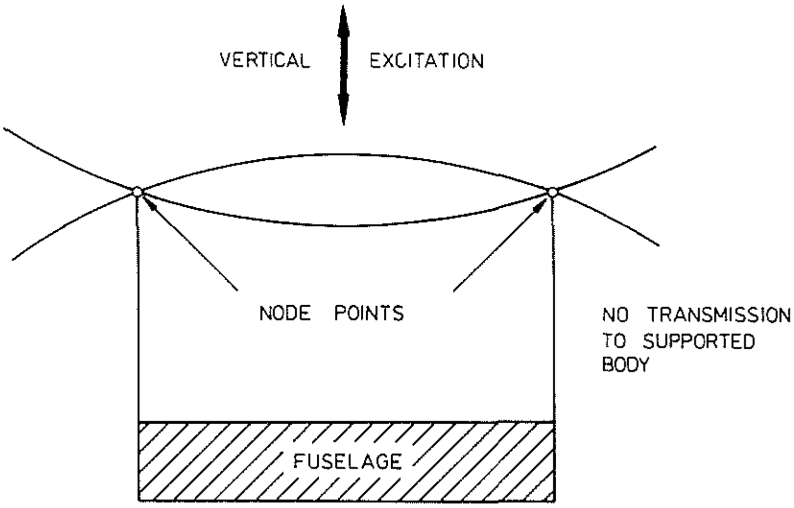
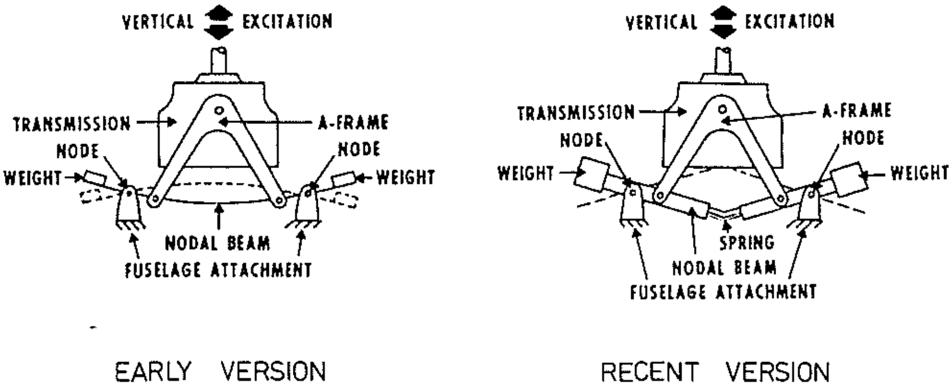


Figure 19 Principle of Nodalization



EARLY VERSION RECENT VERSION

Figure 20 Focused Pylon/Nodal Beam Isolation System (Bell)

and the Boeing UTTAS prototype, References 35, 36. The rotor/transmission unit is mounted on the fuselage by special isolator elements as illustrated in Figure 21. Operation of the isolator can be followed in Figure 22. The action of a nodal isolator differs significantly from a conventional isolator. A transmissibility plot for a conventional isolator has a resonant frequency with low tuning and then isolates above a certain frequency with the isolation improving as the frequency increases, reaching 100 percent isolation at infinite frequency. A nodal isolator has a resonant frequency with

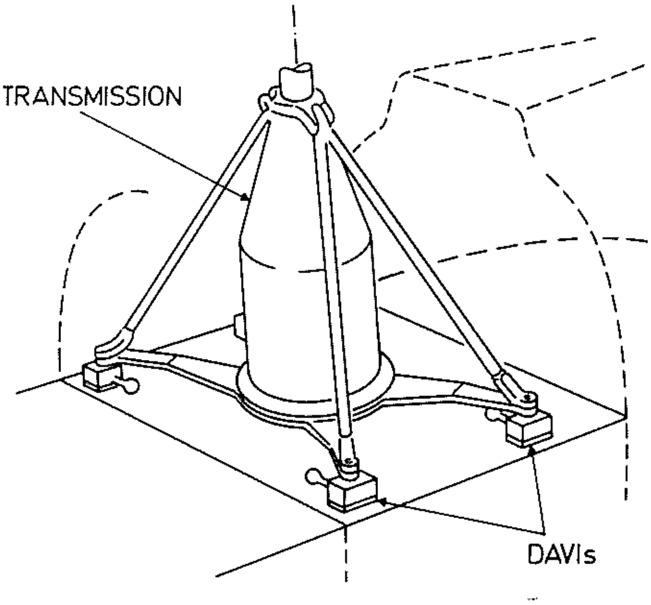


Figure 21 BO 105 Isolation System (Boeing Vertol)

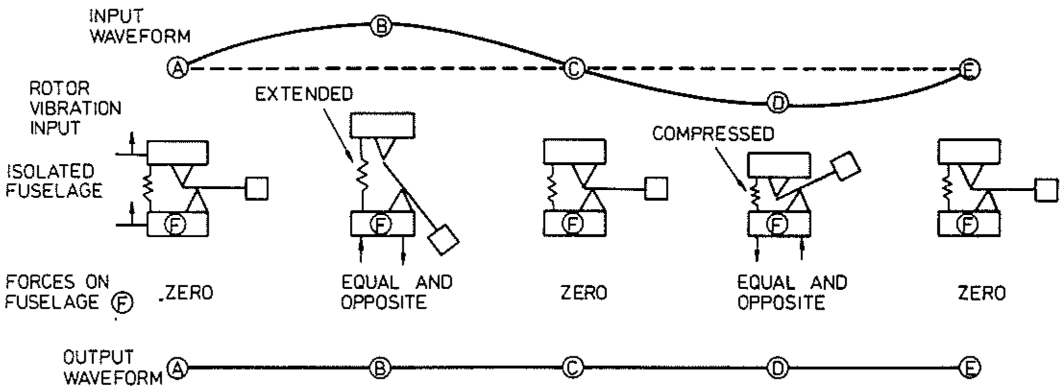


Figure 22 Concept of Antiresonance Isolation System

higher tuning, but then has a specific antiresonant frequency at which 100 percent isolation is achieved as shown in Figure 23. In case of damping the degree of isolation will be reduced. Figure 24 shows the effect of damping and isolator tuning, i.e. antiresonance frequency to isolator resonance. The isolator elements consist of spring elements to which pendulums are attached as illustrated in Figure 25. There are also isolators with dual

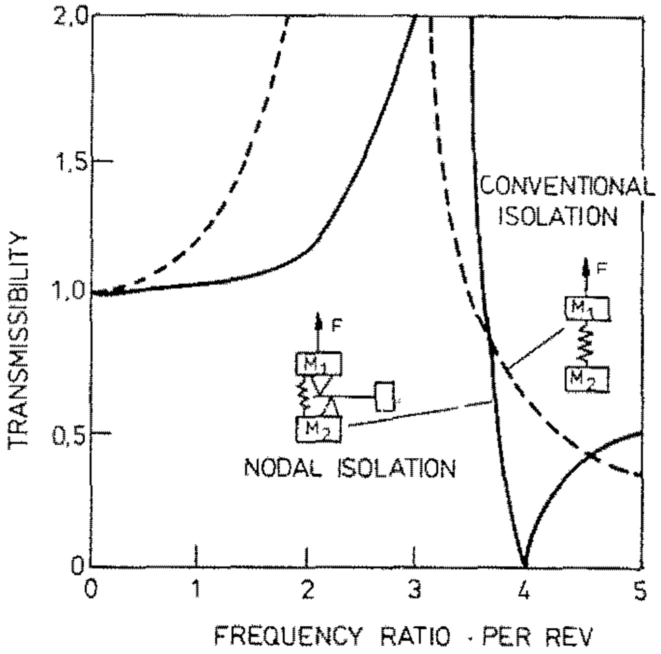


Figure 23 Comparison of Transmissibility Without Damping

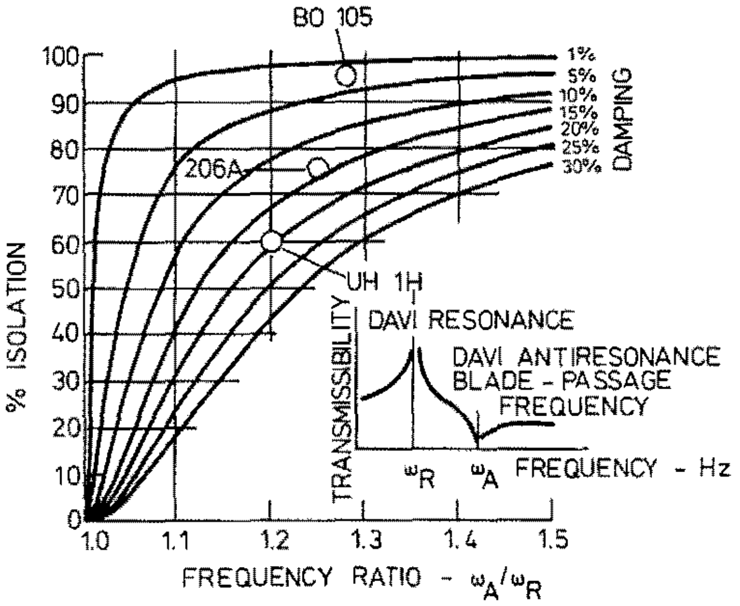


Figure 24 Isolation Efficiency for Different Frequency and Damping Ratio

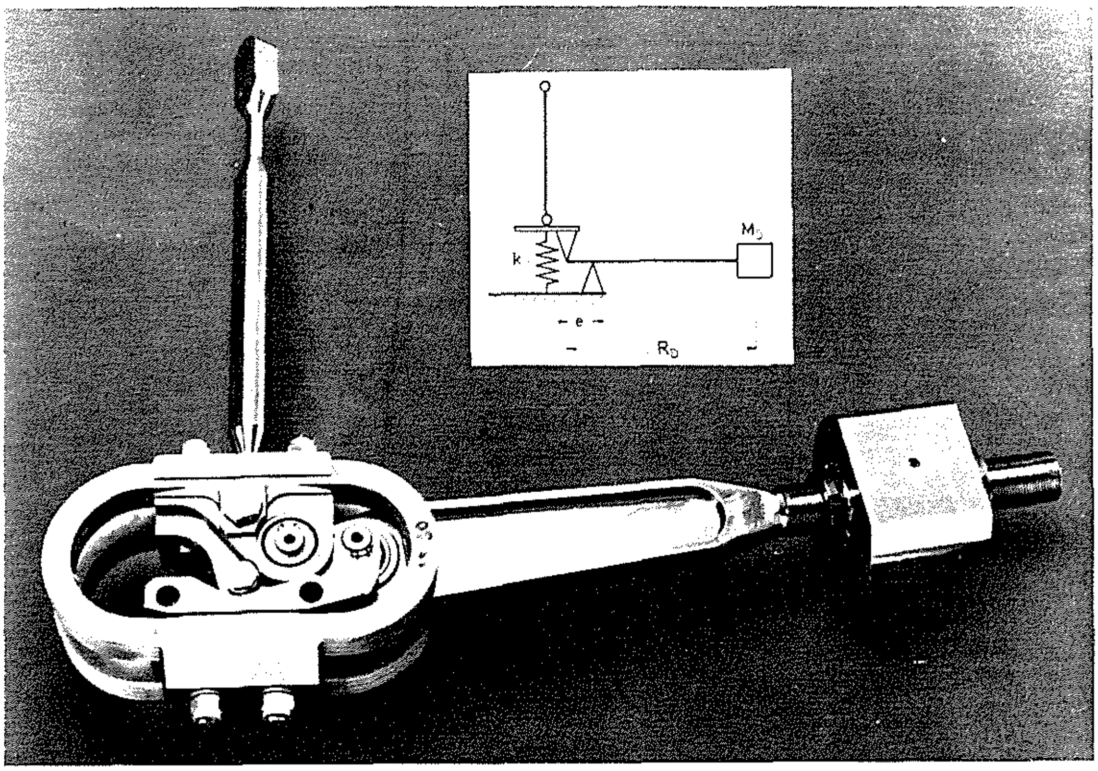
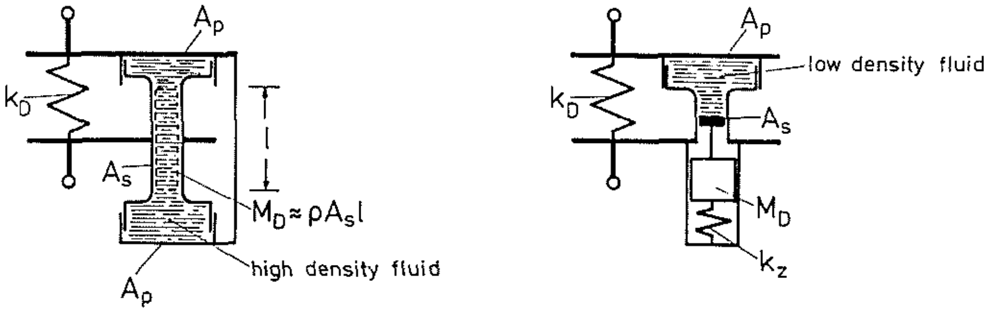


Figure 25 Antiresonance Isolator (MBB Design with Low Damping)

pendulums with two antiresonance frequencies and three dimensional isolators, References 36, 37. The full isolation of a rotor requires isolation in all axes, and this makes the system rather complicated. For maintenance and reliability the many additional bearings seem to be problematic. Therefore, possibilities for mechanical simplification have to be found. Two new isolator elements following the same principle seem to be very interesting and on the right way: the LIFE element of Bell, Reference 38, and MBB's hydraulic antiresonance isolàtor, Reference 39. The principle of both is illustrated in Figure 26 in comparison. Both systems use "hydraulic pendulums".

Passive nodal isolators are at a stage that they can be used for production helicopters. But they add mechanical complexity to the helicopter (as all other systems do also), and they get even more complex if more than one frequency has to be isolated.

A next step would be an active isolation concept. In the past several studies have been conducted, but they were not really successful not least by the lack of a sufficiently supported theory of the control system design, especially in the case of multi-axis isolation, and also by technological problems with the required high frequency actuating systems. In recent years, MBB has studied current possibilities of active force isolation systems, References 40 - 42. The progress of the overall understanding, of modern control theory, of electronics and modern servohydraulics seem to make such systems feasible as can be shown with functional tests. The principle of isolation is very similar in its operating mechanism as Figure 27 illustrates. The active system can be used as a force isolator, this means in comparison to the passive system that the pendulum is replaced by an electrohydraulic



LIQUID INERTIA VIBRATION
ELIMINATOR (LIVE) OF BELL

HYDRAULIC ANTIRESONANCE
ISOLATOR OF MBB

Figure 26 Antiresonance Isolator with Hydraulic Pendulum

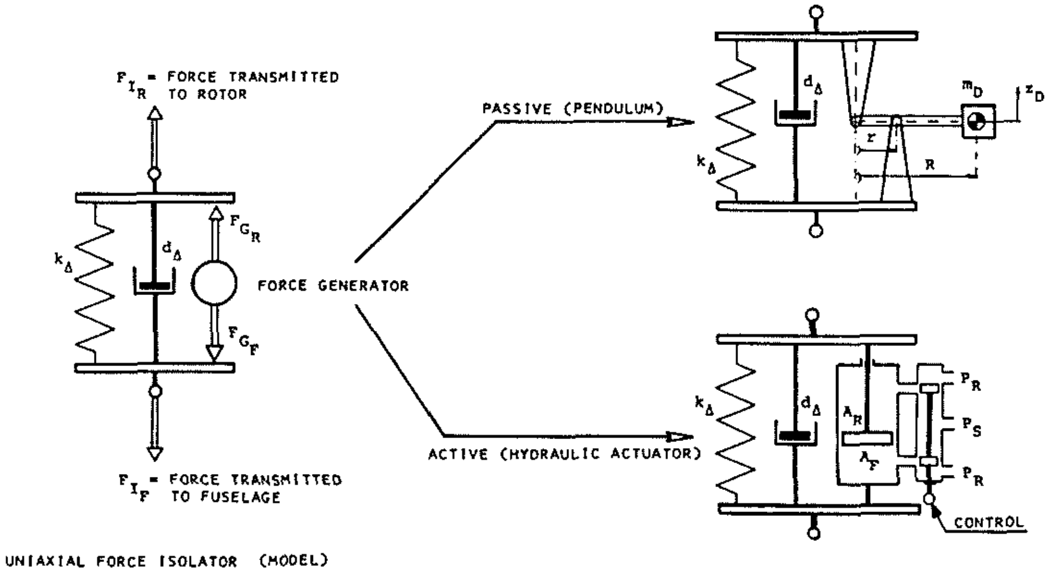


Figure 27 Realisation of Passive and Active Force Isolator

actuator, the dynamic characteristics of which are provided by the active, closed loop control system. The active system of rotor isolation can be easily adapted dynamically and optimised. It permits, without additional complication complete compensation of multi-frequency rotor excitations. It remains effective within the whole flight range, i.e. including variations in rotor speed, and it permits automatic trim of quasi-static relative displacement of the rotor/transmission unit. The advanced technology of servohydraulic actuating systems enables an efficient active isolation system to be realised that compares well, even today, on a weight basis with passive systems. In future, with the use of microprocessors for signal processing, even its cost may be comparable. But there is still technological work to be done.

Another different active isolation system is used with Sikorsky's Rotor Systems Research Aircraft (RSRA), Reference 43. The purpose of this system is to allow aircraft operation, with an arbitrary rotor system, over a wide rotor speed range and maneuver envelope without vibration restrictions, while simultaneously providing measurement of rotor system loads. The approach to vibration control of the RSRA which was selected was a transmission isolation system. It was envisaged that for some applications extremely soft transmission supports would be required for acceptable isolation. This led to the decision to use displacement feedback servo null hydropneumatic "active isolators" to recenter the transmission under the influence of flight loads. This active feature allowed arbitrary selection of unit spring constants to achieve isolation while ensuring that system interface motions would always be acceptable. Shown in Figure 28 are the primary elements in the isolation system: hydropneumatic, servo controlled actuator units. The unit is basically a hydraulic piston reacting against captured air chambers with a relatively low gain mechanical displacement feedback servo valve. The captured air bulk modulus provides a spring restoring force with piston displacement. Also when the piston displaces, the servo valve feeds hydraulic fluid into the piston chamber in the direction of motion, compressing the air and creating a restoring force on the piston 90 degrees out of phase with the piston displacement. The net result is that for static or transient loads on the isolator, the displacement servo feature keeps the unit centered in midstroke, while for high frequency motion, for which isolation is required, the unit acts as a soft air spring, as insufficient fluid flow through the servo occurs to create appreciable forces. This means that its basic principle is passive isolation but with active trim.

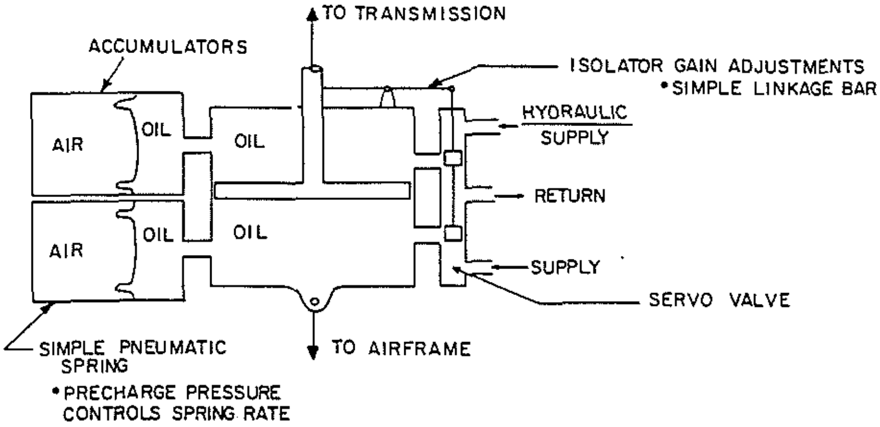


Figure 28 Schematic of Hydropneumatic Active Isolator

A classification of rotor isolation systems with regard to their physical principles and their applications is given in the table of Figure 29.

	PASSIVE	ACTIVE
CONVENTIONAL ISOLATION	SPRING-DAMPER ELEMENT - NOT PRACTICABLE BECAUSE OF LOW TUNING	SPRING-DAMPER ELEMENT WITH ACTIVE TRIM - MULTI-AXIS ISOLATION BY SEVERAL ISOLATORS - BROAD BAND ISOLATION
NODAL ISOLATION	FOCUSING - ISOLATION OF LONGITUDINAL OR/AND LATERAL AXIS - SINGLE FREQUENCY ISOLATION	
	NODAL BEAM - ISOLATION OF VERTICAL AXIS - SINGLE FREQUENCY ISOLATION	
	ANTIRESONANCE ISOLATOR - MULTI-AXIS ISOLATION BY SEVERAL ISOLATORS - DUAL FREQUENCY ISOLATION POSSIBLE	ELECTRO-HYDRAULIC ACTUATOR WITH DISTURBANCE REJECTION CONTROLLER - MULTI-AXIS ISOLATION BY SEVERAL ISOLATORS - MULTI-FREQUENCY ISOLATION POSSIBLE

Figure 29 Rotor Isolation for Helicopters

Vibration Control in the Fuselage

The methods for vibration control in the fuselage are mostly designed to produce a reduction in a local area only. This local area, for instance, could be the pilot seat, the instrument panel or in combination with installation of special equipment.

Such local reduction effects can be obtained with classical vibration absorbers involving the mounting of a suitably heavy mass with a spring system tuned close to the troublesome frequency. Sometimes the helicopter battery can be used, but in most cases a parasitic mass will be taken. Many helicopters under production use such absorbers. There are no problems for selection and design of such absorbers, so no further discussion is needed. Also soft mounting systems for equipment and instruments need no further discussion.

An interesting, but also complicated approach to vibration control at the fuselage is the integrated floor/fuel isolation system as used for the commercial Chinook, Reference 44. The passenger floor is isolated from the airframe on a series of passive nodal isolation units. In addition, the fuel tanks are isolated so that their dynamic mass is effectively nulled at all fuel levels, thereby avoiding any deleterious effect on airframe natural frequency placement. Aircraft tests demonstrated that the floor isolation could lower the vibration to an average of 0.05 g on the passenger floor.

5. Concluding Remarks and Future Prospects

There has been enormous progress with vibration reduction, but throughout the years requirements for vibration levels have been for lower values than could be realized with production helicopters. Because of the continuing progress of technology there will always be a high expectation on the side of the helicopter users, who are no longer willing to accept high vibration levels. All the helicopter manufacturers are optimistic for the future, and it is clear that further progress has to be made.

Today's and future stringent vibration requirements demand some additional resources for vibration control. Improved dynamic rotor design and improved structural design of the fuselage are a matter of course, but they are not sufficient for low vibration. With future helicopters it is necessary to make special provisions for vibration control as some of today's production helicopters are already doing. There are several concepts and means available as have been shown. Some methods are already applicable to production helicopters - others are still in the research phase. The most promising methods are for vibration control at the blades or the hub with special absorbers, or for the future with active higher harmonic control, and vibration isolation of the fuselage from the rotor/transmission unit using the antiresonance principle. Nodal beam isolation systems and concepts based on special antiresonance isolator elements (e.g. DAVI) are of a high standard. In the future active isolator elements may also be used.

Vibration control systems should be as simple as possible so as not to create new functional problems - functional reliability and maintainability contribute directly to the cost effectiveness of the whole helicopter. Of course, the weight of antivibration equipment should be as low as possible - for the future the target weight will be less than 1% of gross weight whereas today's systems are still higher than this. It seems that all the different systems, including the active ones, will have similar weights. Last but not least the direct production costs of the systems should be low - today passive systems still seem to be more advantageous, but the enormous progress of electronics and electro-hydraulics will bring active systems to a good position. Finally, the users of helicopters have to pay for all additional costs resulting from vibration control - therefore, vibration specifications have to be realistically determined to avoid excessive weight and cost penalties.

Vibration and its control will always remain a helicopter problem, but the "smooth helicopter" will become a reality in future as the understanding of the fully coupled rotor/fuselage system improves and vibration control techniques achieve perfection.

6. References

1. D.E. Brandt — Vibration Control in Rotary-Winged Aircraft. AGARD CP No. 7 (1966)

2. D.L. Kidd, R.W. Balke, W.F. Wilson, R.K. Wernicke — Recent Advances in Helicopter Vibration Control. 26th Ann. Nat. Forum of the American Helicopter Soc., Paper No. 415 (1970)

3.	D.E.H. Balmford	The Control of Vibration in Helicopters. Aeronautical J. of the Royal Aeronautical Soc. (1977) 81 (794)
4.	D.P. Schrage, R.E. Peskar	Helicopter Vibration Requirements. 33rd Ann. Nat. Forum of the American Helicopter Soc., Paper No. 77.33-33 (1977)
5.	D.E. Goldman, H.E. v.Gierke	Effects of Shock and Vibration on Man. Shock and Vibration Handbook, edited by C.M. Harris, C.E. Crede, McGraw-Hill Book Company (1961)
6.	R. Gabel, B.O. Henderson, D.A. Reed	Pilot and Passenger Vibration Environment Sensitivity. J. of the American Helicopter Soc. (1971) 16 (3)
7.	R.R. Lynn, W.G.O. Sonneborn	Rotorcraft Technology for the Year 2000. XII. Internationales Hubschrauberforum Bückeburg (1978)
8.	G.T.S. Done, M.A.V. Rangacharyulu	Use of Optimisation in Helicopter Vibration Control by Structural Modification. 5th European Rotorcraft and Powered Lift Aircraft Forum, Amsterdam, Paper No. 68 (1979)
9.	A. Mc Laughlin	Finite Element Analysis of Production Aircraft. 4th European Rotorcraft and Powered Lift Aircraft Forum, Stresa, Paper No. 20 (1978)
10.	J. Stoppel, M. Degener	Investigation of Helicopter Structural Dynamics and a Comparison with Vibration Tests. 6th European Rotorcraft and Powered Lift Aircraft Forum, Bristol, Paper No. 12 (1980)
11.	A.J. Landgrebe, R.C. Moffitt, D.R. Clark	Aerodynamic Technology for Advanced Rotorcraft. Nat. Symposium on Rotor Technology, American Helicopter Society (1976)
12.	R.B. Taylor, P.A. Teare	Helicopter Vibration Reduction with Pendulum Absorbers. J. of the American Helicopter Soc. (1975) 20 (3)
13	K.B. Amer, J.R. Neff	Vertical-Plane Pendulum Absorbers for Minimizing Helicopter Vibratory Loads. J. of the American Helicopter Soc. (1974) 19 (4)
14.	R. Gabel, G. Reichert	Pendulum Absorbers Reduce Transition Vibration. 31st Ann. Nat. Forum of the American Helicopter Society, Paper No. 930 (1975)

15.	H. Weiss	Vibration Treatment of BO 105 Rotor. 1st European Rotorcraft and Powered Lift Aircraft Forum, Southampton, Paper No. 26 (1975)
16.	W.F. Paul	Development and Evaluation of the Main Rotor Bifilar Absorber. 25th Ann. Nat. Forum of the American Helicopter Soc., Paper No. 354 (1969)
17.	R.W. White	A Fixed Frequency Rotor Head Vibration Absorber Based Upon G.F.R.P. Springs. 5th European Rotorcraft and Powered Lift Aircraft Forum, Amsterdam, Paper No. 69 (1979)
18.	N.D. Ham, R.M. McKillip	A Simple System for Helicopter Individual-Blade-Control and its Application to Gust Alleviation. 36th Ann. Forum of the American Helicopter Soc., Paper No. 80-65 (1980)
19.	C.E. Hammond	Wind Tunnel Results Showing Rotor Vibratory Loads Reduction Using Higher Harmonic Blade Pitch. 36th Ann. Forum of the American Helicopter Soc., Paper No. 80-66 (1980)
20.	E.R. Wood, R.W. Powers	Practical Design Considerations for a Flightworthy Higher Harmonic Control System. 36th Ann. Forum of the American Helicopter Soc., Paper No. 80-67 (1980)
21.	J. Shaw, N. Albion	Active Control of the Helicopter Rotor for Vibration Reduction. 36th Ann. Forum of the American Helicopter Soc., Paper No. 80-68 (1980)
22.	J.G. Yen	Vibration Reduction with Higher Harmonic Blade Feathering for Helicopters with Two-Bladed Teetering and Four-Bladed Hingeless Rotors. 36th Ann. Forum of the American Helicopter Soc., Paper No. 80-69 (1980)
23.	J.L. Mc.Cloud	Multicyclic Control for Helicopters: Research in Progress at Ames Research Center. 36th Ann. Forum of the American Helicopter Soc., Paper No. 80-70 (1980)
24.	R.B. Taylor, F.A. Farrar, W. Miao	An Active Control System for Helicopter Vibration Reduction by Higher Harmonic Pitch. 36th Ann. Forum of the American Helicopter Soc., Paper No. 80-71 (1980)

25.	T.J. Brown, J.L. McCloud	Multicyclic Control of a Helicopter Rotor Considering the Influence of Vibration, Loads, and Control Motion. 36th Ann. Forum of the American Helicopter Soc., Paper No. 80-72 (1980)
26.	J. Shaw, N. Albion	Active Control of Rotor Blade Pitch for Vibration Reduction: a Wind Tunnel Demonstration. Vertica (1980) 4 (1)
27.	M. Kretz, M. Larchê	Future of Helicopter Rotor Control. 5th European Rotorcraft and Powered Lift Aircraft Forum, Amsterdam, Paper No. 47 (1979), also Vertica (1980) 4 (1)
28.	N.D. Ham	A Simple System for Helicopter Individual Blade-Control Using Modal Decomposition. Vertica (1980) 4 (1)
29.	J.L. McCloud	The Promise of Multicyclic Control. Vertica (1980) 4 (1)
30.	E.R. Wood, R.W. Powers, C.E. Hammond	On Methods for Application of Harmonic Control. Vertica (1980) 4 (1)
31.	L. Beiner	Optimal Second Harmonic Pitch Control for Minimum Oscillatory Blade Lift Loads. 5th European Rotorcraft and Powered Lift Aircraft Forum, Amsterdam, Paper No. 43 (1979)
32.	R. Jones, J.H. McGarvey	Advanced Development of a Helicopter Rotor Isolation System for Improved Reliability, Volume I - Summary Report. USAAMRDL-TR-77-23A, AD-A051318 (1977)
33.	D. Shipman	Nodalization Applied to Helicopters. SAE-Paper 730 893 (1973)
34.	D.P. Shipman, J.A. White, J.D. Cronkhite	Fuselage Nodalization. 28th Ann. Nat. Forum of the American Helicopter Soc., Paper No. 611 (1972)
35.	A.D. Rita, J.H. McGarvey, R. Jones	Helicopter Rotor Isolation Evaluation Utilizing the Dynamic Antiresonant Vibration Isolator. 32nd Ann. Nat. V/STOL Forum of the American Helicopter Soc., Paper No. 1030 (1976)
36.	W.E. Hooper, R.A. Desjardins	Anti-Resonant Isolation for Hingeless Rotor Helicopters. SAE-Paper 760 893 (1976)

37.	R. Jones	The Exploratory Development of the Three-Dimensional Dynamic Antiresonant Vibration Isolator for Rotary-Wing Application. USAAVLABS TR 70-30, AD 875285 (1970)
38.	D.R. Halwes	LIVE - Liquid Inertia Vibration Eliminator. 36th Annual Forum of the American Helicopter Soc., Paper No. 80-22 (1980)
39.	D. Braun	Development of Anti-Resonance Force Isolators for Helicopter Vibration Reduction. 6th European Rotorcraft and Powered Lift Aircraft Forum, Bristol, Paper No. 18 (1980)
40.	G. Reichert, H. Strehlow	Investigations of an Active Vibration Isolation System for Helicopters. RAE Library Translation 1993 (1979) from Luftfahrtforschung und Luftfahrttechnologie Statusseminar (1977)
41.	H. Strehlow, R. Mehlhose, M. Obermayer	Active Helicopter Rotor-Isolation with Application of Multi-Variable Feedback Control. 3rd European Rotorcraft and Powered Lift Aircraft Forum, Aix-en-Provence, Paper No. 23 (1977)
42.	R. Mehlhose, M. Obermayer, M. Degener	Model Tests for an Active Rotor Isolation System. 5th European Rotorcraft and Powered Lift Aircraft Forum, Amsterdam, Paper No. 44 (1979)
43.	W.A. Kuczynski, J. Madden	The RSRA Active Isolation/Rotor Balance System, 4th European Rotorcraft and Powered Lift Aircraft Forum, Stresa, Paper No. 18 (1978) also J. of the American Helicopter Soc. (1980) 25 (2)
44.	R.A. Desjardins, V. Sankewitsch	Integrated Floor/Fuel Isolation System for the Model 234 Commercial Chinook. 5th European Rotorcraft and Powered Lift Aircraft Forum, Amsterdam, Paper No. 39 (1979)