NINETEENTH EUROPEAN ROTORCRAFT FORUM

Paper n° G17

INFLUENCE OF DISSIMILAR BLADES ON VIBRATIONS.

by

M. ANTHOINE, F. BEROUL
EUROCOPTER FRANCE

A. OTHO, J. VINCENTI
SERAM

September 14-16, 1993
CERNOBBIO (Como)
ITALY

ASSOCIAZIONE INDUSTRIE AEROSPAZIALI
ASSOCIAZIONE ITALIANA DI AERONAUTICA ED ASTRONAUTICA

INFLUENCE OF DISSIMILAR BLADES ON VIBRATIONS.

M. ANTHOINE, F. BEROUL
EUROCOPTER FRANCE

A. OTHO, J. VINCENTI
SERAM

1) Introduction:

A major improvement to future helicopters is going towards ever increasing speeds. EUROCOPTER FRANCE's research work in this area has met success with the High Speed Dauphin. But, introducing such high performance helicopters must go beyond record breaking and take crews' and passengers' comfort into account.

Many vibration control systems have been developed to counter the N-per-rev loads transmitted by the rotor to the structure. However, very little attention was paid to other rotor harmonic frequencies transferred to the structure only in case of blade dissimilarities. Most efforts have been focused on the stability problems induced by blade dissimilarities as proved by the papers referred to herein (Ref 1, 2, 3).

Higher speeds and higher loads on blades combined with the search for a better comfort will lead to the study of loads other than N-per-rev and not only stability problems.

Although small, these harmonic loads can become a concern for passengers through fuselage structural response, vibration control systems resonant frequencies and beating phenomenon.

This paper describes the results obtained by ECF on non isotropic rotors with two complementary computation codes.

The first code - RNU - is an analytical model of the rotor which enables a simulation of defects on blades for a trimmed helicopter in hover and in forward flight. This model saves calculation time for rotor balancing simulation and provides evidence that balancing a blade in hover may not be enough to cancel loads in forward flight. Correcting defects in hover may even induce additional loads in forward flight.

A more sophisticated model - R85 - was used to confirm and extend the study of non isotropic rotor. Loads are calculated for each individual blade and are then combined to provide the total dynamic loads on the rotor hub for all harmonics.

The most important findings with this code relate to the way various defects generate loads with various phases, which may thus combine to obtain very different rotor hub loads depending on the relative blade positions on the rotor head.

2) Blade balancing industrial method:

Blade dissimilarities can be induced by manufacturing errors or various damages. Although produced on an industrial basis, composite blades vastly rely on workers' rigour and skill to ensure the required quality. Many inspections are made at each manufacturing stage (weight, mechanical properties, mold temperature, holographic inspection . . .). Each blade is still slightly different from the others and cannot be fitted to the aircraft before being balanced.

Blade defects may be of different types : weight, spanwise and chordwise c.g. position, spanwise weight distribution, airfoil shape, blade twist, leading and trailing edge shape. All can have consequences on the dynamic behaviour. Therefore, a short presentation of blade balancing may be useful prior to the presentation of work on rotor anisotropy.

First, all blades must have the same first moment of inertia. This adjustment is made on a balance and must be very accurate to obtain the same centrifugal force for all blades. Adjustment weights are added to the blade tip along the pitch axis (25% chord).

The blade is then tested on a rotor dynamic balancing stand. This rotor uses three blades (even for four-bladed helicopters) : the blade to be balanced, a master blade and a companion blade. The master blade is representative of the "average" production blade. Its role as reference makes it very valuable and it must be protected from rain and dust. The companion blade is less important, it is used to check possible changes in the rotor behaviour.

The goal is to obtain, for all blades, the same track (height H_θ) and control loads (pitch moment M_θ) for the whole pitch range through pitch rod length, trim tabs and dynamic weights (figure 1).

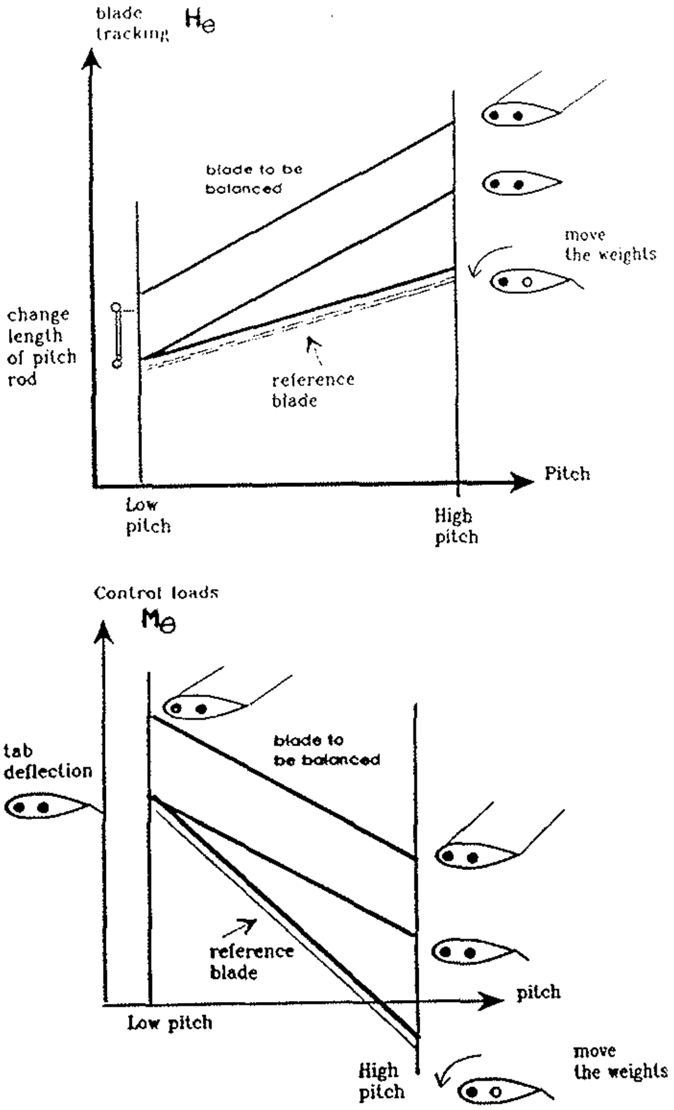


Figure 1: Blade track and balance on balance stand

At low pitch, the pitch rod length is adjusted so that the tested blade has the same track as the others. This change in blade angle-of-attack is called ΔI. Track is then recorded at high pitch.

Also at low pitch, the trim tab is deflected to obtain the right control loads. Tab deflection has almost no direct consequences on lift but it twists the blade and changes the pitch thus playing on control loads (nose down for downward tab deflection).

At high pitch, the dynamic weights are moved to get the same blade tracking and control loads. Dynamic weights are placed at blade tip symetrically to the pitch axis. Weights produce a pitch-proportional moment due to the centrifugal forces on them (nose down moment for weights moved forward) (figure 2). At low pitch, the centrifugal forces are almost parallel to the blade and do not generate any pitching moments.

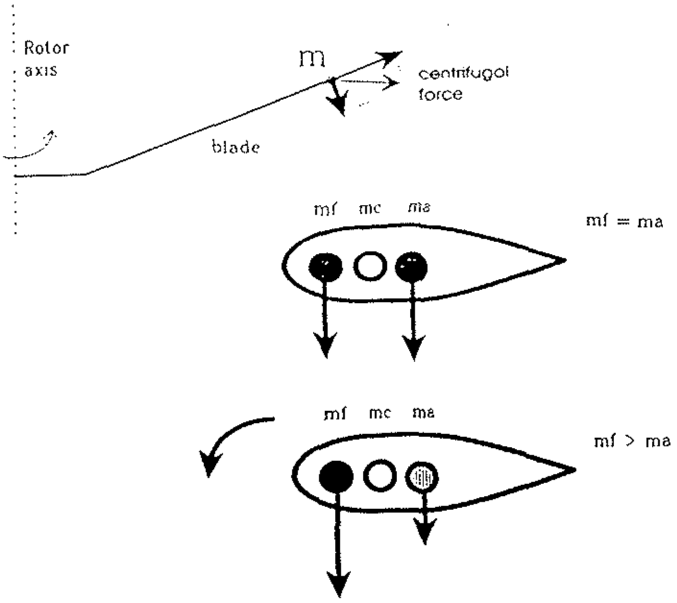


Figure 2: Centrifugal forces on blade tip weights

Perfect adjustment is seldom achieved but a compromise on all parameters enables to get all the blades in a very narrow window as concerns track and loads whatever the pitch. Despite the accuracy of these tests, minor corrections to pitch rod length and tab deflection are still necessary on the aircraft due to the rotor hub and in order to obtain a satisfactory compromise between hover and forward flight (which cannot be simulated on the stand).

3) Description of analytical model:

In order to improve our understanding of balancing problems related to the main rotor, an analytical model of the helicopter has been developed.

This model is intentionally simplified and does not take into account all dynamic and aerodynamic interactions on the aircraft.

First, an isolated non isotropic rotor model was developed. An analytical model of the aircraft fuselage was then added to simulate the configurations used for rotor balancing (aircraft on ground, in hover and at high speed). This model resulted in the RNLI calculation code. This program provides the 1-per-rev loads generated on the rotor head due to anisotropy.

The following hypotheses have been made.

Fuselage

- Aerodynamic efforts on fuselage limited to drag;
- Inclined rotor hub (angle γ_q)
- Aircraft pitch (τ) and roll (φ) attitudes taken into account
- Tail rotor efforts limited to thrust

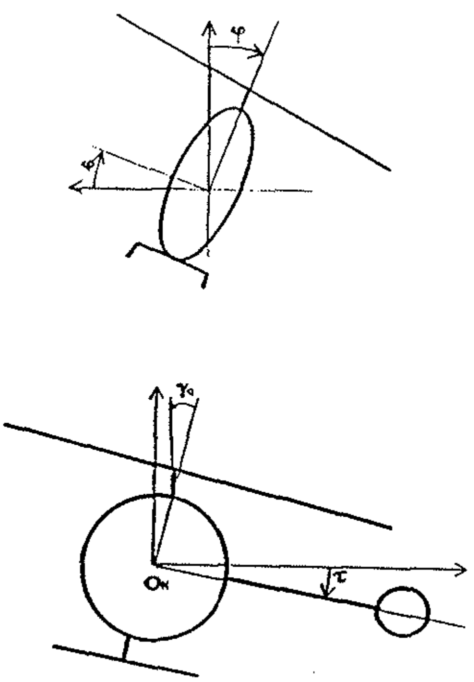


Figure 3: Aircraft attitude

Rotor

- Rigid blades
- Pitch, flapping and drag hinges concentrated at a single location
- Center of gravity and thrust center offsets disregarded
- Twisted blades
- Blade aerodynamics simplified:
  Lift and drag coefficients are constant since stall effects are not considered and the effect of Mach number on lift coefficient is also disregarded.
- The pitch-flapping link is not modelized
- Pitch, flapping and drag angles are described using Coleman transform

$$\theta = \theta_0 + \theta_{1C}.\cos\Psi + \theta_{1S}.\sin\Psi$$
$$\beta = \beta_0 + \beta_{1C}.\cos\Psi + \beta_{1S}.\sin\Psi$$
$$\delta = \delta_0 + \delta_{1C}.\cos\Psi + \delta_{1S}.\sin\Psi$$

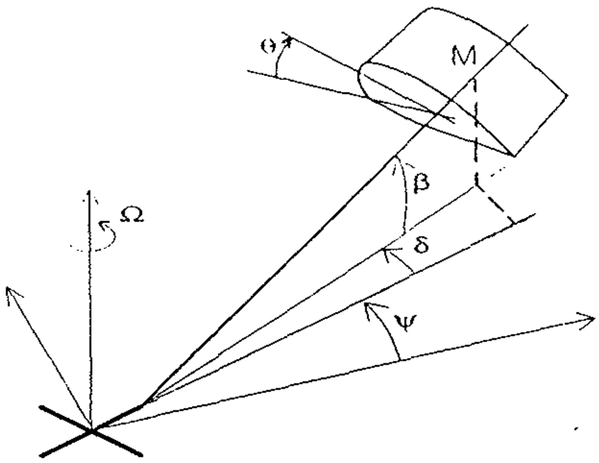


Figure 4: Angle definition

The system of equations to be solved, for describing a flight configuration includes 11 non linear equations with 11 unknowns:

$$\{\varphi, \tau, \theta_0, \theta_{1C}, \theta_{1S}, \beta_0, \beta_{1C}, \beta_{1S}, \delta_0, \delta_{1C}, \delta_{1S}\}$$

First, we find the rotor tilt angle, then the inflow ratio is evaluated by MEIJER-DREES formulation and the system of non linear equations is solved using a modified Newton method.

After solving the problem, the loads on the rotor head are calculated by adding the contribution of each blade. The rotating load modulus and phase generated by one or several defects is obtained.

R85 computations validate this new code. The main discrepancy relates to the lateral balance parameters at high speed $\{\beta_{1S}, \theta_{1C}, M_X, F_Y\}$. This is partly explained by the important pitch on blades at this speed which would lead to use a real polar with the lift coefficient depending on the angle of attack. Moreover, since lateral rotor flapping is low, the system of equations is poorly conditioned despite the use of dimensionless parameters.

The analytical formulation and the R85 numerical simulations provide very similar results.

Defect simulations

RNU allows to simulate the following characteristics for each blade

- blade weight
- blade first moment of inertia
- blade second moment of inertia
- static stiffness of lead lag damper
- tab deflection

Several computations (figure 5 and 6) show simulations of such defects. The first figure shows calculations in hover and the second in high speed level flight .

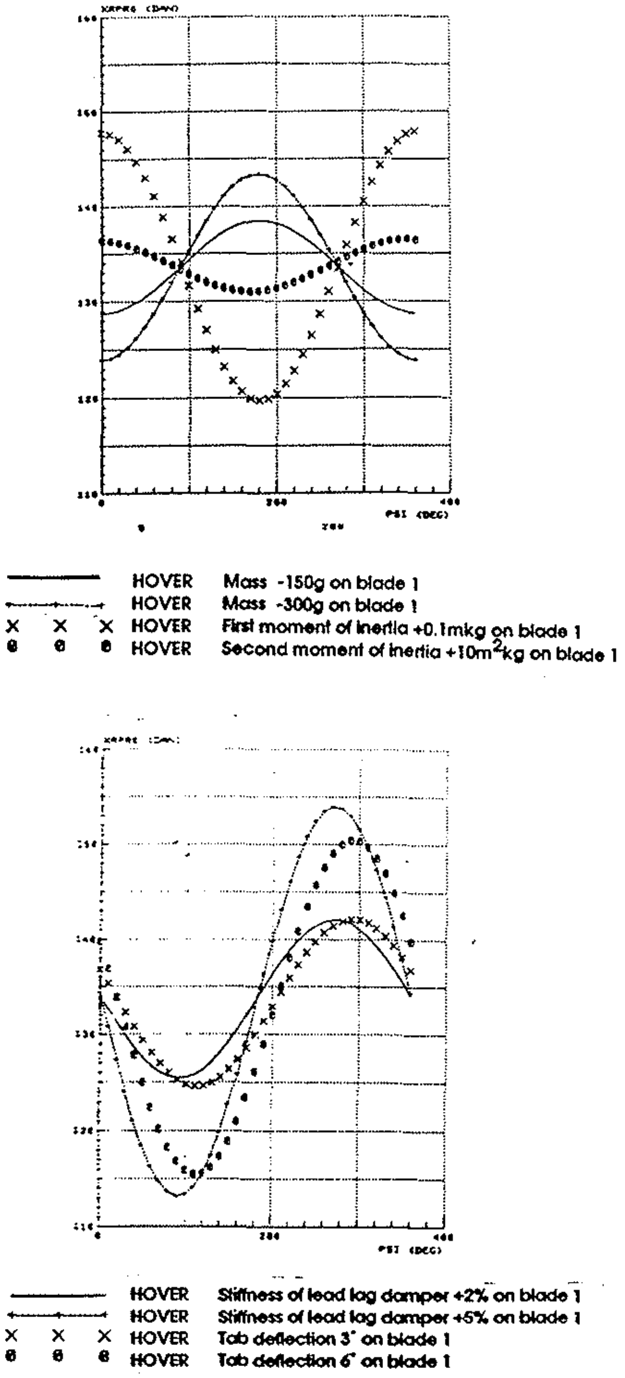


Figure 5: One per rev loads for several defects in hover

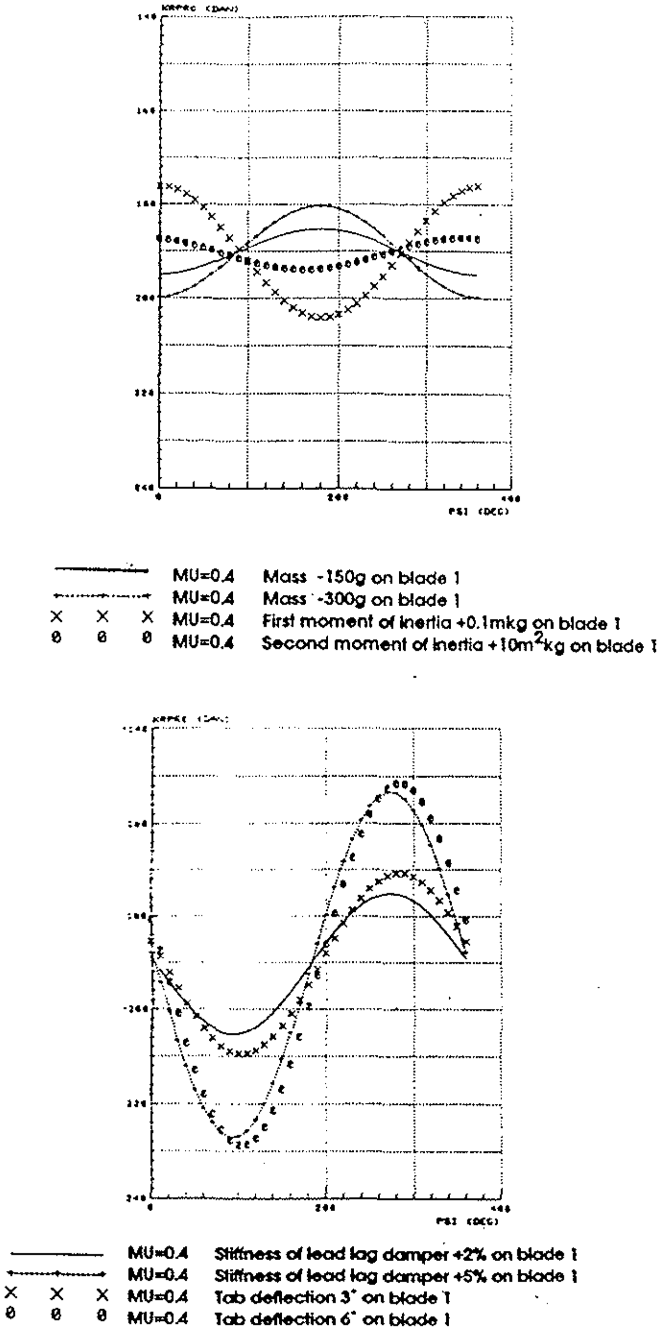


Figure 6: One per rev loads for several defects in high speed flight

All these defects induce a one-per-rev rotating load whose modulus and phase depend on the type of defect.

Blade weight defect

A blade weight difference $\Delta m(i)$ on blade "i" induces load F in fixed coordinate system.

$$F = e.\Delta m(i).\Omega^2.\cos(\psi_i) \qquad (1)$$

e: rotor eccentricity

Ω: rotation speed

The load vector is along the faulty blade.

First moment of inertia defect

This defect is similar to the above defect

$$F = \Delta ms(i).\Omega^2.\cos(\psi_i) \qquad (2)$$

$\Delta ms(i)$: first moment of inertia difference on blade "i"

The load vector is along the faulty blade. For this defect, as for the previous one, the modulus of the one-per-rev load does not depend on flight conditions. Formulas (1) and (2) confirm the simulations of figures 5 and 6. The imbalance depends only on rotor rotation speed which is constant.

Second moment of inertia defect

Our model assumes the same lift for each blade. When the second moment-of-inertia is different on a blade, the coning angle is modified in order to obtain the required lift. Blade tracking is disturbed.

The resulting load is:

$$F = \Delta\beta_0.\left[\frac{\lambda_0}{4} - \frac{\theta_{tw}}{8} - \frac{\theta_0}{6}\right].\rho.a.c.\Omega^2.R^3.\cos(\psi_i)$$

θ_0: collective pitch

θ_{tw}: total twist on blade

λ_0: inflow ratio

β_0: collective flap

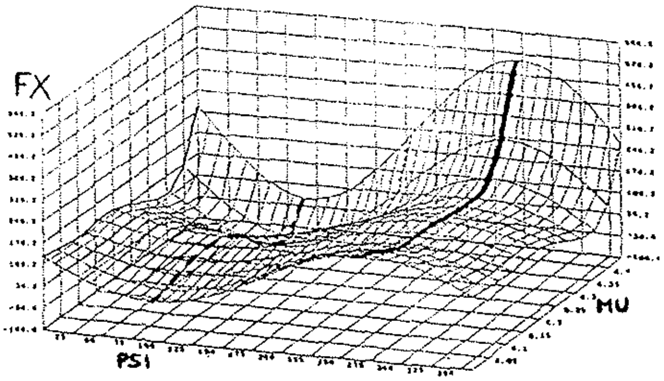
For this defect, the generated imbalance is along the faulty blade. The modulus of the load depends on many parameters (λ_0, θ_{tw}, θ_0) and hence on flight conditions.

Static stiffness of the lead-lag damper

When the damper stiffness is different, the corresponding blade drag is modified by $\Delta\delta_0(i)$. Blade drag angle is a linear function of the rotor power.

$$F = \Delta\delta_0(i).ms.\Omega^2.\sin(\psi_i)$$

The imbalance is generated with a $\pi/2$ phase lead. This defect generates the most significant one-per-rev load. That is why Eurocopter requires from lead-lag dampers manufacturers a very high level of quality and especially a small scatter on damper static stiffness. Moreover, the modulus of the load increases rapidly with the helicopter speed, while, as shown on figure 7, the phase does not depend on this parameter.



- - - - - - ISO 90°
——— ISO 270°

Figure 7: One per rev load versus azimuth and speed

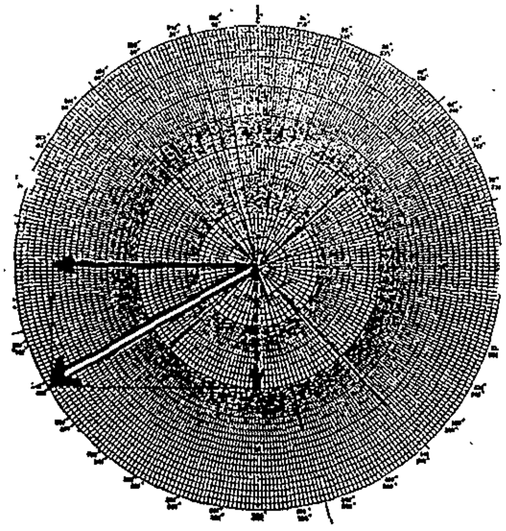
Tab deflection

Influence of tab deflection is realized through modification of the blade angle of attack. A moderate deflection of tab (about 3°) generates a significant load.

The phase of the load generated depends on the deflection and on flight conditions as well. The difference on figures 5 and 6 between hover and high speed level flight is about 10°.

When several blades show defects, the resulting imbalance is very close to the sum of loads from each individual defect.

For example, figure 8 illustrates the loads obtained with a blade having weight and static stiffness of the lead-lag damper defects, compared to the addition of both defects considered separately.



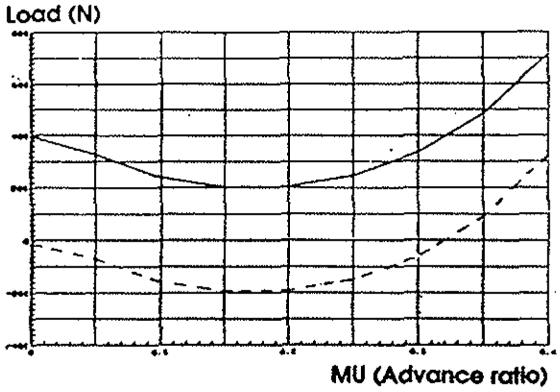
- - - - - Mass defect on one blade
——— Static stiffness of the lead-lag damper
═══ Simulation with both defects

Figure 8: Combination of weight and first moment of inertia defect

Balancing the rotor is achieved by adding weights on sleeves. For blade weights and first moment of inertia defects, rotor setting remains correct for all flight conditions.

The other three defects studied are difficult to balance because the generated load changes with helicopter speed and power.

Figure 9 shows an example for a static stiffness defect of a lead lag damper. The modulus of the one-per-rev load is plotted as a function of the advance ratio. The rotor has been balanced in hover for a given power. For other advance ratios the rotor presents phase- and modulus-changing loads.



———— **Lead lag damper defect**

- - - - - - - **Weight correction in hover of lead lag damper defect**

Figure 9: Influence of weight correction on one per rev loads

In hover, for a different aircraft weight, the imbalance reappears. This example explains that for problems related to lead lag dampers, the rotor tuning depends on power and advance ratio.

4) Rotor balancing on aircraft:

Balancing the rotor on a helicopter requires 3 to 4 well defined aircraft configurations and two accelerometric measurements.

Typically the 4 configurations are:

- on the ground
- in hover, in and out of ground effect
- high speed level flight
- high speed turn.

Both accelerometers are mounted in the fuselage or on the main gearbox, depending on the aircraft: one vertical and the other lateral.The first one being more indicative of a track problem and the second of a balance problem.

The three ways to balance the aircraft are: length of pitch change rod, tabs and weights on rotor sleeves.

Track tuning often requires some compromise between hover and forward flight.

Balancing also requires compromise, a perfectly hover-balanced rotor may cause problems in forward flight since all defects are corrected by weights but all type of defects do not create the same imbalance for the whole speed range.

This balance methodology is well adapted to current helicopters. For future high speed and low vibration aircraft, we should analyse whether this methodology is to be improved.

5) Numerical model:

The dynamic response of the rotor under aerodynamic excitations is too complex for being fully investigated by analytical calculations. Therefore, the anisotropy study is also conducted with a numerical model which takes the following phenomena into account :

- non linear aerodynamic forces : stall and compressibility effects, non uniformity of inflow velocity distribution (including wake effects or interactions with the fuselage).
- the elastic response of the blade due to : its local mass and stiffness characteristics in flap, lag and torsion as well as the local offsets of elastic centers (and center-of-gravity) which govern the blade coupling.

EUROCOPTER FRANCE started the development of a general aeroelastic rotor model in 1985 (so-called R85 model) which is still going ahead (References 4 and 5).

This code was developed to predict the response of a rotor and the loads induced in all flight conditions. It is based on an energetic formulation (LAGRANGE equations) coupling aerodynamic (2D airfoil characteristics) with elasticity (beam theory). It uses all rotor characteristics (structural, geometrical and aerodynamical properties of the hub and the blades) to compute aerodynamic and dynamic properties (simulation, performance, loads and stability studies).

The results have been validated by test campaigns in ONERA's wind tunnels as well as during flight tests. Figure 10 represents the correlations on flatwise bending moments calculated and measured on the experimental SA349 GAZELLE (with 2 MEIJER DREES and METAR inflow models : lifting line theory).

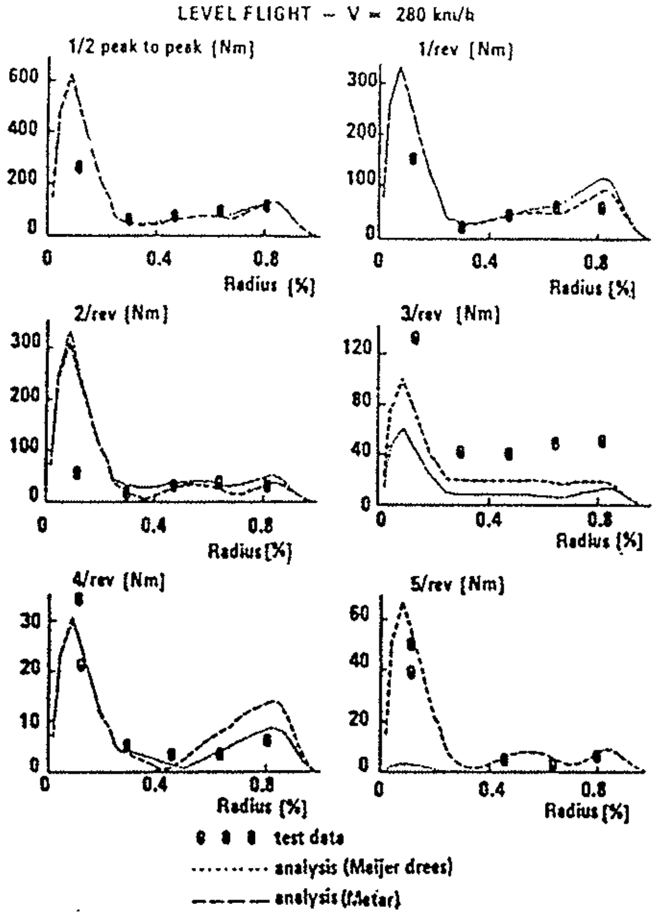


Figure 10: SA 349/2 Flat wise bending moment distribution (flight test)

ROTOR DYNAMIC BEHAVIOUR

As a first step in the study of anisotropy, calculations were run assuming the following points :

- the induced velocities are not affected by the rotor non-isotropic behaviour (MEIJER DREES model without wake effects).
- the effect of the hub motion is disregarded (the rotor head is considered as fixed).

Calculations are applied to each kind of blade (as far as structural and geometrical properties are concerned : stiffness and mass distribution or twist and airfoil characteristics) which leads to know the loads transmitted by this blade to the rotor head. The total loads are obtained by adding each blade contribution.

Figures 11 and 12 show the in-plane shear forces (in rotating coordinate system) transmitted by the reference blade to the blade attachment (Fy). All computations presented are applied to a 4 bladed fully articulated rotor of a 4 ton class helicopter (DAUPHIN successor).

As shown in figure 12 , in plane shear forces increase versus speed and decrease when harmonic increases.

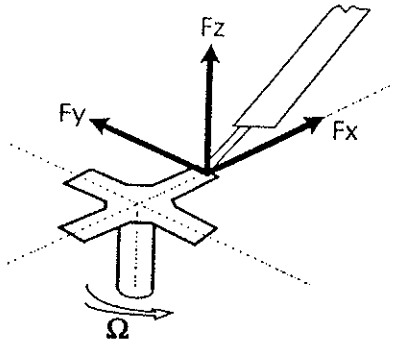


Figure 11: Rotating axes

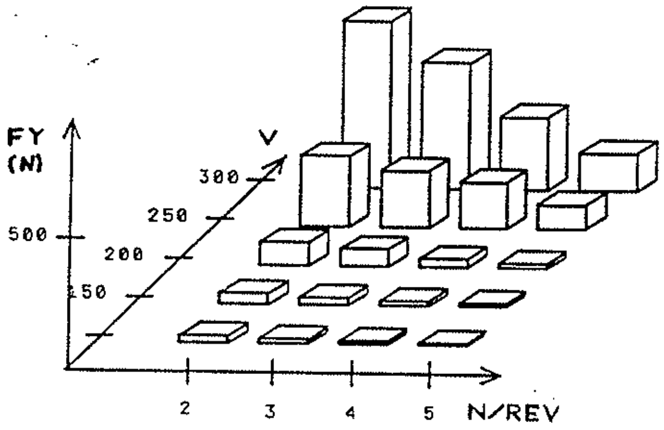


Figure 12: In plane force F_Y versus speed in rotating axes (harmonic content)

NON ISOTROPIC CALCULATIONS

The rotor behaviour has been studied for several defects and different flight configurations (from hovering conditions to high speed flight).

For isotropic rotors, only the N-per-rev loads do not cancel in fixed coordinate system (N : number of blades) but for non-isotropic rotors all harmonics can be injected into the airframe.

In fact, the N-per-rev loads are generated by the addition of the corresponding stresses on each blade while the loads at other harmonics are generated by their differences.

Calculations have been run for the following defects :

- defect of blade weight balanced with a blade-tip weight (to ensure the right first moment-of-inertia) : A
- lead-lag damper stiffness (with elastomeric dampers) : B
- blade flapping stiffness : C
- blade torsional stiffness : D
- chordwise center of gravity offset : E

Mixing a faulty blade with 3 reference blades generates additional dynamic loads with specific modulus and phases at each harmonic for each defect. The in plane-shear forces for harmonics 3- and 5-per-rev (*in fixed coordinate system*) are shown in figures 13 and 14 for flight speeds ranging from 200 to 325 kph.

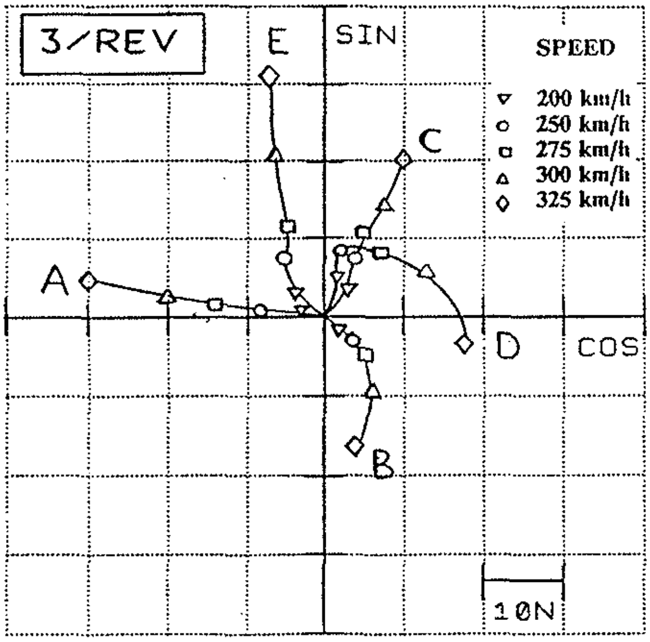


Figure 13: Lateral forces in fixed axes generated by each defect

In the case described, the deficient blade is in position 4 on the rotor head (see figure 15).

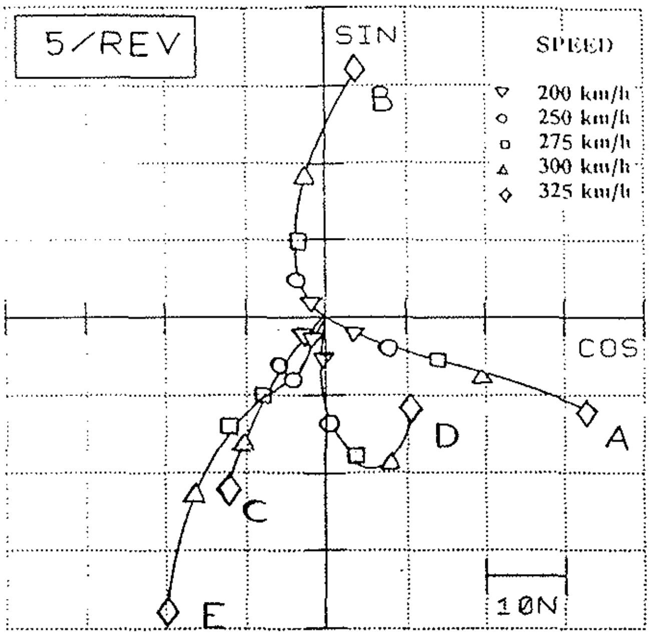


Figure 14: Lateral forces in fixed axes generated by each defect

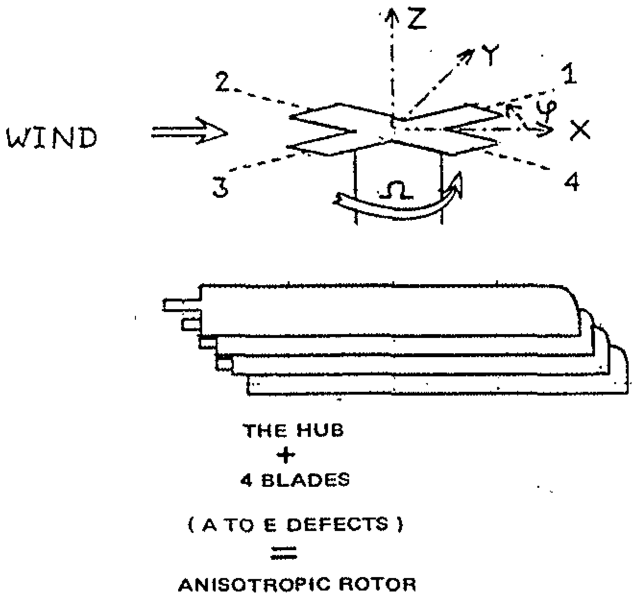


Figure 15: Anisotropic rotor

The load levels at 3- and 5-per-rev in fixed axes are small when compared with the corresponding loads at 4-per-rev (twenty times smaller for realistic defects) but their effect on the vibration level can be significant.

Indeed the MGB suspension system response is designed to filter the main rotor excitation frequency (N per rev). Its response on other frequencies may be important in particular with resonating devices whose resonant frequency could be close to a rotor harmonic (see figure 16).

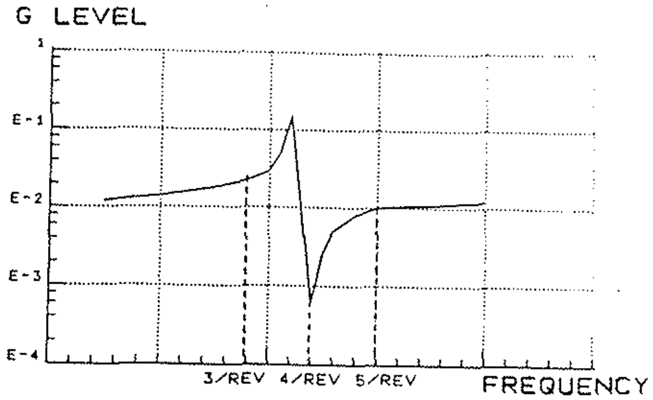


Figure 16: Suspension response

The resulting vibration levels through the airframe can become similar to the N-per-rev vibration levels and their association produces a beating phenomenon at a low frequency which can be disturbing for the crew (figure 17).

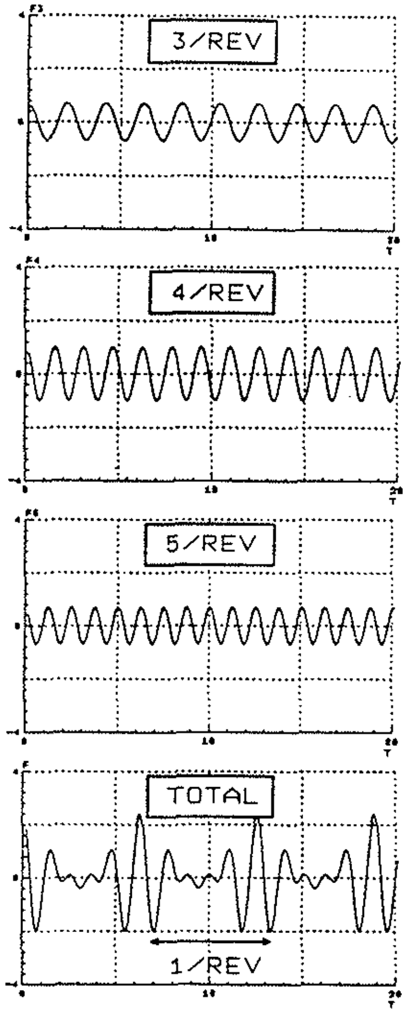


Figure 17: Beating phenomenon

The global loads can be important or close to zero depending on the relative positions of the faulty blades on the rotor head. For example, to fit similar blades facing each other on the hub will lead to cancel all uneven harmonics. The behaviour of these blades is then the same as a two-bladed rotor.

To illustrate the association of several defects, figure 18 shows the hub loads obtained at 300 kph with E defect on blade 4 and C defect on the four different blades.

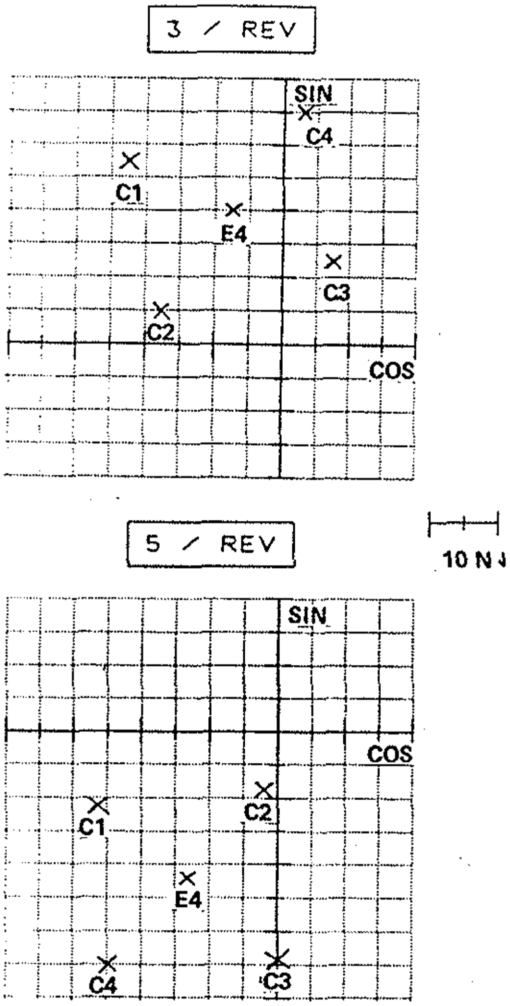


Figure 18: Fy force in fixed axes. E and C defects combinations.

For E blade in position 4, adding the C defect on the same blade generates anisotropic loads about 3 to 5 times larger than the loads obtained with the C blade in position 2.

In this case, N-1- and N+1-per-rev loads add or cancel for the same defect position. But defects can add for a given harmonic and cancel for another.

Mixing the A and E defects does not allow to minimize simultaneously the 3- and 5-per-rev forces. Reducing the 3-per-rev response leads to increase 5-per-rev loads (figure 19).

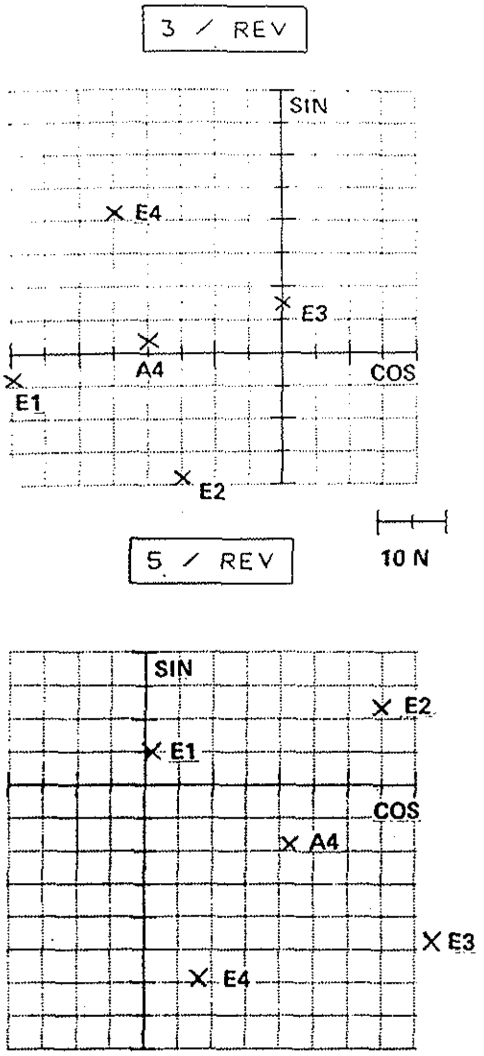


**Figure 19: Fy force in fixed axes.
E and A defects combinations.**

Mixing all the blade defects can produce various loads depending on their relative setting.

6) Conclusion:

Most helicopter manufacturers are mainly focused on rotor and fuselage dynamics at N per rev (N : number of blades). This optimization seems to be insufficient for the future high-speed and low-vibration aircraft due to anisotropic rotors. This study shows that :

- The compromise required for the track and balance of high speed rotors can hardly be achieved for all flight configurations using the current methodology.
- The non-isotropic rotors characteristics can affect the suspension system tuning in order to avoid the resonances for harmonics other than N-per-rev.
- The beating phenomenon can play a significant role for the vibratory comfort of future helicopters.
- Mixing blades with slightly different characteristics can produce various loads depending on their relative setting.

For current helicopters the manufacturing blade tolerances are sufficient but additional simulations will help evaluate the influence of various defects and define the improvements which will be required for future helicopters. The understanding of non-isotropic rotor behaviour forms part of Eurocopter's research program and flight tests will be performed with faulty blades in order to validate the theoretical prediction codes.

7) References:

1. J. Wang and I. Chopra, Dynamics of helicopters with dissimilar blades, 47th Forum of the A.H.S., Phoenix, May 1991.

2. M. McNulty, Effects of blade-to-blade dissimilarities on rotor-body lead-lag dynamics, 11th European Rotorcraft Forum, Sept. 1985.

3. C.E. Hammond, An application of Floquet theory to prediction of mechanical instability,NASA Langley Research Center, Virginia.

4. M. Allongue and T. Krysinski, Validation of a new general AEROSPATIALE aeroelastic rotor model through the wind tunnel and flight test data,46th Forum of the A.H.S. Washington DC May 1990.

5. G.K. Yamauchi, R.M. Heffernan and M. Gaubert, Correlation of SA349/2 helicopter flight test with comprehensive rotorcraft model. 12th European Rotorcraft Forum, Sept. 1986