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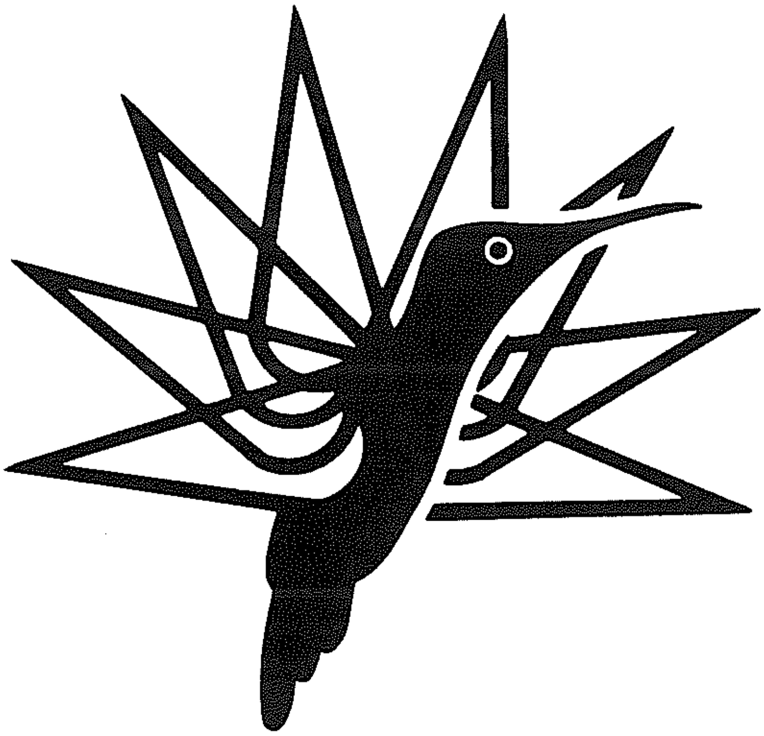

ASPECTS OF SEE-SAW TAIL ROTOR BALANCING

BY

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Abstract

Balancing of a tail rotor is favourably done with the aid of linear theory. Hereby it has to be clarified whether anisotropic properties of the rotating components have to be considered.

The results of balancing tests on helicopters and on a test bench are used to illustrate several effects on unbalance, such as

- incorrect rotor hub mounting,
- pitch,
- track,
- unsymmetric blade feathering moments.

Results of theoretical evaluations are used to demonstrate the impact of profile contour deviations on the aerodynamic properties of the rotor blades since these deviations influence the rotor balance in addition to mass effects.

Illustrated by an analysis of load frequencies and amplitudes, the effect of rotor unbalance on vibrations in the fixed and in the rotating system is discussed.

Notations

a_{ij}; i, j = 1,2	[ips/gcm]	influence coefficients
m	[kg]	mass
n	-	number of harmonic
t	[m]	blade chord
u	[gcm]	unbalance
v	[ips]	velocity
x/y/z	-	coordinates
A	-	influence coefficient matrix
A^{-1}	-	inverse of A
D_{δ}	[°]	pitch angle
F	[N]	force
M	[Nm]	moment
M	-	Mach number
R	[m]	radius
α	[°]	angle of attack
θ_V	[°]	twist
ψ	[°]	azimuth angle
ω, Ω	[rad/s]	angular velocity
Φ	[°]	phase angle

Indices:

1 (2)	concerning blade 1 (2)
I (II)	concerning plane I (II)
M	mast
PL	pitch link
TR	tail rotor
β	concerning flapping
ζ	concerning lagging

Superscripts:

$\rightarrow$	vector
$'$	fixed system
$\cdot$	time derivative

1. Rotor Balancing - Definition and Reasons

To assure the absence of basic rotational frequency vibrations at the bearings of a rigid rotating body in vacuo, this body's mass distribution has to be arranged in such a way that there are no remaining centrifugal forces acting at the position of the rotational axis.

To achieve this, the following conditions must be satisfied (see Fig. 1.1):

- The center of gravity must lay on the rotational axis.
- The rotational axis must be a principal axis of inertia.

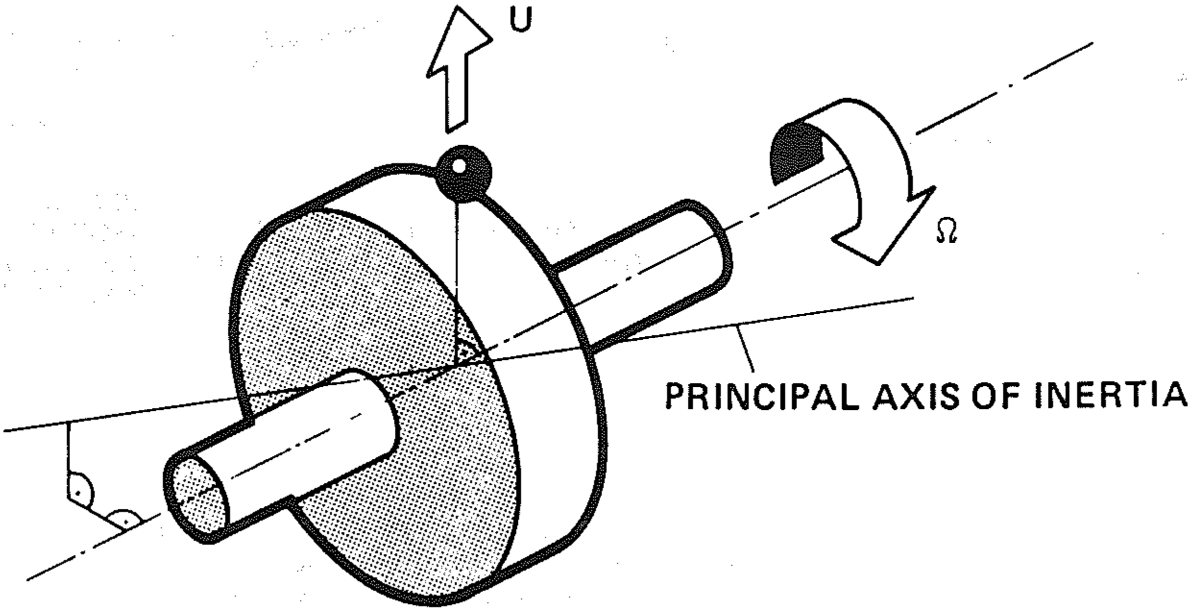


Figure 1.1: Rotor balancing

These conditions are not sufficient for non-rigid rotors, as for example helicopter rotors, since here centrifugal and aerodynamic forces lead to elastic deformations going along with mass displacements, which in turn create additional centrifugal forces (ref. 1-7).

Commonly balancing literature deals with pure mass unbalances (ref. 1-13). In contrary to this helicopter rotors additionally experience aerodynamic unbalances (see Fig. 1.2)

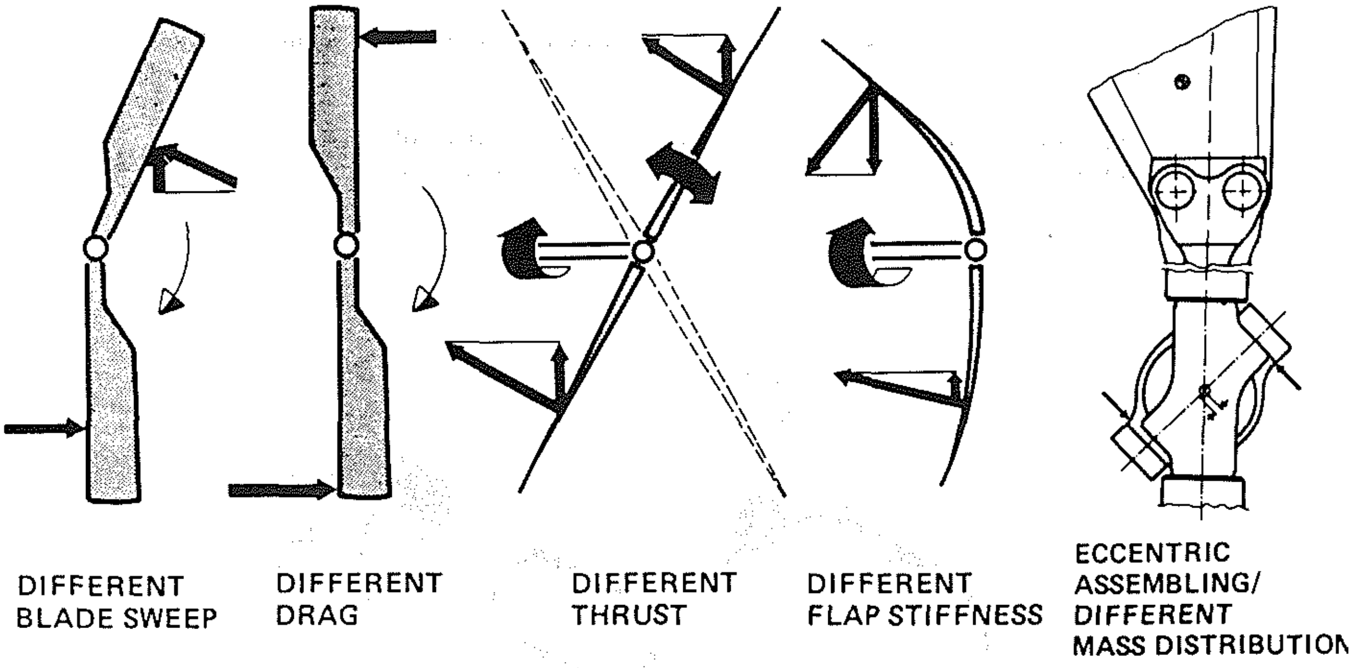


Figure 1.2: Balancing of a nonrigid rotor with aerodynamic properties

So an ideally balanced helicopter rotor has to imply the same static, dynamic, and aerodynamic properties of the blades. The rotor hub then transfers only the periodic forces *into the fuselage and the resulting vibrations include frequen*cies which are multiples of the blade number harmonic.

An unbalanced rotor on the other hand gives rise to frequencies which show a greater variety of rotor harmonics ($n_{Harmonic} = 1,2,3,4...$).

The aim of balancing is the compensation of all forces acting on the hub bearings, in such a manner that the remaining unbalance doesn't exceed a given tolerance limit, for example a defined vibration speed. This is to be achieved for all frequently-used operational conditions of the rotor. The reduction of vibrations by balancing improves the ride comfort and greatly enhances the service life of components and structural parts.

The appearance of unbalance is conditioned by manufacturing and rotor assembly and influenced in its intensity by operational conditions. Examples of the influence of manufacturing are:

- a built-in different pre-sweep or cone angle of the blades,
- deteriorations of the profile contour,
- an improper mass distribution in radial or chordwise direction of hub and blades,
- different stiffnesses in flap, lead-lag or torsion of the blades.

Operational conditions of the helicopter such as ground run, hover, horizontal flight etc., vary the unbalance by:

- the different pitch angle required. (critical for improper chordwise mass distribution and differences in the aerodynamic properties of the blades),
- the varying incident velocity particularly of the advancing blade (critical for aerodynamic differences of the blades),
- the change of structural body modes and response amplitudes of the helicopter depending on its position - on ground or airborne (critical for vibration amplitudes)

To prevent the most important unbalance source, the mass force unbalance, equal radial and chordwise static moments have to be provided. To achieve this, there are two steps:

1. Balancing in the gravity field, i.e. statically.
2. Balancing in the centrifugal force field, which takes into account eccentric mounting of the tail rotor, and elastic deformation of the rotor blades (see Fig. 1.3).

Balancing in the centrifugal field additionally allows a certain compensation of aerodynamic non-symmetries, but it is not able to take into account a change of the operational conditions mentioned before.

Sometimes balancing in the centrifugal field is called "dynamic balancing" but this would include balancing in two different plains perpendicular to the rotational axis (see Fig. 1.3), which is uncommon for helicopter rotors.

Origins of unbalance which are of no great importance such as for example second harmonic excitations of one blade, transferred into the fixed system as first harmonic vibrations are not discussed in this paper.

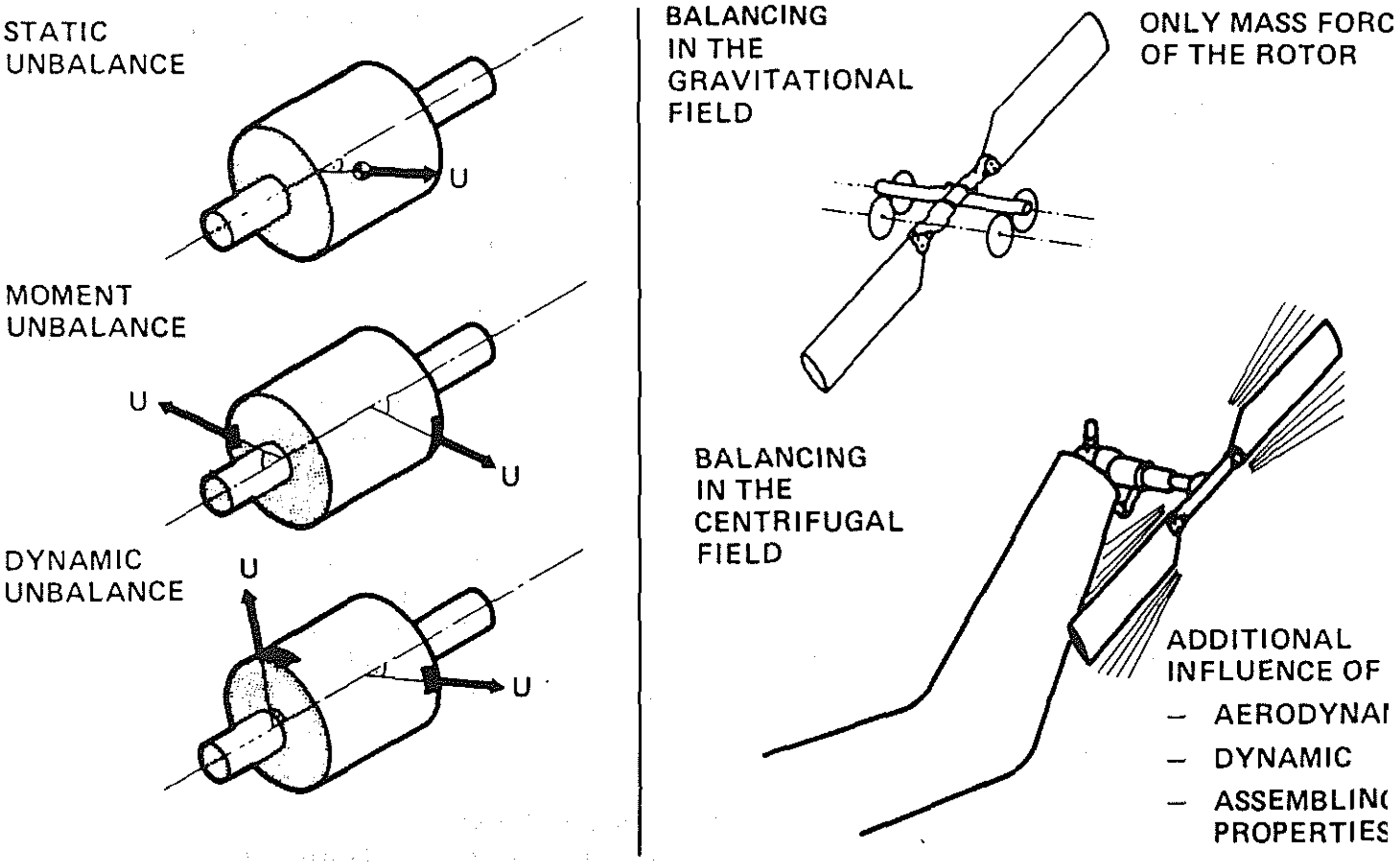


Figure 1.3: Balancing definitions

2. Linear Theory of Balancing

According to the experience at MBB, linear theory is sufficient to cope with the common balancing problems.
The model used here implies the following assumptions:

- linear relation between unbalance and vibration of the shaft bearings,
- disc-shaped rotor.

The latter is balanceable with sufficient accuracy in one plane (i.e. the rotor plane). Shaft unbalance is neglected.

The relation between unbalance $\vec{u}$ and bearing vibration $\vec{v}$ is

$$\vec{v} = A \cdot \vec{u}$$

$$\begin{pmatrix} v_x \\ v_y \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} \\ -a_{21} & a_{22} \end{pmatrix} \begin{pmatrix} u_x \\ u_y \end{pmatrix}$$

where $\vec{v}$ is directly measurable by a single pick-up in the fixed system. The phase angle of $\vec{v}$ may be arbitrarily chosen, measured by a phase indicator pick-up, or by a stroboscope, triggered by the accelerometer/velocity pick-up (see Fig. 2.1 and section 3.)

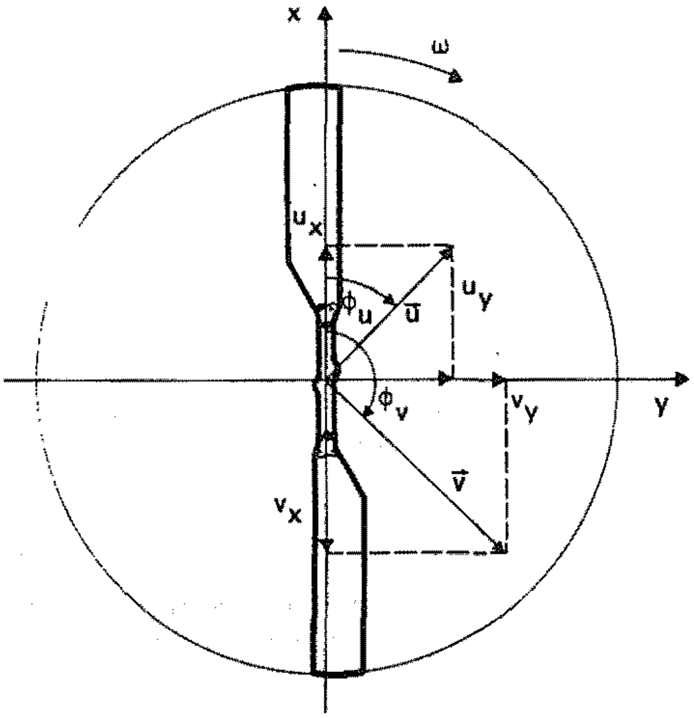


Figure 2.1: Linear theory of balancing

The unbalance is evaluated by:

$$\vec{u} = A^{-1} \cdot \vec{v}$$

In order to define the coefficients of A, 3 runs are usually necessary:

1. To measure the actual unbalance.
2. To measure the effect of a test unbalance in x-direction.
3. To measure the same in y-direction.

If the tail rotor mast and the flap bearings are isotropic in their stiffnesses, then:

$$a_{11} = a_{22}$$

$$a_{12} = a_{21}$$

applies and only 2 runs are necessary.

The more general anisotropic case with different stiffness of rotor mast and flap bearings in perpendicular directions yields a dependency of the vibration vector from the unbalance position in the rotating system.

The influence coefficients are in this case:

$$a_{11} = (v_{x2} - v_{x1})/\Delta u_x$$

$$a_{12} = (v_{x3} - v_{x1})/\Delta u_y$$

$$a_{21} = -(v_{y2} - v_{y1})/\Delta u_x$$

$$a_{22} = (v_{y3} - v_{y1})/\Delta u_y$$

with:

- v_{xi}, v_{yi} : components of vibration vector in the rotating system (i = number of run)
- Δu_x, Δu_y : test unbalances.

3. Balancing Procedure

The linear relation between unbalance and vibration vector is used to evaluate the necessary compensating balance weights, geometrically or numerically.

In both cases two or three runs with the unbalance weights have to be conducted, depending on the isotropic/anisotropic properties of rotor mast and flap bearings (see section 2). The vibration vector $\vec{v}$ in the rotating system is measured:

- In its amplitude by an accelerometer/velocity pick-up at the tail rotor transmission box.
- In its phase angle either by a phase indicator pick-up at the rotor mast, or by a stroboscope triggered by an accelerometer pick-up.

In the case of geometrical determination of the balancing weights, the measured amplitudes and phase angles of the test runs are used to attune a diagram according to Fig. 3.1, by scaling the weight axes and rotating the phase dial. This method is used with good success for routine balancing.

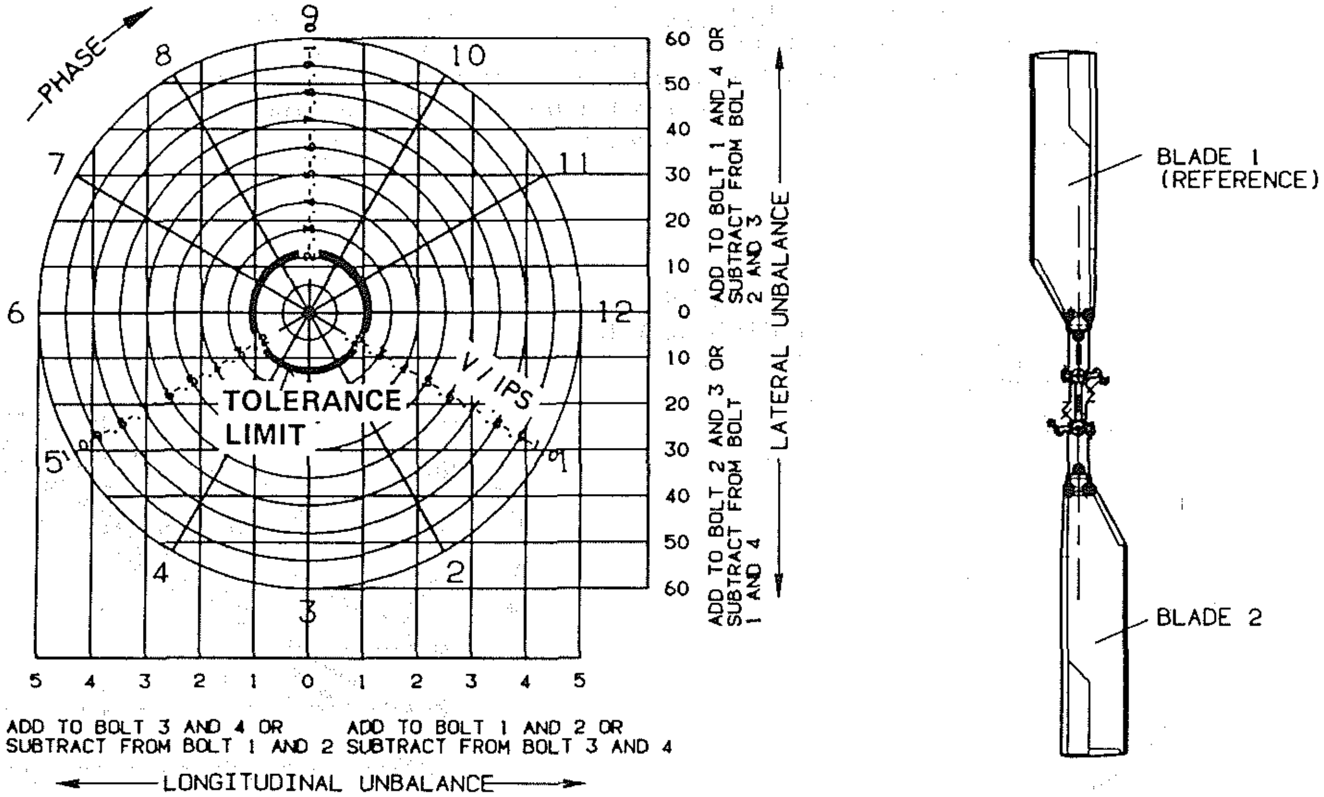


Figure 3.1: Balance diagram PAH 1

In the case of numerical determination of the balancing weights, the influence coefficients explained in section 2 are used. This can be provided by a small programmed calculator which directly gives the necessary amount of compensating balancing weights. Furthermore, the numerical balancing can take into account possible anisotropies of rotor mast and flap bearings, which is more difficult to accomplish by geometrical procedures. On the other hand, geometrical balancing usually is a simple straightforward paperwork which clears up the physical process and facilitates the control of perpetual scattering of the balancing values.

Both balancing methods are independent of a proper calibration of the pick-up, and independent of any reference of the phase angle. It is irrelevant whether displacements, speeds or accelerations are measured. However, the conditions must be the same for both, the calibration and measurement runs.

Influence of inaccurate unbalance identification

As shown in Fig. 3.2 the success of a balancing action heavily depends on the accuracy of the determination of the phase angle and the amplitude of vibration, the correct identification of the phase angle having the greater impact on the success of the balancing procedure as shown in Fig. 3.2.

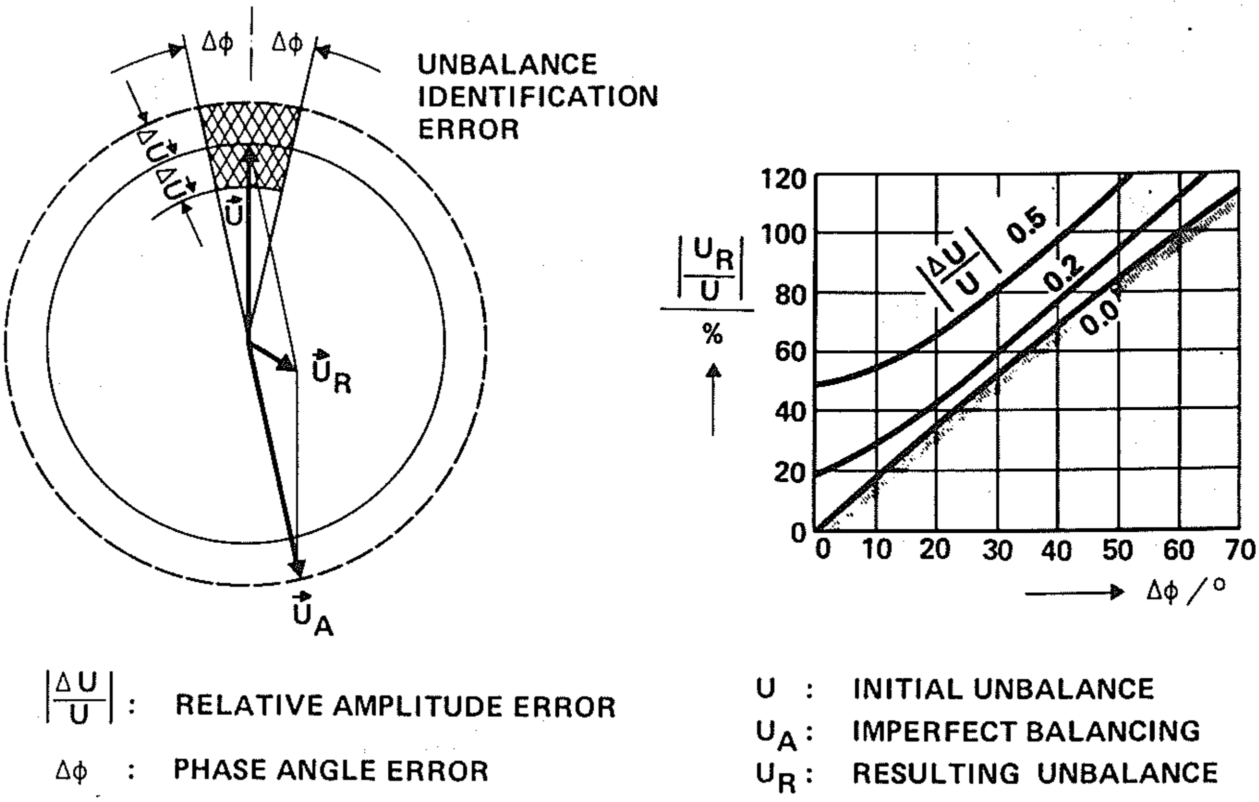


Figure 3.2: Unbalance identification error

The tolerable remaining tail rotor unbalance, expressed by the vibrational velocity amplitude at the position of the transmission box has been fixed to v = 0.2 ips (see Figs. 3.1 and 5.6) according to recommendations of the Verein Deutscher Ingenieure - VDI (see also ref. 6, 13 and 14).

4. Vibration Pick-up Position

As indicated in section 2 and 3 a single pick-up in the fixed system is sufficient to measure the vibration level due to unbalance. In order to warrant a sufficient signal-to-noise ratio, the following has to be taken into account:

- The separation of the 1-per-rev unbalance signal from the adjacent natural frequencies of rotor/structure components, as for example the tail rotor shaft (see section 5.3).
- A high response of the structure where the pick-up is attached (usually the tail rotor transmission box).

The first postulation can be satisfied in most cases by a filter and by a proper selection of the direction in which the pick-up is mounted. This direction of the pick-up axis is also relevant for the second postulation. In addition, the position of the pick-up has a great influence on the receivable vibration signal, as can be derived from the Figs. 4.1 and 4.2.

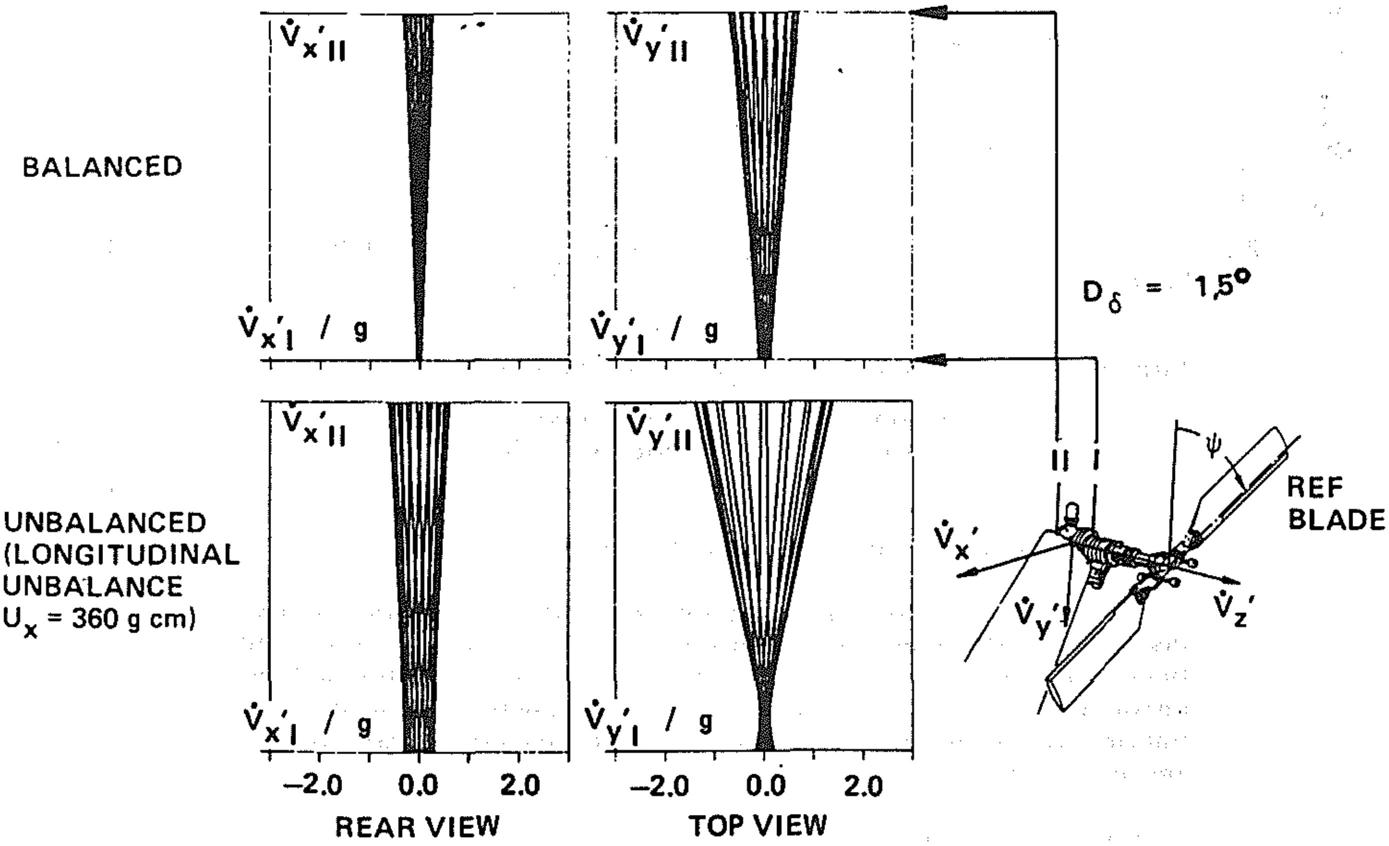


Figure 4.1: Acceleration of the tail rotor mast $\dot{v}_x'$, $\dot{v}_y'$ in the fixed system. Rear and top view

In the case of the tested helicopter the optimal pick-up position is on the starboard side with the pick-up axis in vertical direction.

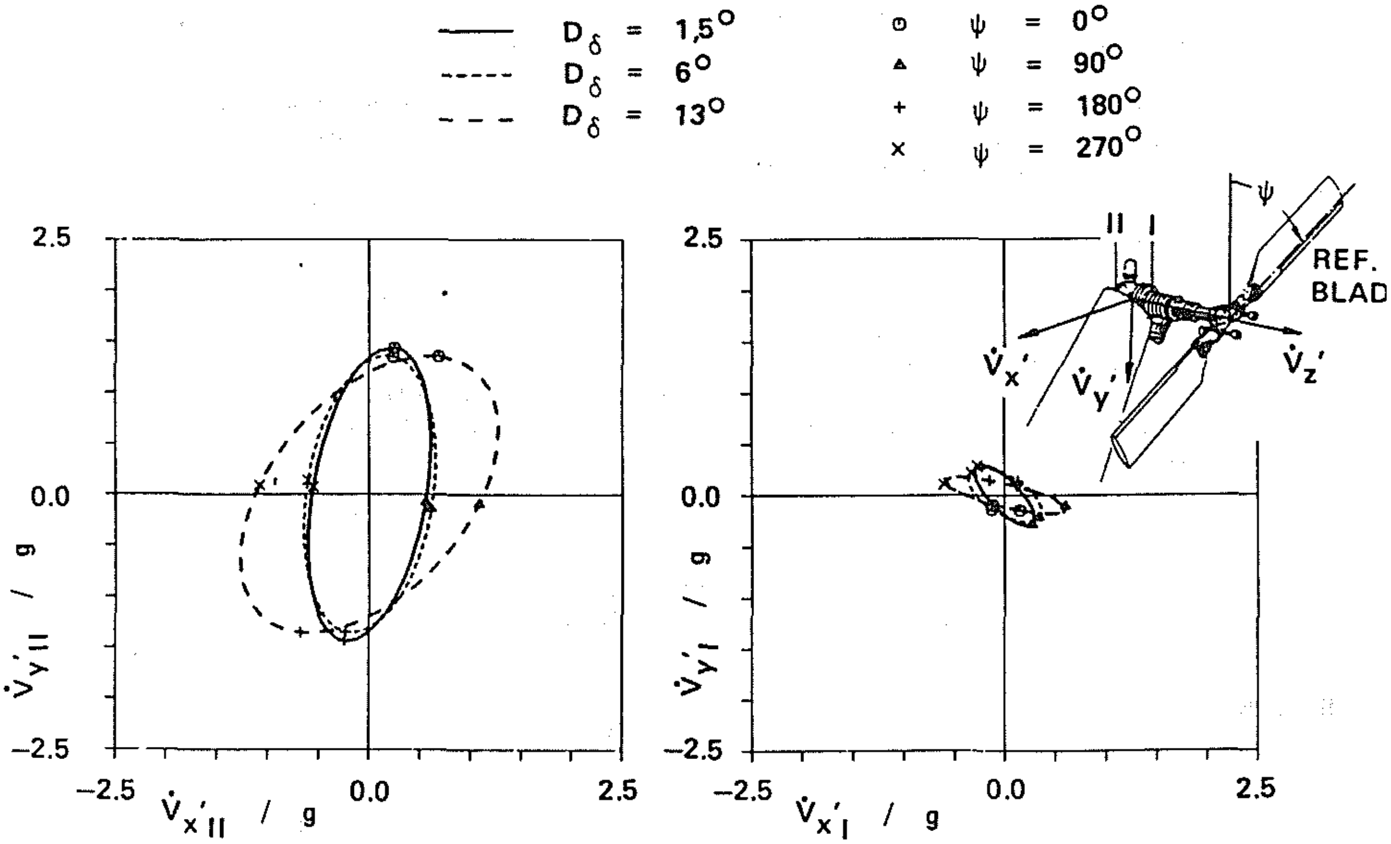


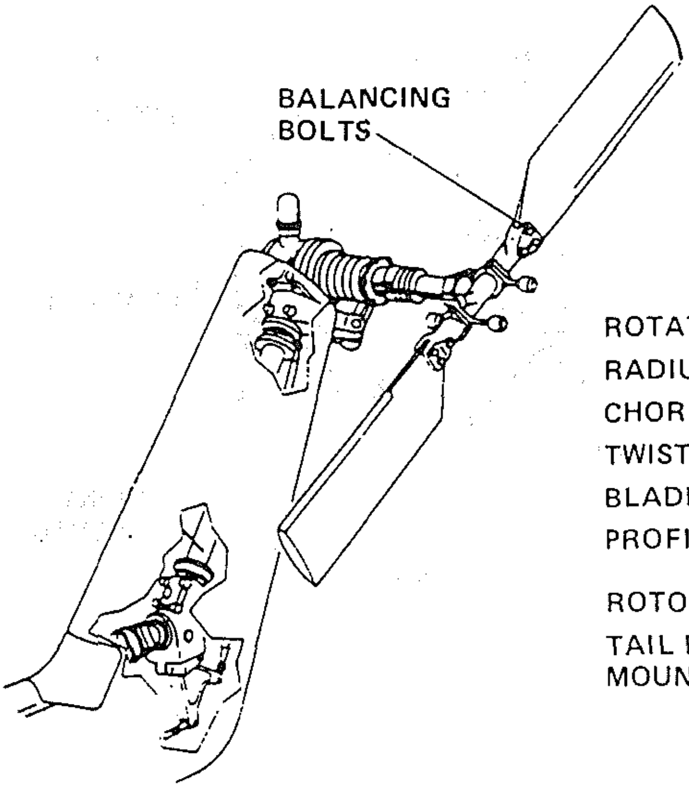
Figure 4.2: Acceleration of the tail rotor mast $\dot{v}_x'$, $\dot{v}_y'$ (fixed system) in the planes I and II. Longitudinal unbalance u_x = 360 gcm

5. Test Results and Particular Aspects

For a better understanding of the balancing characteristics of different helicopters and tail rotors, tests have been conducted with 23 tail rotors, mounted on the helicopter respectively on a test bench. The test results as well as some particular balancing aspects are summarized in the following sections. They deal with:

- rotor assembling,
- blade pitch and aerodynamic blade properties,
- transformation of harmonic loads between rotating and fixed system,
- anisotropy of rotor mast and flap bearings.

The tail rotor data are presented in Fig. 5.1.



ROTATIONAL SPEED	Ω_{TR}	= 2170 – 2200 ROT/MIN
RADIUS	R	= 0,975 m
CHORD	t	= 0,18 m
TWIST	θ_v	= 0^o
BLADE MASS	m	= 1,1 kg
PROFILE	NACA 0012, S102E	
ROTOR TYPE	SEE–SAW	
TAIL ROTOR MOUNTED ON:	TEST BENCH, BO 105, BK 117	

Figure 5.1: Balance test data

The tail rotor blades, tested on the test bench, showed a certain scatter within the manufacturing tolerances as for example blade pre-sweep, pre-cone, inertial moments, center of gravity position and twist, but these characteristics had no significant effect on the balance status.

5.1 Effect of Rotor Assembling Accuracy

Main influence factors with respect to tail rotor balance are the correct centering of the rotor hub, and the correct mounting of the flap bearings. (see Fig. 5.2).

The support vibrations of a first test bench run without blades with the rotor hub eccentrically assembled, are shown in Fig. 5.3 together with the following run after centric assembling of the hub.

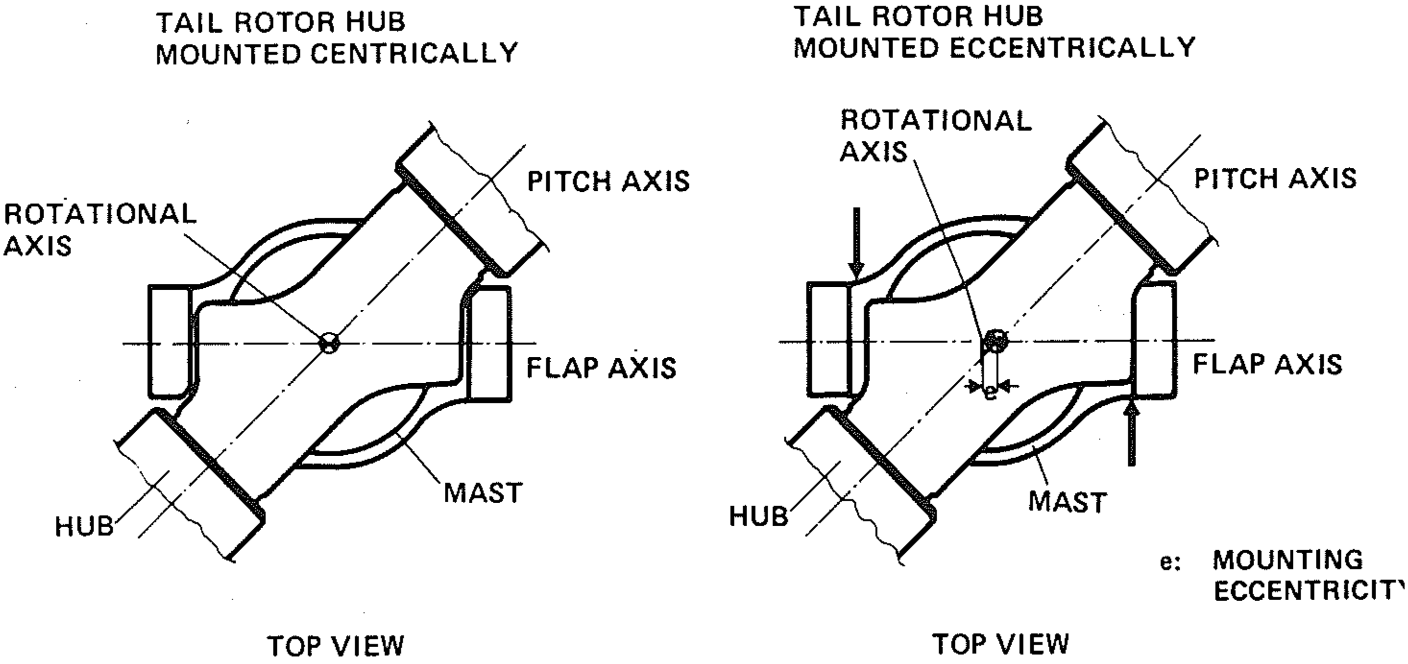


Figure 5.2: Mounting eccentricity

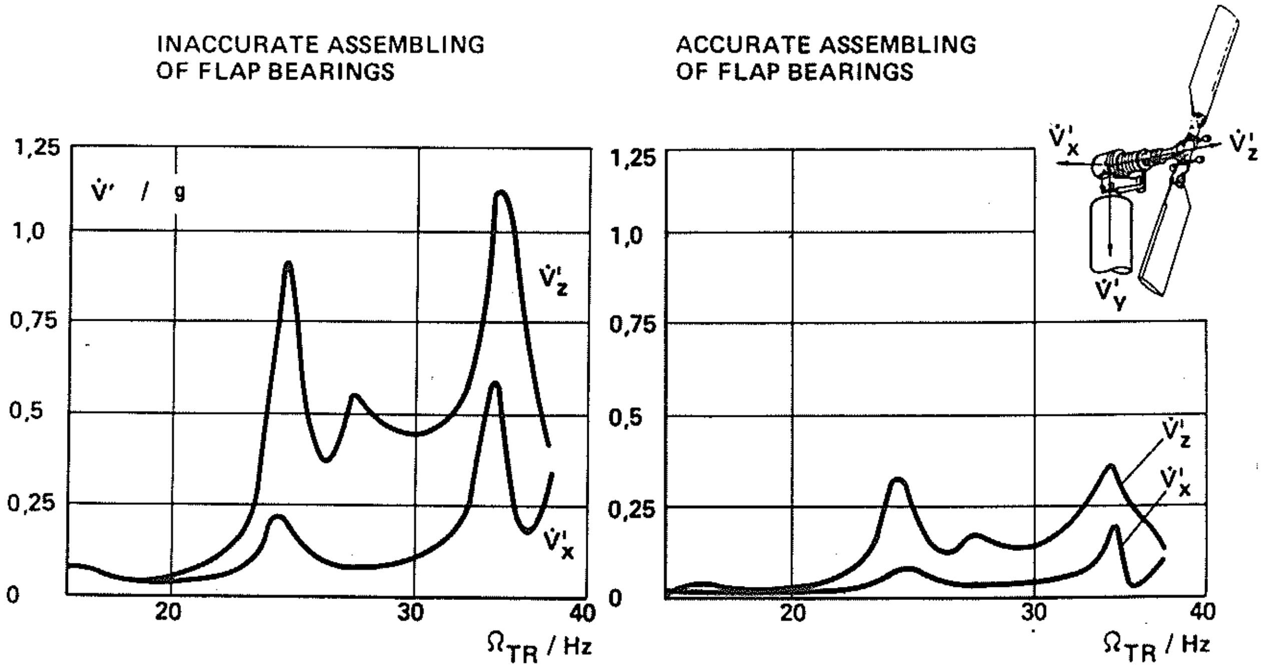


Figure 5.3: Effect of mounting on accelerations in the fixed system

5.2 Influence of Unbalance on Dynamic Tail Rotor Loads

During the bench tests the dependency of unbalance on the rotor loads was determined. Fig. 5.4 summarizes the results of this research for:

- the mast moment M_{MTR},
- the lead-lag bending moment M_ζ at the pitch sleeve,
- the flap bending moment M_β at the same position,
- the force in the pitch links (rotating system) F_{PL} and
- the acceleration of the tail rotor transmission box in x- and z-direction

(for pitch angle D_δ = 0° and 9°).

As expected, all dynamic loads increase significantly with increasing unbalance and this effect is frequently intensified in the case of the higher pitch angle.

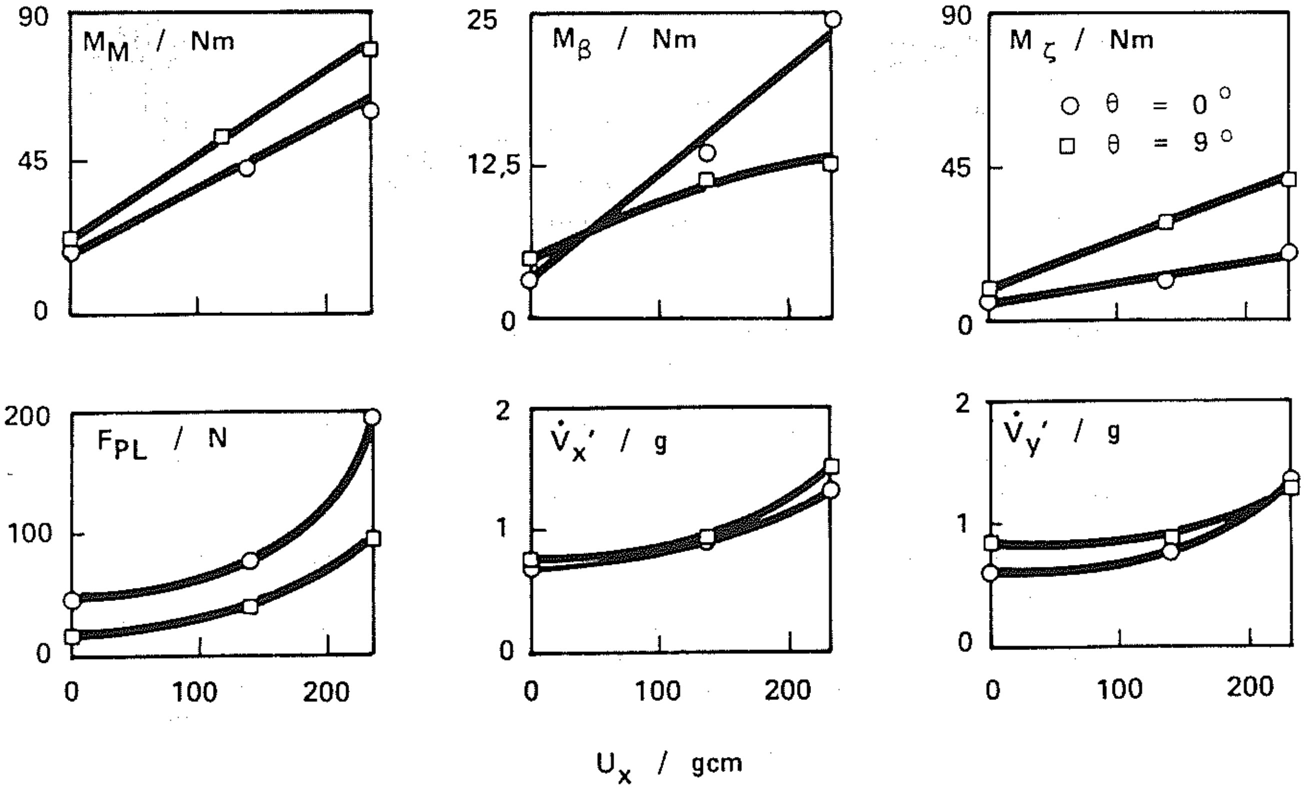


Figure 5.4: Influence of unbalance on dynamic tail rotor loads

5.3 Effect of Unbalance on Rotor Harmonics

The effect of a defined unbalance on the amplitude spectrum of the support vibrations is presented in Fig. 5.5, illustrating a typical example.

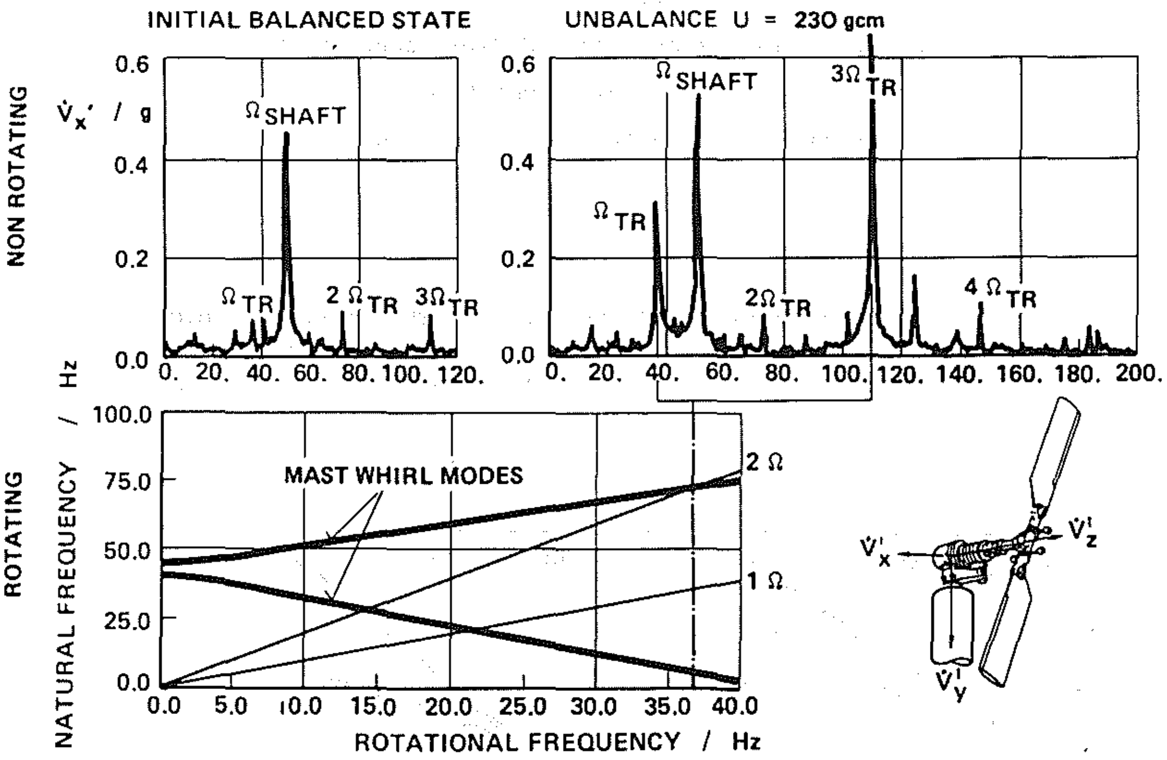


Figure 5.5: Amplitude spectrum of the longitudinal acceleration in the fixed system

The signal analyzed is the acceleration of the tail rotor transmission box in longitudinal (x) direction. The initial balanced state besides the shaft frequency contains:

- the basic rotational frequency caused by the remaining unbalance,
- the second harmonic as the common vibration of a two bladed rotor which is not influenced by unbalance, and
- the third harmonic, caused by a transformation of the first harmonic from the fixed system into the rotating system and then back into the fixed system.

Adding a defined unbalance leads to a significant increase of the first, and an even stronger increase of the third harmonic. This is caused by the coalescence of the second harmonic and a natural bending frequency of the rotor mast, shown in the lower part of Fig. 5.5 ("whirl mode", theoretical result).

5.4 Impact of Blade Pitch and Aerodynamic Blade Properties on Rotor Balance

Influence of Blade Pitch

In addition to classical unbalance, in the case of helicopter tail rotors also unbalances due to blade pitch have to be taken into account. The blade pitch implies a number of effects such as:

- blade feathering moment (propeller-moment) about the blade pitch axis,
- pitch moments due to non-coincidence of center of gravity and pitch axis of the blade, brought about by centrifugal forces together with a non-zero flapping angle,
- aerodynamic forces and moments (see Fig. 1.2).

These effects may evoke unbalances if the tail rotor blades are unequal with respect to chordwise mass distribution and profile geometry. As the blade pitch varies with the operational conditions the unbalance compensation by balance masses can only be a compromise. Other possibilities to balance the rotor are the use of pitch links of variable length and the correction of different feathering moments by adjusting the radial distance of the counter weights or washers.

The influence of blade pitch variation is shown in Fig. 5.6, illustrated by a balancing procedure, recorded on a BO105 balancing diagram, and in Fig. 5.7 with the aid of test bench results.

Fig. 5.6 shows the typical elliptic unbalance pattern which is reduced to tolerable values in two steps:

1. in longitudinal direction (from position 1 to position 2)
2. in lateral direction (from position 2 to position 3)

It is important for the balancing procedure to shift the center of the unbalance ellipse in such a way that it is placed finally inside the tolerance limit of the diagram.

Fig. 5.6 and 5.7 both demonstrate the typical increase of the pitch influence with increasing unbalance.

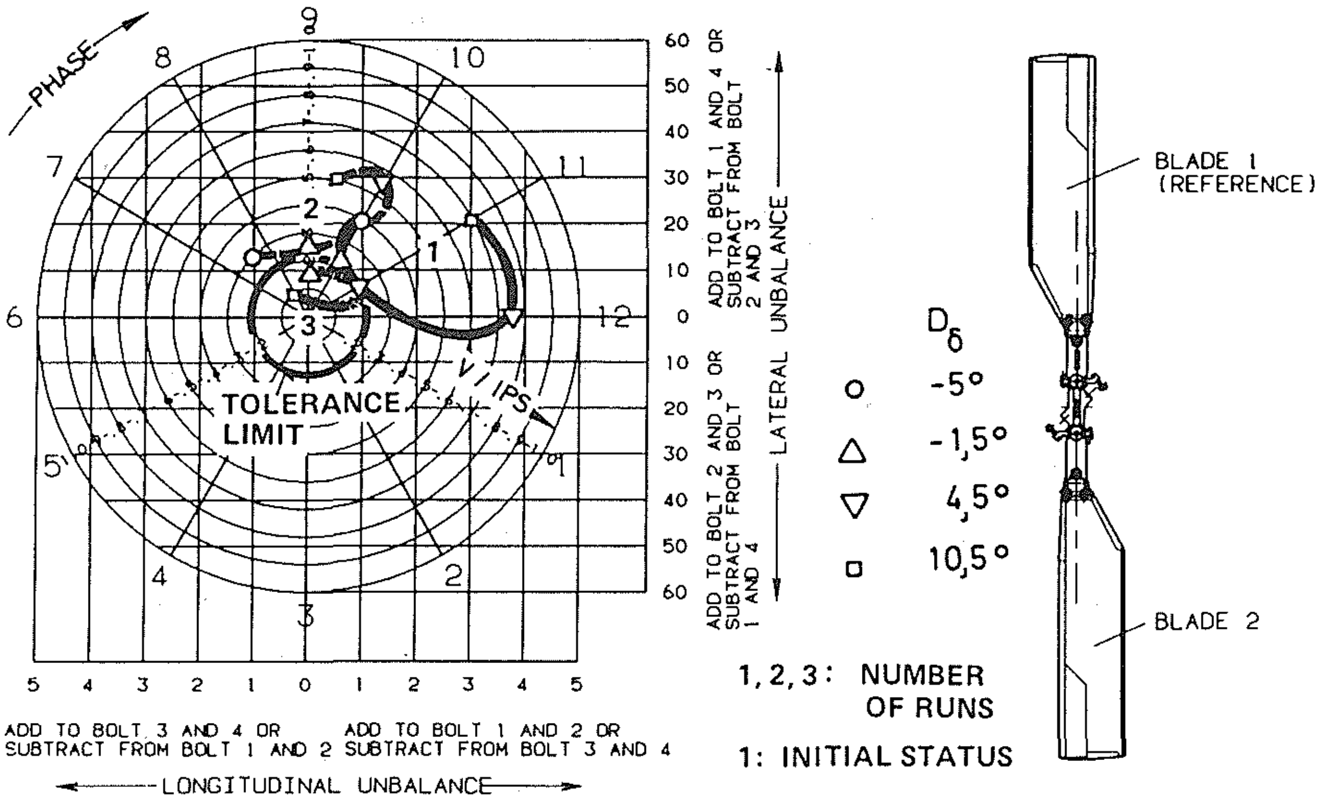


Figure 5.6: Effect of pitch variation on tail rotor unbalance

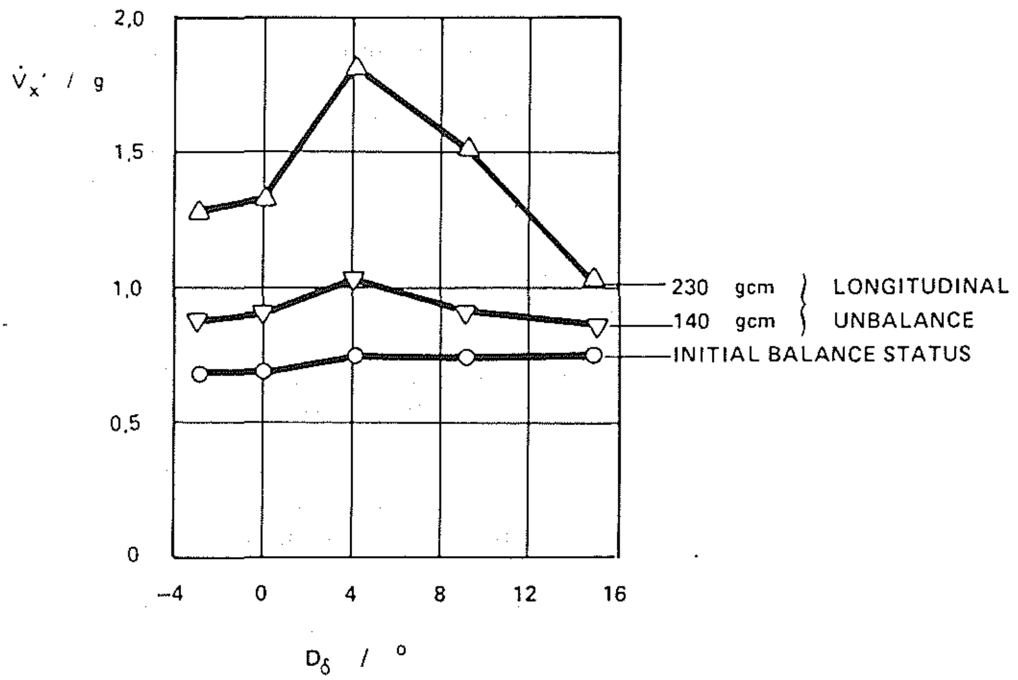


Figure 5.7: Impact of blade pitch and defined unbalances on the longitudinal acceleration $\dot{v}_x'$ in the fixed system

Rotor Tracking

Aerodynamically unequal rotor blades which imply different lift are recognizable by a track split. During the bench tests this track split has been compensated by varying the length of one pitch link. The results were not very significant since no large track splits were measured (see Fig. 5.8) but this behaviour may change under forward flight conditions.

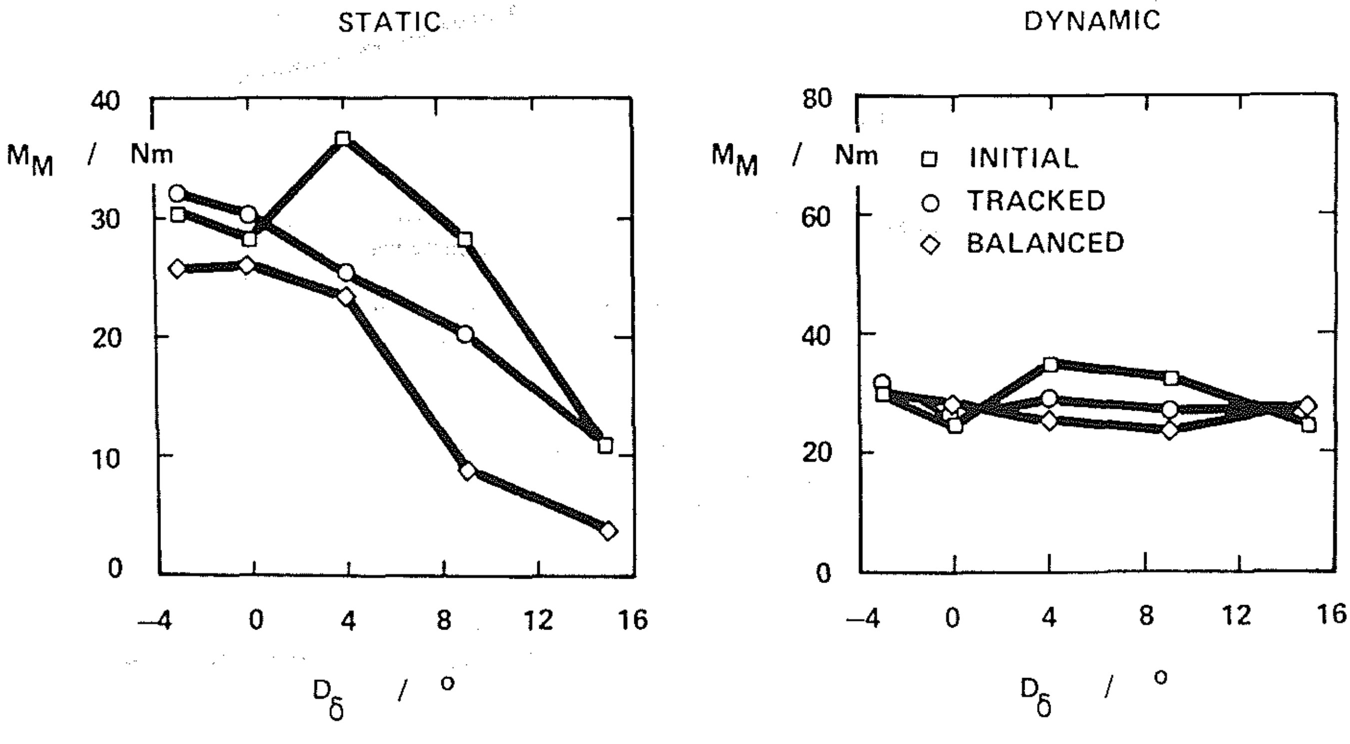


Figure 5.8: Influence of blade tracking on unbalance, illustrated by the mast moment (bench test)

Effect of Profile Contour Deviations on the Aerodynamic Blade Properties

The origin of aerodynamic unbalance are different blade profile contours. In order to show the qualitative influence of profile deviations on blade loads Fig. 5.9 and 5.10 demonstrate, as a result of a theoretical evaluation, the effect of defined contour inaccuracies on lift, torsional moment and critical mach number (wave drag). For this reason a thickness increase and decrease of 0.1 % was introduced in the whole section of the four profile quadrants (Fig. 5.9).

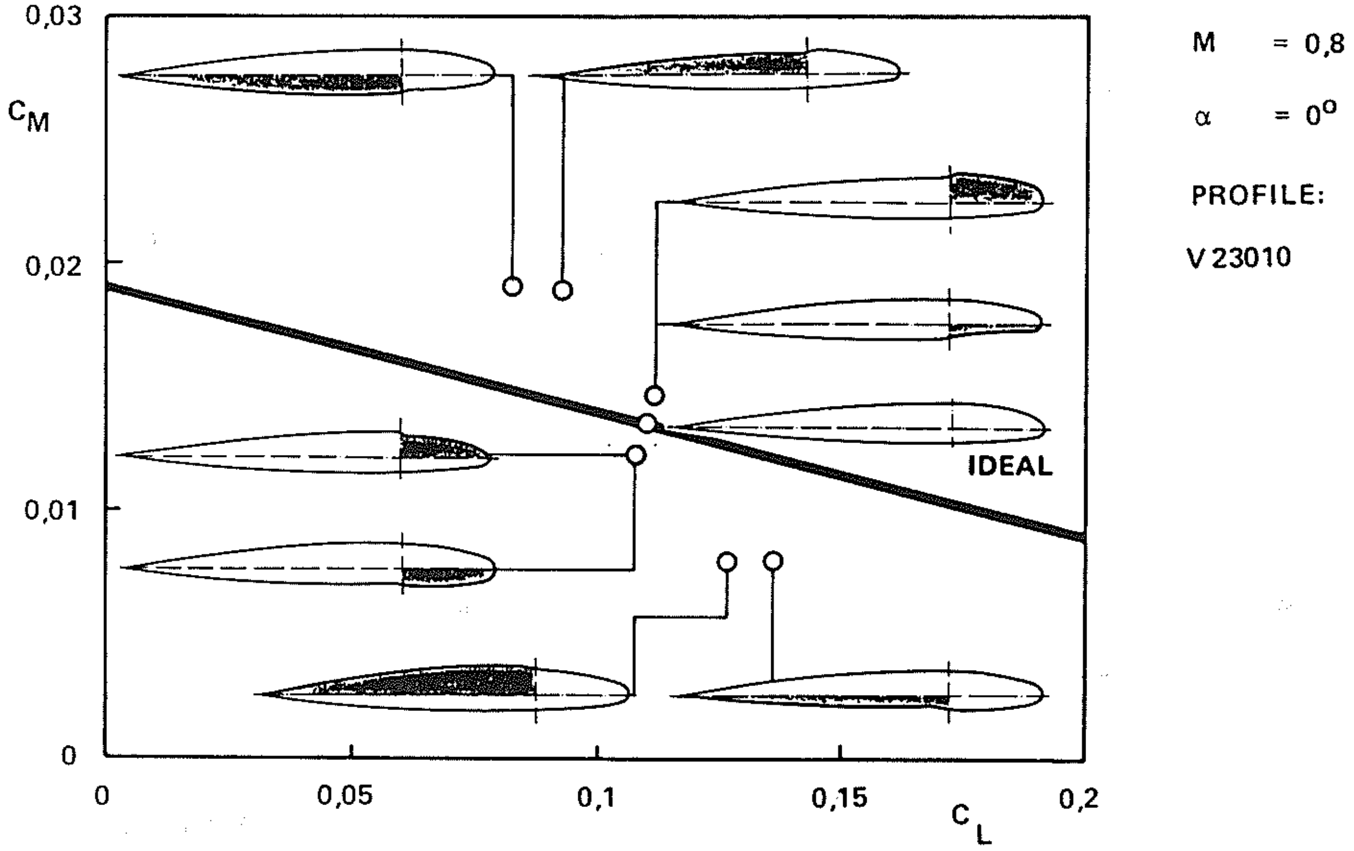


Figure 5.9: Effect of profile contour deviations on torsional moment and lift.
Deviation size 0.1 % over the whole profile quadrant

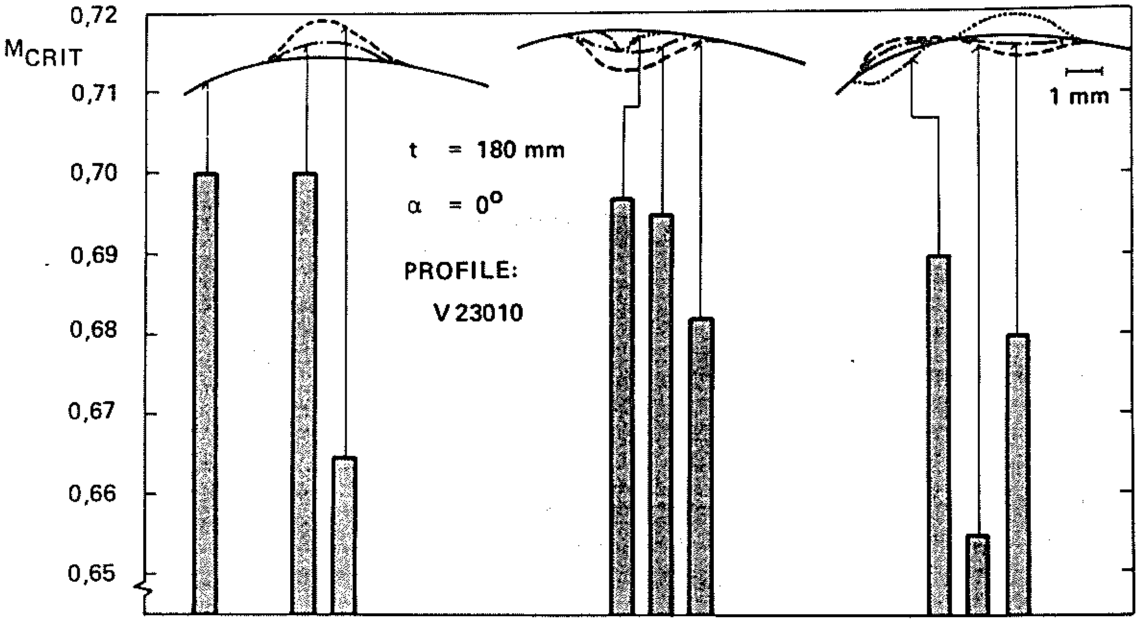


Figure 5.10: Change of critical mach number by different profile contour deviations near the profile nose

For the wave drag particularly contour deviations near the profile nose are of importance (see Fig. 5.10).

The existence of aerodynamic unequalities has been indicated by flight tests with tail rotors, balanced in ground runs. In some cases an increase of the remaining unbalance during cruise was observed which points to aerodynamic origins.

Blade Feathering Moment

In addition to aerodynamic properties the blade pitch also influences the feathering moment of the blade, revealing hereby the existence of chord-wise mass non-symmetries. If the feathering moments of both tail rotor blades do not cancel mutually the remaining moment vector influences the rotor's unbalance.

As an example Fig. 5.11 shows the effect of a change of the feathering moment of one blade. For this purpose the radial distance of the counter weights of one blade was decreased by about 0.3 %, leading in this case to an improvement of the balance status of the tail rotor.

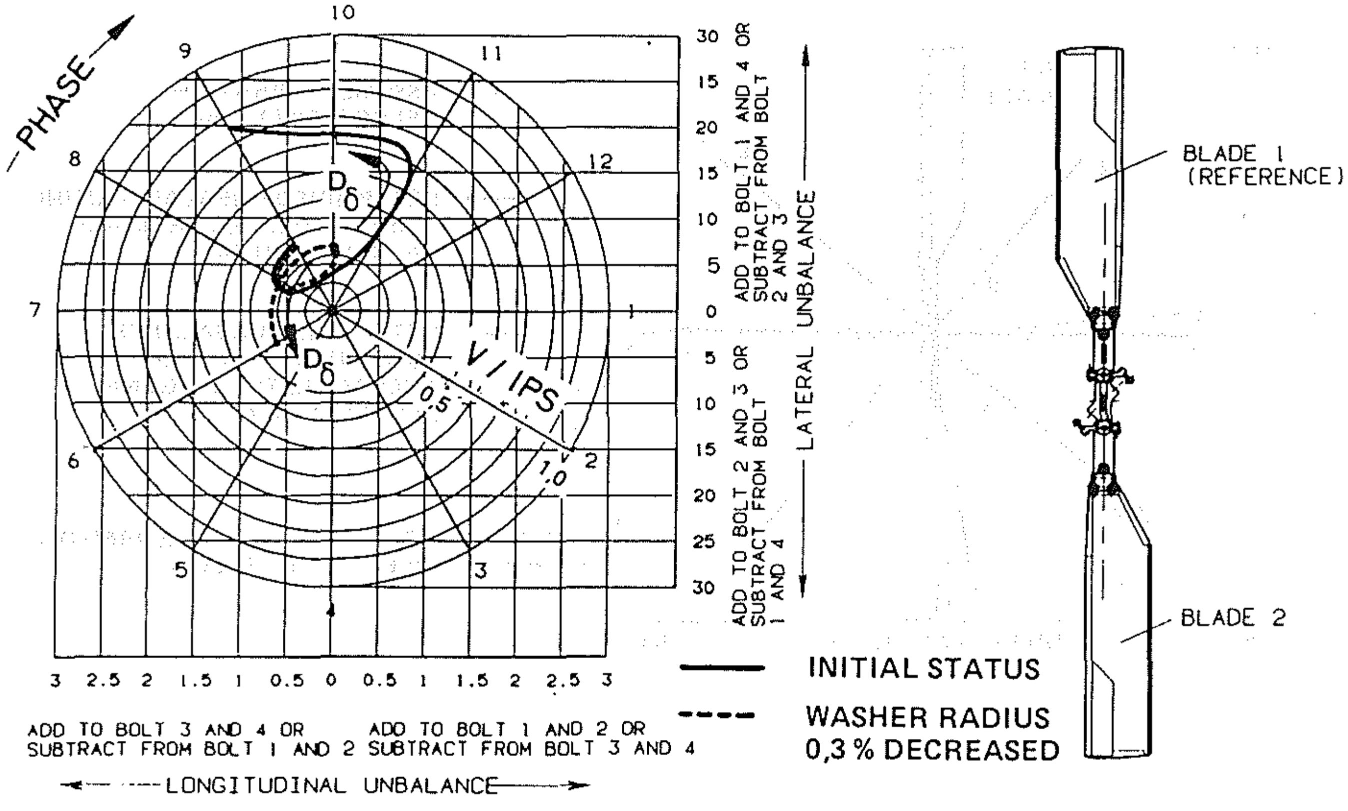
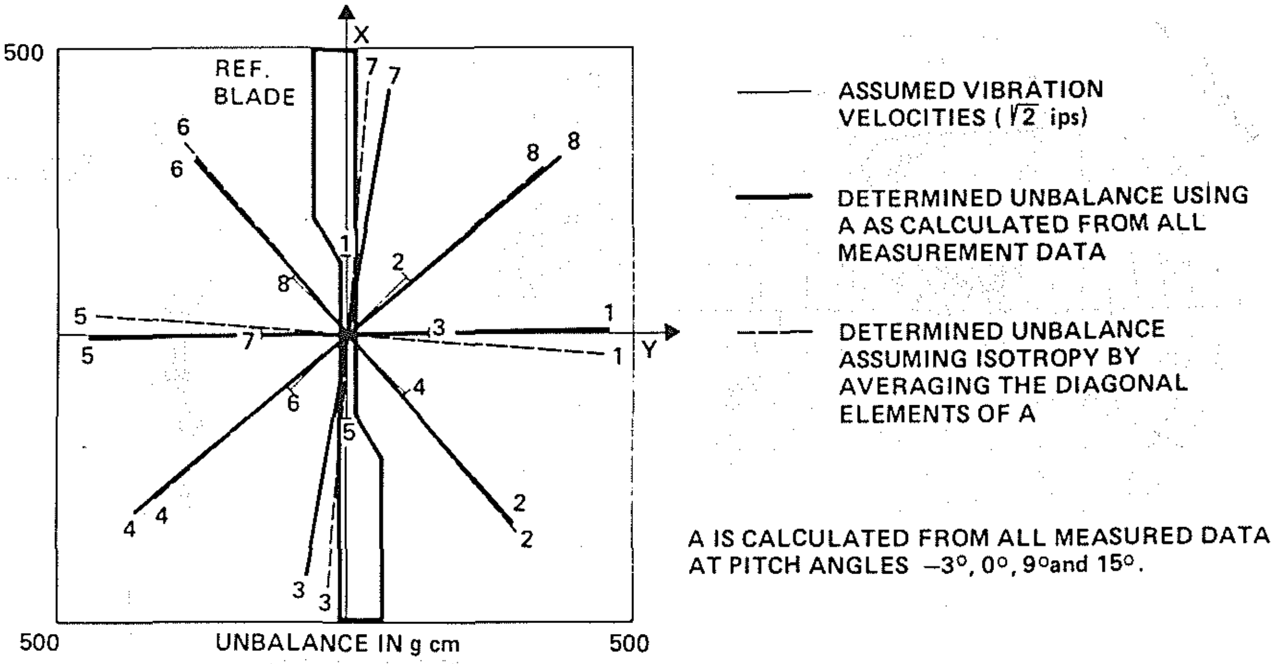


Figure 5.11: Influencing of unbalance by change of the blade feathering moments

5.5 Anisotropy of Rotating Components

Anisotropy of the elastic stiffnesses of the tail rotor mast and the flap bearings (see section 2) does not substantially influence tail rotor dynamics of the MBB helicopter family, since common balancing diagrams, which imply isotropic behaviour of the tail rotor system, yield good results. This is demonstrated in Fig. 5.12 which shows for 8 assumed vibration velocities the corresponding unbalance vectors, calculated using isotropic and anisotropic models (see section 2). As can be seen, the results of both models demonstrate negligible differences.

Anisotropy of the support stiffness of the tail rotor system leads to an elliptic tumbling motion of the rotor/mast system (see Fig. 4.2). This effect does not influence the processing of the measured data, as the reaction of the support has been taken into account by the calibration procedure before the balancing process.



A IS CALCULATED FROM ALL MEASURED DATA AT PITCH ANGLES –3°, 0°, 9° and 15°.

Figure 5.12: Comparison of isotropic/anisotropic unbalance prediction

6. Conclusions

The balancing tests on the test bench and on the helicopter resulted in the following conclusions:

- Balancing with the aid of linear theory yields good results.
- The main origin of unbalance is the eccentric assembling of the tail rotor hub.
- Besides this also manufacturing tolerances, resulting for example in aerodynamic unbalance and unbalance caused by non-symmetric blade feathering moments have to be considered.
- Unbalance mainly excites the first and third harmonic of fixed system vibrations and also influences the dynamic loads in the rotating system.
- In the case of the MBB tail rotors the anisotropy of the rotating rotor components is low or non-existent.

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