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HELICOPTER GROUND AND AIR RESONANCE DYNAMICS

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Helicopter Ground and Air Resonance Dynamics

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Abstract

The paper reviews the state-of-the-art in understanding of helicopter rotor/fuselage dynamics phenomena and discusses the methods to study and predict the behaviour. Main objectives are the techniques to avoid or overcome instabilities and to eliminate design penalties.

For ground and air resonance problems a good understanding and useful analytical and experimental methods have been developed, but the influencing design parameters - e.g. coupling effects of the rotor dynamics need more systematic studies.

The influence on stability of dynamic inflow, aeroelastic and structural coupling of flap and lead-lag motion as well as pitch-lag coupling is investigated. Theoretical results are compared with test data of a model rotor.

1. Introduction

Problems with ground and air resonance are known since the beginning of helicopter construction. Due to the development of rotor systems from an articulated to a hingeless and finally to a bearingless rotor, however, there arise new points of view which always require the better idealization of airframe and, in particular, of rotor blades and blade connections (Fig.1).

Whereas, with articulated rotors, the large required dampings can be estimated with simple mechanical models, with hingeless and, especially, with bearingless rotors, more refined modelling is necessary. Furthermore, it has turned out that modelling of aerodynamical components, like forces, moments and down wash, also requires refinement. This is necessary for examinations of ground resonance as well as especially for examinations of air resonance in fast forward flight where reversed flow areas and Mach number effects have to be taken into consideration, too.

If these effects are included in a detailed mechanical substitute model, it turns out in comparison to measurements, that a possible instability in ground and air resonance behaviour of a helicopter can be quite exactly determined in advance. The influence of quite different geometrical quantities and coupling parameters can be examined as well as required dampings, and thus optimal configurations can be determined.

An examination of the vibrations of a helicopter becomes more and more important. While the behaviour of the structure, i.e. of airframe as well as of rotor blades, can be very well determined experimentally as well as mathematically, this is not possible in the case of determining the exciting aerodynamic forces. Here, additional fundamental research is necessary.

A good overview about these subjects is given by Johnson /1/, Friedman /2/ and Reichert /3/.

2. Mechanical Models of Fuselage and Rotor Blades

A quite simple mechanical model is the planar model with different behaviour in x and y direction (Fig. 2). It has been used by Coleman and Feingold /4/ for phenomenologial examinations. The blade properties are characterized by the point mass m_b, its radial position and the distance of the lag-hinge to the rotor hub. By inserting a hinge stiffness a hingeless and bearingless rotor can also be idealized with this model. Aerodynamical influences cannot be considered. But in addition, this model does not permit a complete reduction of size in the real helicopter. The position of the prevailing momentum pole is important for the movement of the three-dimensional helicopter. Both for the x and y direction there exist two positions of the momentum pole and therefore two planar models are needed to reduce the tree-dimensional system. An exact reduction furthermore can only be used in case of symmetrical properties of the fuselage. This behaviour, however, is never in existence for a real helicopter. Therefore, it is always advantageous to use three-dimensional models for the investigation of ground resonance of real helicopters (Fig. 3). Here, as well, the number of the examined degrees of freedom can vary.

In addition to the roll and pitch motion also the translatory degrees of freedom in x and y direction should be taken into consideration: Via the landing gear there exist a strong coupling of the x and pitch motion as well as of the y and roll motion. Using a spatial mechanical model the flap motion and therefore aerodynamic forces and moments can be included in the examination, which make an important contribution to the damping of pitch and roll motion of a hingeless helicopter.

The torsion motion can be also introduced as an additional degree of freedom of the blade. In order to include the different coupling effects of the blade motions, however, a quasi-stationary examination of the torsion motion is sufficient. The differential equation system, which describes the motion of the entire system, is homogeneous and has often periodical coefficients.

Sometimes the flexibility of the airframe cannot be neglected, especially if it is in the same order of size with the flexibility of the landing gear. In this case, the regressing frequency of the lead-lag motion can correspond to an eigen frequency of the airframe, whose mode contains, aside from the rigid body motion, flexible distortions.

The discretization of the airframe can be carried out very roughly (Fig. 4) for ground resonance examinations, or, by means of the Finite Element Method, also for vibration examinations (Fig.5). According to the use of particular elements like poles, beams, shells, etc., as well as to the position of node points, the number of the degrees of freedom is varying strongly. Depending on this number of freedom, the number of the caculated eigen frequencies can be attained. Here, the agreement between measurement and calculation in case of the lower eigen frequencies is increasing with an increasing number of degrees of freedom. Figure 6 shows a comparison of measured and by FE Methods calculated eigen frequencies. A model with 1302 degrees of freedom has been used /5/. The agreement is very good for the lower frequencies. In the upper frequency range, however, divergences amount to more than 10%.

Mechanical Model of Rotor Blade

Many coupling effects of the blade motions arises from the forces affecting the rotor blades. These forces are lift, drag, inertia forces, centrifugal forces and in particular the coriolis forces. But also the relative motion of the rotor blade in opposite to the rotor hub, i.e. flap, lead-lag and torsion movement, is responsible for coupling effects (Fig. 7).

Detailed examinations to this subject were made by e.g. Hodges and Ormiston /6/ Friedman /7/, Schrage and Peters /8/. The investigations by Huber /9/, Ormiston /10/, Shamie and Friedman /11/ as well as by Reichert and Huber /12/ include also the effects on the behaviour of the motion of the airframe.

In the following, a brief mention shall be made of some coupling effects which arise from the inclusion of the torsion flexibility of the interior region of the rotor blade as well as of the pitch links. On one hand, there is the pitch-lag-flap-coupling which results in case of a linearisation in a pitch-lag and a pitch-flap-coupling and on the other hand, there is a pure flap-lag-coupling. The flap-lag-coupling results from an unmatched stiffness of flap and lead-lag motion, depending on the blade pitch angle. This coupling effect is often called structural flap-lag-coupling.

According to Fig. 8, a simple relation for pitch-flap-lag-coupling results from inclusion of the torsion flexibility of the blade fitting. In forming the balance of moments around the torsion hinge, one immediately gets the relation:

$$\vartheta = \frac{C_\zeta - C_\beta}{C_{\vartheta_E}} \cdot \beta \cdot \zeta$$

in which C_ζ and C_β describe the stiffness of lead-lag and flap hinge whereas $1/C_{\vartheta_E}$ describes the flexibility of the blade fitting.

Furthermore, there exist some geometrical parameters of the blade which are of influence on the pitch-lag-flap-coupling (Fig. 8). These are on one hand sweep and torque offset in lead-lag direction and precone and droop in flap motion. Thus, the relationship for coupling effects can be described as:

$$\frac{\delta\vartheta}{\delta\zeta_e} = \frac{C_\zeta - C_\beta}{C_\vartheta} \cdot \beta_e - \frac{C_\zeta}{C_c} \cdot \beta_d \ , \quad \frac{\delta\vartheta}{\delta\beta_e} = \frac{C_\zeta - C_\beta}{C_\vartheta} \cdot \zeta_e - \frac{C_\beta}{C_c} \cdot \zeta_s$$

in which C_ϑ takes the total stiffness of the blade attachment and C_C the stiffness of the pitch link into consideration. The stationary flap and lead-lag angles β_e and ζ_e, due to flexible destortions, are again dependent on the geometrical parameters. A detailed description is given in Johnson /1/ and Hodges /6/. Figure 9 finally shows the idealization of a bearingless rotor blade. The blade itself is supposed to be rigid and is connected to the rotor hub via flap, lead-lag and blade pitch hinge. The flap and lead-lag motions are distributed on 2 hinges each in this case. The exterior hinges are following the blade pitch angle. Through this, a structural coupling of flap and lead-lag motion is caused. Because of the flexibility of the pitch links as well as because of the torsion stiffness of the flex beam, this results again in a pitch-flap-lag-coupling.

3. Ground Resonance and Required Damping

The phenomenon of ground resonance, which is a self excited vibration caused by coupling of the motion of fuselage and rotor, can arise by correspondence between the regressing lag frequency and one of the eigen frequences of the airframe. Fig. 10 shows in principle the course of frequencies in a body-fixed coordinate system dependent on the rotor angular velocity. The figure also shows the different courses of a regressing lag frequency for an articulated and a hingeless rotor. The possible instability ranges are shifted to higher rotor angular velocities in case of the hingeless rotor. Some instability areas are even outside the normal range for revs per minute. For the frequency crossings inside the normal range of revs per minute, the dampings of lead-lag motion and airframe are important for the preventation of an instability.

Aside from mechanical lead-lag dampers as used with articulated rotors, the origin for damping of the lead-lag motion can be structural and frictional dampings which are e.g. completely sufficient to avoid instability with hingeless rotors. Additional damping effects can emerge from the coupling of the blade motions, especially from the flap-lag-torsional coupling and also from dynamic inflow effects. The damping of the airframe can also emerge because of structural damping in the landing gear or because of friction between landing gear and the ground. With hingeless rotors, the aerodynamic rotor moments originating from the flap motion contribute considerably to damping the airframe. In some cases, especially with articulated rotors, some special landing gear dampers are necessary.

A first estimation of the damping required can be made with a simple one-dimensional substitute model. The motion of the airframe as well as the lead-lag motion are, in this case, understood as forced vibrations in which the excitation is on one hand the rotating centre of gravity of the rotor blades and on the other hand the motion of the airframe itself. With the extending function, one finally attains the following relation for neutral ground resonance stability, which is also called Deutsch-criterion in literature /1/:

$$d_\zeta \cdot d_x \geq \frac{n}{4} s_\zeta^2 \frac{\omega_x^3}{\omega_\zeta}$$

On the left is the product of airframe and lead-lag dimensional damping values, on the right, there is indicated by:

n = the number of blades
s_ζ= the first moment of inertia of the blade for lag hinge
ω_x= the airframe eigen frequency
ω_ζ= the lead-lag eigen frequency at the critical number of revs of the rotor

From the Deutsch-Criterion, the following conclusions can be drawn:

- For the stability of the system, the product of lead-lag damping and airframe damping is decisive.
- The quantity of the damping required in the most unfavourable case is dependent on the location of the critical airframe frequency and of the lead-lag frequency.

From this, it follows immediatly, that the damping required for a hingeless soft-in-plane rotor is considerably smaller than for an articulated rotor. For a stiff-in-plane rotor, there even is no danger of ground resonance (Fig. 12).

As an articulated rotor needs a large required damping and the coupling effects have only a small contribution to the damping, an accurate modelling of the coupling effects is not necessary in this case. Using a hingeless or bearingless rotor, where the required damping is lower considerably, the coupling effects may have a large influence.

A further important difference between an articulated and hingeless rotor is the frequency at which an instability can occur. Using an articulated rotor this frequency is quite low, whereas it may be much higher by a hingeless rotor. In way of comparison a calculation has shown that a helicopter with a hingeless rotor without any damping has a double time of about 4 sec in case of an instability. In opposit to that a helicopter with an articulated rotor has an explosiv instability with a double time of about 0,3 sec.

To show the dangerousness of the explosive instability the result of a ground resonance experiment is presented in the following. In this case also it was known on the basis of theoretical studies, that an instability can occur, but there was some doubt about the applicability of the mechanical substitute model, in which higher elastic modes of the airframe were included. Furthermore the opinion existed, that an arising instability can be prevented by a fast working destortion device of the airframe. The protocollation of this ground resonance experiment is shown in Fig. 13. In the first case the pilot had adjusted a collective pitch angle of 4° and carried out a cyclic excitation of ±2°. After ending the excitation the amplitudes of airframe and tail boom went down rapidly. In the second case a collective pitch angle of 6° was adjusted and a cyclic excitation of ±1,8° was carried out. The amplitude especially of the tail boom increased so fast, that the destruction of the helicopter in spite of the fast working destortion device could not be prevented. The result of this ground resonance experiment is shown in Figure 14. The airframe which was fixed on the ground, broke away and turned of about 90°. The rotor hub with the gearbox and one turbine broke away from the helicopter. One rotorblade was seperated from the hub. The airframe itself was destroyed completely also. The rotor used in this case was an articulated rotor.

In order to prevent accidents of this kind - the history of helicopter development has shown quite many - naturally exact calculations in advance are necessary for which extensive mechanical models describing the physical system as exactly as possible are required. Here, it is imperative to examine the quality of the mechanical and mathematical models by comparison of the calculated data with test results.

Bousman /13/ examined ground and air resonance in hover in very extensive tests at a test bed. He also included different cases of coupling of rotor blade motions in this examination. The measurements he determined thus represent a very good reference for assessing calculation models. Informations about the tests, the experimental plant as well as about the systemparameters can be found in /13/. In the following the calculation results obtained at the Institut of Flight Mechanics are presented briefly and are to be compared with the measurement data.

Fig. 14 shows the determined eigen values applied to the dynamic inflow model according to Johnson /14/ with CIF=0,5. In opposite to the dynamic inflow model according to Peters/Gaonkar/15/, Johnson inserts the stationary inflow + disturbance already in the mass flow rate (m), whereas with Peters/Gaonkar, the inflow is completely stationary. The determined eigen frequencies, (Fig. 14) show very good agreement with the measured data. The course of the regressing lead-lag frequency again shows the course typical for the hingeless rotor. The accompanying dampings are to be discussed in particular in additional figures.

Figure 15 shows the damping of the regressing lag mode in dependence of different inflow models. The two quasi-stationary inflow models do agree well with the measurement area in the maximum value, but are, however, shifted to a higher rotor angular velocity. Using the constant inflow model and the dynamic inflow model with CIF=1,0, the damping maximum is not attained.

The best agreement is attained by using the dynamic inflow model with CIF=0,5 as shown in Figure 16. The calculation results are entirely in the area of the measured points (except the area of $\Omega \sim 20$ rad/sec, where the regressing lag frequency curve and the roll frequency curve interfuse). The two best of totally eight calculation results which are compared to the measurement data by Bousman /13/ are included in Figure 3 furthermore.

The comparison of measurement and calculation results for pitch damping is to be seen in Fig. 17. While both the quasi-stationary inflow models deviate largely from the test data, the constant inflow model gives at least the characteristical course of the curve. The agreement of both the dynamic inflow models with the measurement is very good. Only the maximum value at the rotor angular velocity of about 10 rad/sec is shifted to a lower rotational speed.

In Fig. 18 the damping of the roll motion attained with the different inflow models is presented. In this case, the results determined with constant inflow show the largest deviance. The two quasi-stationary inflow models also provide no satisfactory agreement between calculation and measurement. Again the best results are attained with both the dynamic inflow models whose course of curves is only slightly deviant. It is conspicuous that the increase in stability of roll damping in the resonance range ($\Omega \sim 80$ rad/sec) was not found at measuring. This increase in stability is determined in every calculation and corresponds to the loss of the damping in the lead-lag motion.

In the previous calculations and measurements the blade pitch angle was set to zero (case 1 by Bousman /13/). In Fig. 19 the damping of the regressing lag mode attained with a blade pitch angle of 9° outbord of the flap and lag hinge is presented. The coupling of flap and lead-lag motion now results on one hand from the aerodynamical forces and on the other hand from the larger flap conus angle β_0 and thus from the coriolis forces. While the quasi-stationary inflow models determine too small the instability in the resonance area with the roll motion ($\Omega \sim 80$ rad/sec), the results in the resonance area with the pitch motion ($\Omega \sim 60$ rad/sec) agree very well with the measurement. The curves calculated by means of the constant or dynamic models are on the whole shifted to slightly more instable values. Therefore the instability maximum is very well determined at $\Omega \sim 80$ rad/sec, but the values in the resonance area with the pitch motion ($\Omega \sim 60$ rad/sec) have a lower amount in comparison to the test data. The best agreement is again attained with the dynamic inflow model with CIF=0,5. Fig. 20 shows the results in comparison to the calculations of CAMRAD and DRAV21.

In the third case examined by Bousman, a lead-lag hinge with a bevelled lead-lag axis was used. Thus a variation of the blade pitch angle is caused by the lead-lag motion. Because of this pitch-lag coupling, which is numerically indicated as 0,4 in Bousman /13/, there occurs aside from the stronger coupling of the blade motion, also a stronger interaction of lead-lag motion and pitch and roll motion of the airframe. In the course of the frequencies (Fig. 21), this can be seen in the fact that regressing lead-lag frequency and the respective airframe frequency are identical for a large area of rotor angular velocity. In case 1 (Fig. 14), in which the interaction of airframe motion and lead-lag motion was small, the areas with identical frequencies degenerated into points of intersection. Differing from the frequency course in case 1, here the eigenvalue of the inflow mode is complex for the whole area of the rotor angular velocity.

Fig. 22 shows the course of the damping of the regressing lead-lag motion including the pitch-lag-coupling. The quasi-stationary inflow model with CIF=0,5 and the constant inflow do not reach the maximum of instability in the resonance area. The quasi-stationary inflow model with CIF=1,0 is not included in Fig. 22.

The dynamic inflow models again result in a good agreement in the range of instability. In the range of resonance with the pitch motion ($\Omega \sim 60$rad/sec), however, the damping is too small. The best agreement with the test data is here attained by using the dynamic inflow model with CIF=1,0 (Fig. 23). In Fig. 23, the calculation results of CAMRAD and DRAV21 (see Bousman /13/) are also included. Comparing the curves with each other and with the measurements, the agreement in spite of the deviance at the rotor angular velocity $\Omega \sim 60$ rad/sec can be described as good.

If the blade pitch angle is adjusted at a hinge inside of the flap and lead-lag hinge, this results in a dependancy of the flap and lead-lag motion on the blade pitch angle as well as in an additional coupling of these blade motions: the structural flap-lag coupling. Calculations are carried out only with the two dynamical inflow models. The results are shown in Fig. 24. The maximum in the instability area is attained very well with the model with CIF=1,0, while in the resonance area with the pitch motion the damping is again too small. The curve calculated with the dynamic inflow model with CIF=0,5 is shifted on the whole to slightly less instable values. The dotted line shows calculation results presented in /16/ by Bousman.

The fact, that the calculated damping of the lag regressing mode is always in a good agreement with the measured data in the range of resonance with the roll motion but predicted too small in the resonance area with the pitch motion (except case 1), led to the assumption, that there could be some small errors in the differential equation system especially in the equation of the pitch motion. Therefore, the entire entry data for the x and y axis were interchanged and control calculations were made. As these calculations led to the same results exactly, this possibility for a mistake can be excluded. An explanation for the damping values determined as too small in the resonance area of lead-lag with the pitch motion could not be found.

Summing up the influence of the coupling effects it can be said, that with increasing coupling of flap, lag and pitch motion, the damping of the lag motion is increasing, too. But in the considered case the existing instability cannot be eliminated by these coupling effects.

The mechanical model, the aerodynamic approaches and the mathematical procedures taken as a basis for the calculations are discussed in detail in /17, 18/.

6. Rotor Forces and Moments for Vibrations

Helicopter vibration is a higher frequency response problem and therefore a better representation of the higher harmonic blade frequencies is needed. Assuming that the aerodynamic forces are periodical in a stationary flight state of a helicopter, they can always be described by means of a Fourier series in rotor harmonic terms. In Figure 25, aside from these rotor harmonic frequencies, also the flap and lead-lag eigen frequencies of the rotor blades are included. It turns out that an intersection of rotor harmonic and blade eigen frequency is hardly avoidable. Thus, some modes of the flap or lag motion are always excited with their eigen frequency. The large amplitudes due to this excitation lead at last to vibrations transfered to the airframe. Therefore, by the dynamic blade design it should be tried to have a large distance between the points of intersection of rotor harmonic and blade eigen frequencies and the nominal rotor angular velocity.

Using structural optimization of the rotor blades it is tried to minimize the amplitudes of the vibrations. The results are definitely good but only particular flight states can be examined.

Aside from nonlinearities in the structure, the reason for the higher harmonic excitation can be especially aerodynamic effects. The irregular flow effects result e.g. from:

- unsteady flow effects
- vortex inference
- stall effects
- transonic conditions
- aerodynamic interaction between airframe and rotor
- non-linear, structural interactions
- Mach number effects

In order to prevent these vibrations transfered from rotor to airframe, different approaches are tried out. In principle, all systems can be divided in passive and active systems and these again in direct and indirect systems. The indirect systems influence the forces from rotor to airframe by subsystems, which have an effect as power generator. On one hand these subsystems work passiv like e.g. pendulum absorber or on the other hand also active via hydraulic system etc.. Both methods have in common that they want to keep forces and moments already originating at the rotor away from the airframe. Thus, this systems can be described as working indirectly.

In opposit to that the direct systems try to prevent or to reduce, respectively, the origin of vibrations already at the rotor blades. A wellknown example for this is the Higher Harmonic Control, which is discussed in lots of analytical as well as experimental examinations. A problem which is up to now unsufficiently resolved is, however, the analytical description and the inclusion of aerodynamical effects in numerical calculations.

Conclusion

Generally, it can be said that the phenomena are understood satisfactorily in further areas. In ground- and air resonance examinations, which represent a low frequent stability problem, the experimental and analytical tools are very good for predicting the dynamic behaviour. The influence of many different system parameters is known but further systematic examinations are necessary especially hingeless and bearingless rotors need more sophisticated models. Active Control Systems in order to prevent instabilities are up to now, hardly examined.

The analytical tools to examine helicopter vibrations, which represent a higher frequent response problem, are unsatisfactory. The optimization of the dynamic behaviour of rotor blades in order to reduce vibrations has definitely turned out to be useful. The knowledge of higher harmonic aerodynamic forces is, however, insufficient. With analytical methods, no satisfactory agreement between theory and measurement can be attained.

In order to reduce the vibration level, active, passive, direct and indirect systems can be used, which like e.g. the HHC still require an intensive further development.

Acknowledgement

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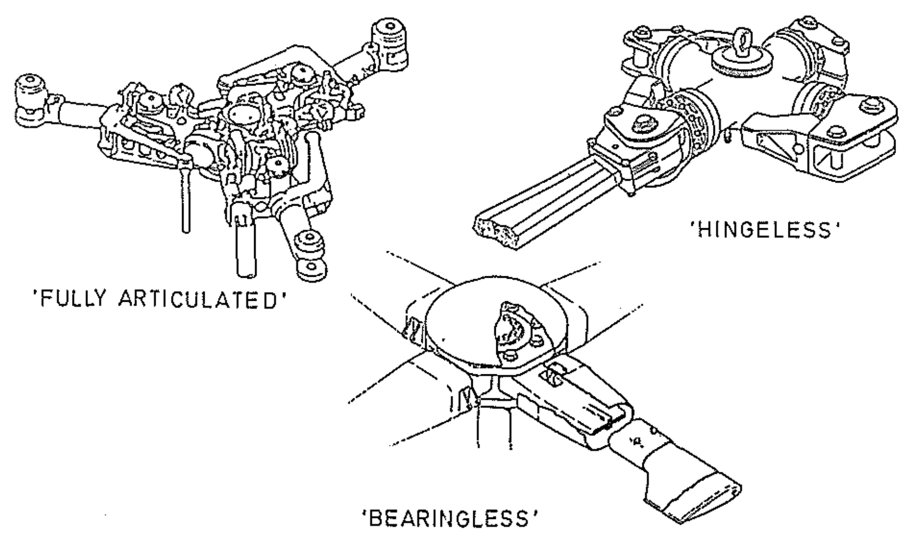


Fig.1: Different rotorsystems

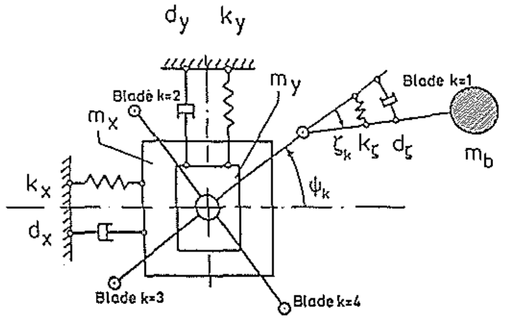


Fig.2: Plane model of ground resonance

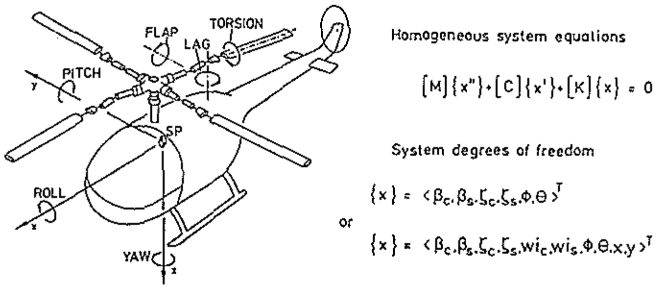


Fig.3: Coupled rotor-body model

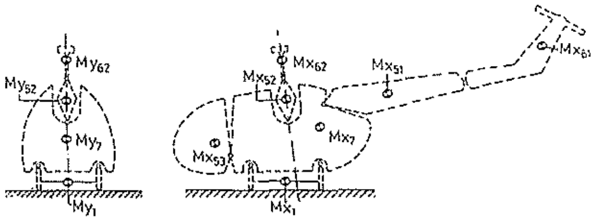


Fig.4: Mechanical model of airframe

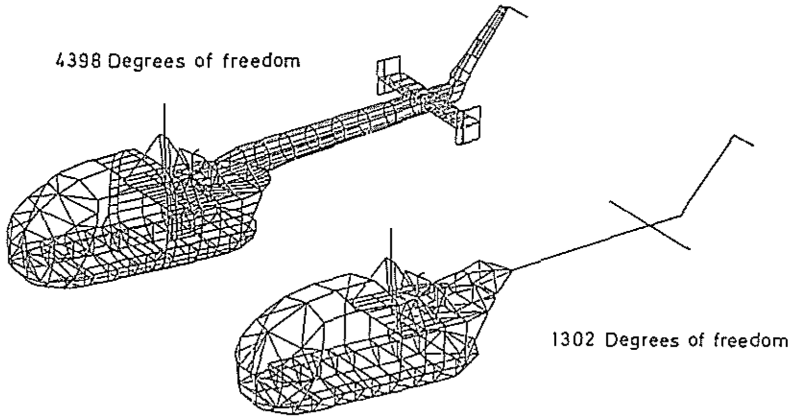


Fig.5: FEM-model of BO 105

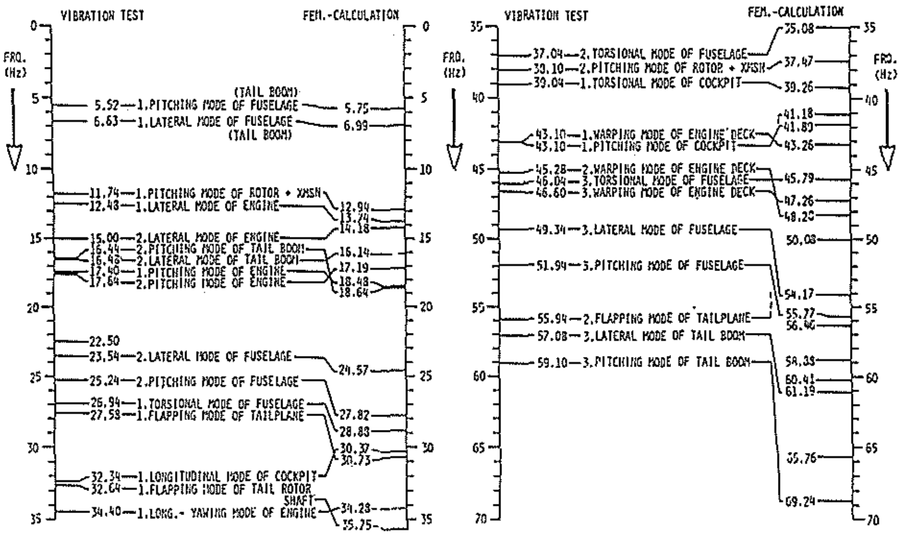


Fig.6: BO 105 body frequencies and modes

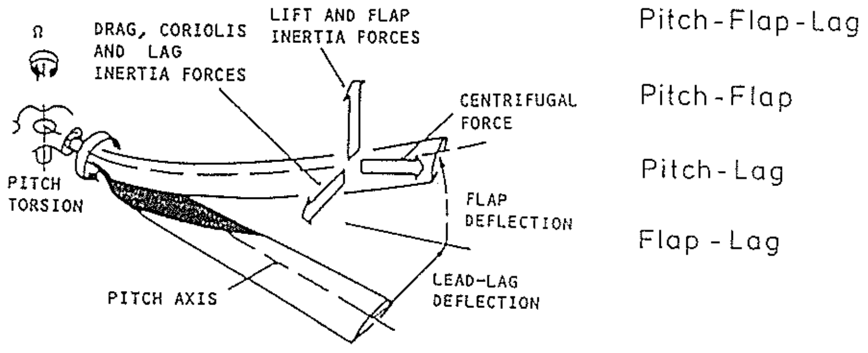


Fig.7: Blade coupling effects

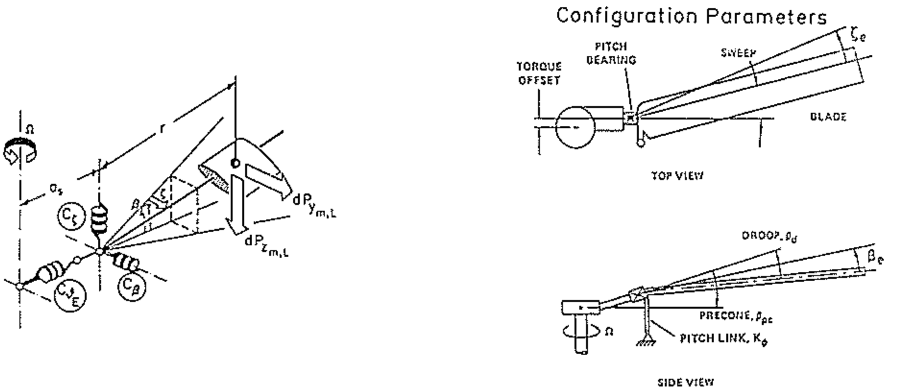


Fig.8: Blade coupling

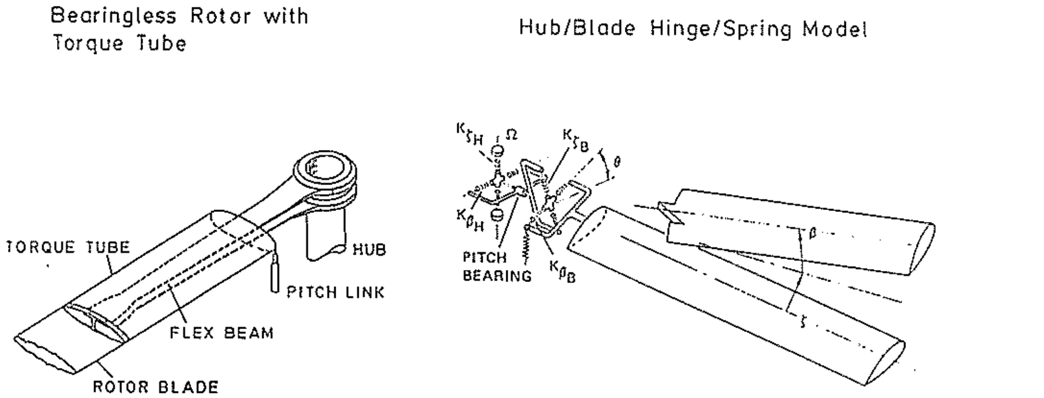


Fig.9: Idealization of a bearingless rotor

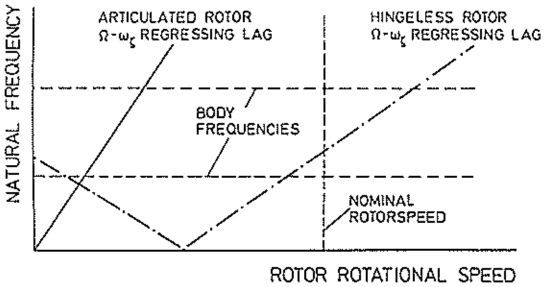


Fig.10: Frequency diagram of ground resonance

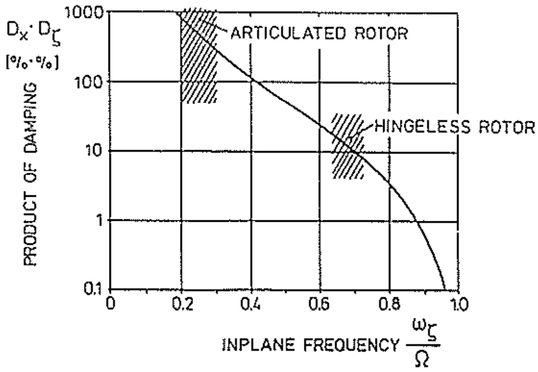


Fig.11: Damping for neutral ground resonance stability

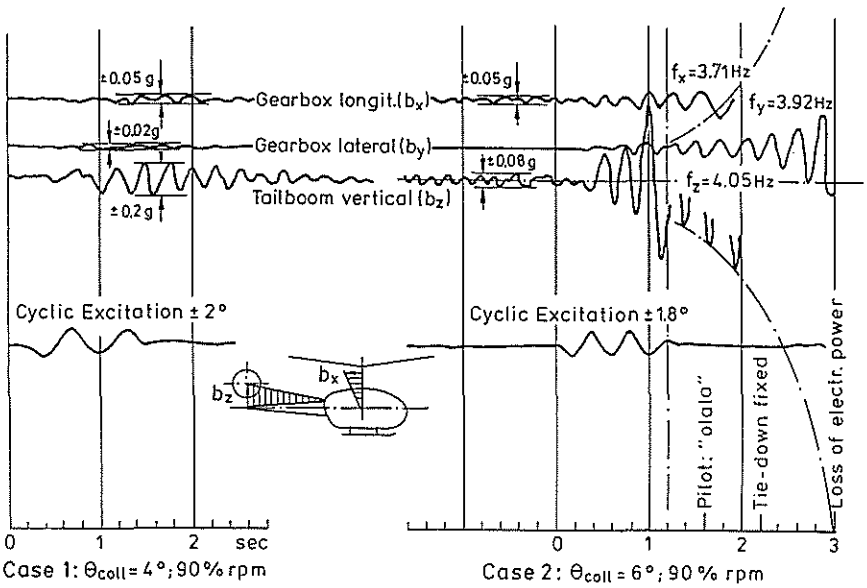


Fig.12: Ground resonance test results

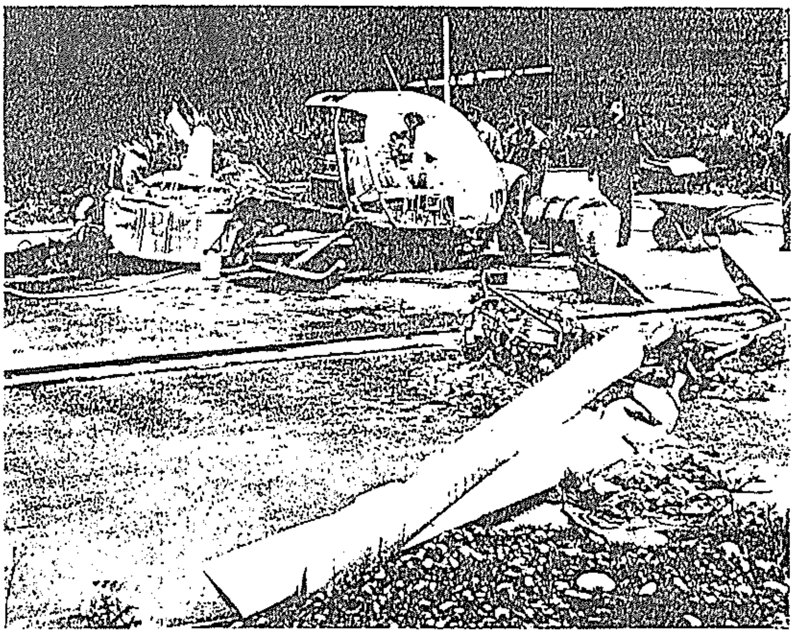


Fig.13: Ground resonance of a helicopter with fully articulated rotor

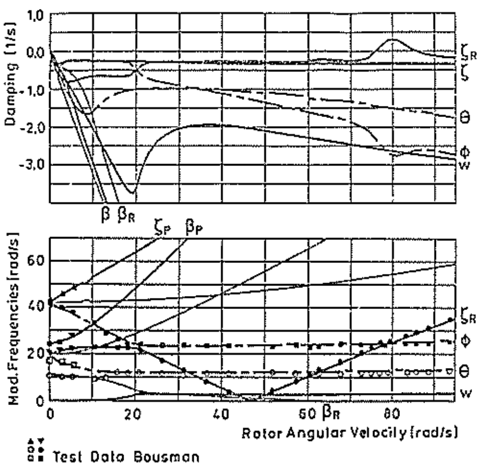


Fig.14: Comparison of theory and experiment damping and modal frequencies

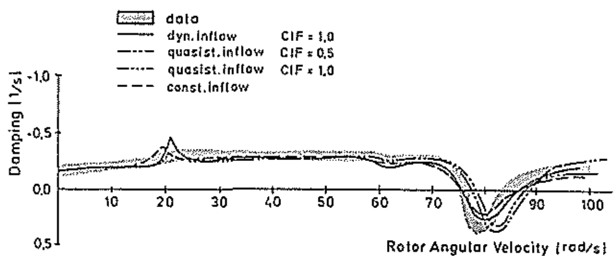


Fig.15: Damping of regressing lag

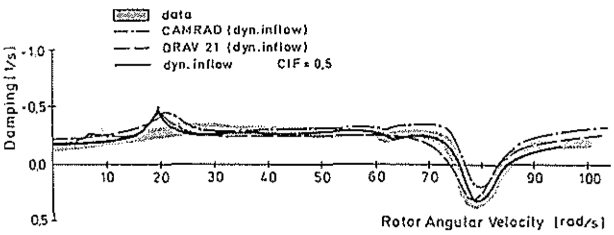


Fig.16: Damping of regressing lag

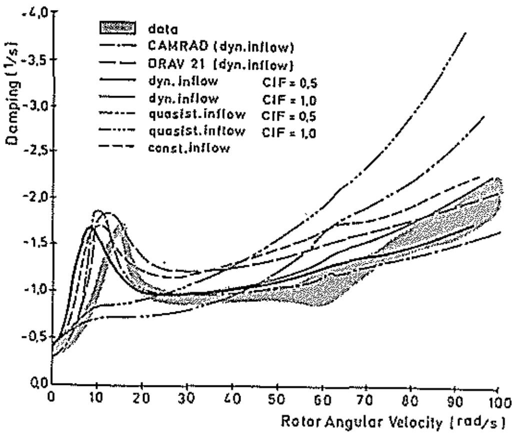


Fig.17: Pitch damping

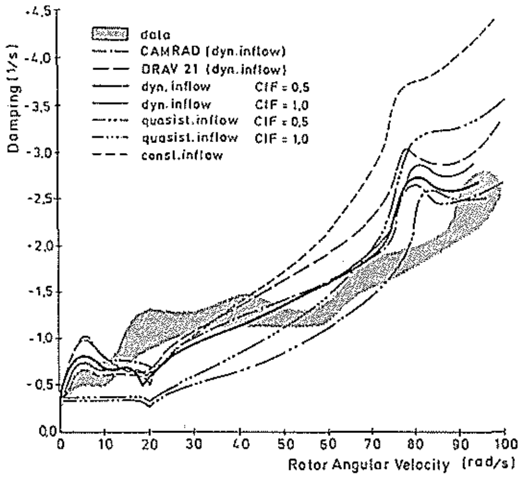


Fig.18: Roll damping

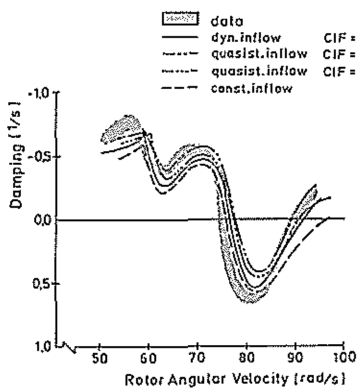


Fig.19: Damping of regressing lag
(blade pitch angle 9° (case 2))

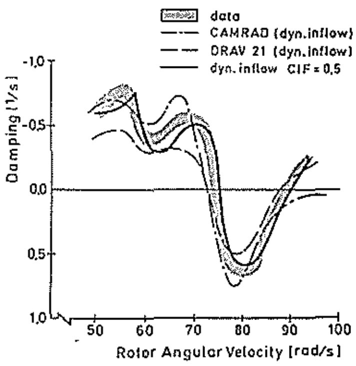


Fig.20: Damping of regressing lag
(blade pitch angle 9° (case 2))

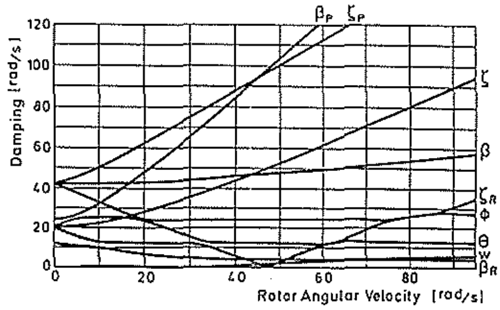


Fig.21: Modal frequencies
(pitch-lag-coupling (case 3))

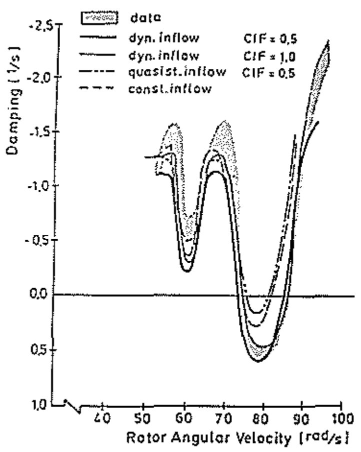


Fig.22: Damping of regressing lag
(pitch-lag-coupling (case 3))

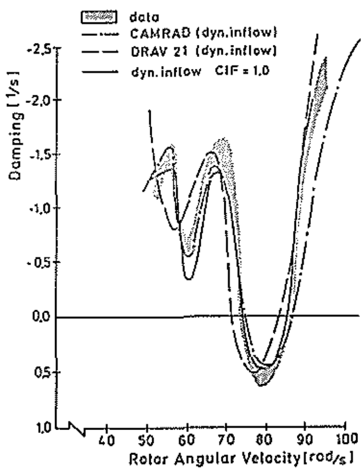


Fig.23: Damping of regressing lag
(pitch-lag-coupling (case 3))

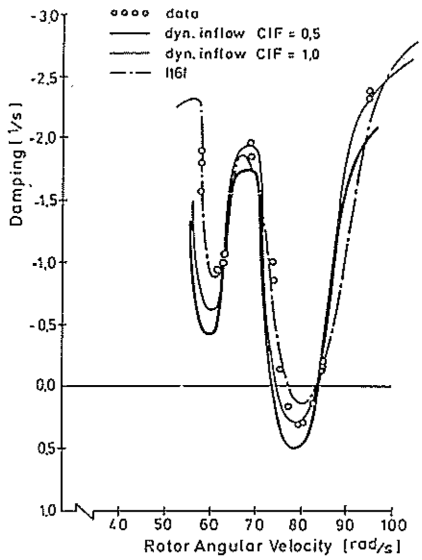


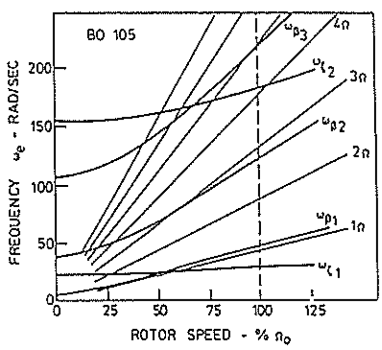
Fig.24: Damping of regressing lag
(structural coupling)

Rotorblade Frequency Diagram

Resulting from aerodynamic and dynamic characteristics.

Higher harmonic behavior determined by

- unsteady flow effects
- vortex interference
- stall effects
- transonic conditions
- aerodynamic interaction between airframe and rotor
- non-linear structural interactions



Dynamic blade design determines dynamic amplification.

Fig.25: Rotor forces and moments for vibrations

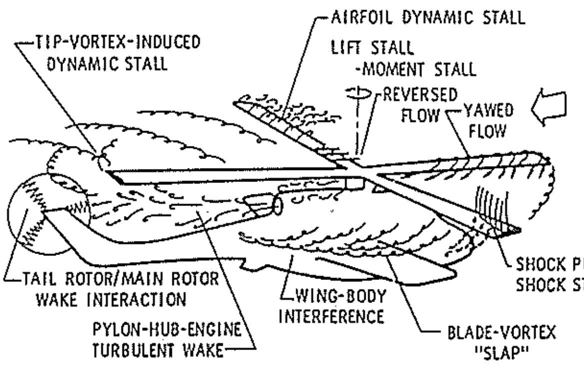


Fig.26: Rotor transient aerodynamics