PAPER Nr. : 49

EXPERIMENTATION OF TRIFLEX ROTOR HEAD ON GAZELLE HELICOPTER

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SEPTEMBER 4 – 7TH 1979 - AMSTERDAM, THE NETHERLANDS

1 - INTRODUCTION

Aerospatiale has been devoting for long a large part of its research and development effort to the study of advanced main rotor hub, with reduced acquisition and maintenance costs.

This effort has led to the definition of the Starflex rotor head (fig. 1), featuring a fiber glass/epoxy body, and laminated spherical bearings providing blade retention as well as blade flap/lag and pitch degrees of freedom. The Starflex rotor hub is fitted on the ASTAR and Dauphin II helicopters.

Going further in the way of main rotor hub simplification, Aerospatiale is now developing the Triflex (fig. 2) in which all hinges have been eliminated and replaced by a flexible arm, made of glass-resin-elastomer composite material.

After feasability of the concept has been demonstrated through conceptual studies and technological tests, decision was made to build a Triflex main rotor hub and to fly test it on an SA 341 Gazelle helicopter shown on figure 3. The development program of this hub included, together with a design analysis, laboratory tests (static and fatigue tests), bench tests, and flight tests.

This paper presents and discusses the design features of the configuration and concentrates on the results of bench tests and flight tests. Topics covered are : aeroelastic stability, structural strength and flying qualities.

2 - TRIFLEX ROTOR HEAD DESCRIPTION

The main part of the Triflex rotor head consists of a set of glass fiber/epoxy resin yarns, maintained together by an elastomeric matrix (see figure 4) to form a flexible arm.

The glass fiber/epoxy resin yarns extend in the hub central section and in the blade attachment block, constituting a glass roving/glass fabric/epoxy resin composite material.

Two interesting features have to be noted :

- For a given tension strength, division of the roving section into separated yarns allows a dramatic reduction of the torsional stiffness of the flexible arm.

- The elastomeric matrix function is two fold : First, as it maintains yarns spacing it prevents them from yielding under the compression load associated with the arm bending deflection. Then it introduces an internal structural damping.

3 - DESIGN PARAMETERS

These are the physical dimensions or material selection which determine the Triflex behaviour. They are adjusted during the design process to satisfy a set of design criteria addressing : (fig. 5)

— resistance to flight loads.

— resistance to static loads, the rotor being at rest when the helicopter is moved on the ground : as no flapping stops are provided, the flexible arm must sustain blade weight moment multiplied by load factor.

— aeroelastic and mechanical stability of the rotor system.

— loads transmitted to the helicopter body : vibration loads and control loads.

The design parameters as listed on figure 6, are discussed below.

*** Triflex arm constitution :**

The total cross section of the roving yarns is determined by the blade centrifugal load, almost independently of the yarns individual diameter and their number. Increasing the yarn diameter, and then reducing their number results in higher torsional stiffness of the Triflex arm, and thus leads to higher control system loads. But in the same time, resistance to static bending loads when the rotor is at rest is improved : increased diameter means higher resistance to yielding of yarns under compression load.

*** Triflex arm length :**

Increasing the Triflex arm length reduces the torsional as well as the bending stiffness. Stresses in the yarns are also reduced.

*** Yarns spacing :**

Fiber glass yarns should not be too close to each other in order to limit shear and tension/compression stresses in the elastomeric matrix. But the arm cross section should be kept to a minimum to limit torsional stiffness. This results in a typical 50% ratio of yarns cross section area with respect to arm cross section area.

*** Triflex arm cross section shape :**

The arm cross section shape is chosen to satisfy two requirements : first, to sustain the blades when the rotor is non rotating, and second, to tune the blade first lag frequency to 0.6 — 0.7 of the rotor RPM. This leads to an elliptical cross section whose large axis is oriented lag-wise.

*** Elastomer characteristics :**

The elastomeric matrix plays a very important role.

First, it binds the roving yarns together and prevent them from yielding under compression loads : in this regard, its participation to static resistance is determining as shown on figure 7. The characteristic involved here is the shore hardness : the roving yarns tend to penetrate the elastomer. Figure 7 shows clearly the benefits of a hard elastomeric matrix.

The second role of the elastomeric matrix is to provide structural damping. Such damping is very difficult to obtain from a theoretical analysis, as it is due to complex three dimensional deflection of the elastomer. It is also difficult to measure because the damping forces are weak as compared to elastic and inertial forces.

However, rig tests have been conducted on several experimental Triflex rotors which were made of different elastomers. During these tests, global damping of the rotor system (aerodynamic and structural) has been determined using the following technique : as the rotor is allowed to to dash out freely to a full stop, the 1^{st} drag natural frequency crosses the rotor RPM. At the frequency cross-over, there is a growth in the blade drag response under turbulence generated aerodynamic excitation. When this growth is compared with the result of mathematical model of the phenomenon, the rotor global damping in drag can be deduced. Results plotted on figure 8 clearly show the elastomer participation to the rotor damping, and the necessity to select an elastomer providing visco-elastic damping.

*** Pitch arm location :**

The pitch arm location governs pitch/flap/lag couplings, and is chosen to ensure aero-elastic stability of the rotor system.

*** Hub precone and blade lag offset :**

They are selected to reduce flag, drag and control system static loads. But they also influence aeroelastic stability of the rotor because of induced flap/lag/torsional couplings.

4 - DESIGN CHARACTERISTICS

During the design process, the design parameters have been adjusted to ensure proper suitability of the Triflex hub model 545 for operation on a SA 341 Gazelle equipped with Alouette III metallic blades. Leading physical characteristics of this hub are given on table 1 and the calculated rotating blade natural frequencies are given on figure 9.

Because the Triflex hub does not use a lag damper, close attention was paid during the design stage to the blade 1st drag mode damping. As structural damping introduced by the arm elastomeric matrix was not known, neither by test nor by theory, only damping due to aeroelastic effects has been considered. Figure 10 shows a theoretical prediction of lag damping as a function of blade pitch when the rotor is in hover. This damping is weak but always positive.

An air-resonance and ground resonance analysis has also been carried out. As a good positioning of the body vibration mode frequencies was found with respect to blade lag frequency, no stability problems were anticipated. However the diagram of figure 11 shows that ground resonance may occur slightly above the rotor RPM operating range.

5 - BENCH TESTS

During the bench tests, complete identification of the Triflex rotor hub has been performed, including determination of :

- control system loads
- control power
- dynamic response to cyclic pitch input
- mechanical stability.

*** Control system loads :**

An advantage of the Triflex arm is a low torsional stiffness which results in relatively low control system loads.

This is illustrated by the measured pitch link load shown on figure 12, as a function of blade pitch angle.

Control system loads are however much higher than that of the SA 341 articulated hub, and control jack stall occurs at collective pitch setting $\Delta\Theta = 15^o$ (maximum collective pitch being $16^o40'$). Thus, control jack stall was expected to occur during the flight tests, but the actual control system of the SA 341 was believed to allow a good low level altitude flight investigation of the Triflex hub.

*** Pitch - flap coupling :**

The pitch - flap coupling is not, as in the case of an articulated rotor, a purely kinematic effect, because it involves elastic deflection of the Triflex arm. Figure 13 shows the δ_3 effect measured during the bench tests. It can be observed that δ_3 is different whether cyclic or collective pitch is considered, due to a coning angle effect. As far as handling qualities are concerned, the value to be used is δ_3 "cyclic" which is relatively high : -0.5 deg/deg.

*** Control power : (fig. 14)**

Control power measured at rotor centre, is half way between that of the articulated SA 341 hub (NAT hub) and that of the stiff hingeless MIR previously built and tested by Aerospatiale. This control power of 145 m.daN/deg expressed in blade true cyclic pitch, or 100 m.daN/deg expressed in cyclic pitch stick input, corresponds to an 8 % equivalent flapping hinge offset. This value is believed to realize a sensible trade off between controllability requirements on the one hand, and flight stability and vibration problems associated with high equivalent flapping hinge offset, on the other hand.

Response to a cyclic step input (fig. 15) shows a 70^o phase offset in the flap response instead of the classical 90^o for the articulated rotor. This is mainly due to the δ_3 effect.

*** Mechanical stability :**

No stability problems were encountered during the bench tests. But as shown on figure 16, a high lag response has been recorded during start up and shut down when the 1st lag natural frequency crosses the rotor RPM.

Decrease of the response when collective pitch is set to an intermediate value of 8 deg (instead of low pitch) seems to indicate a favourable effect of pitch on lag damping.

Spectrum analysis of the lag signal yields a 1^{st} natural lag frequency of 4.1 Hz, which is very close to the theoretical prediction.

In order to characterize the lag motion with more precision, and especially, to determine the lag damping, a lateral excitation of the MGB bottom has been done by means of a hydraulic jack as sketched on figure 16. The lag response of the rotor is plotted on figure 17 versus the frequency of the excitation.

Assuming the rotor behaves as a second order linear system, allows deducing the lag damping from the lag response bandwith : deduced value is one per cent of critical damping, which is less than the theoretically predicted value.

6 - FLIGHT TESTS

The flight tests have been conducted on a SA 341 Gazelle helicopter and was aimed at determining the in flight dynamic behaviour of the Triflex rotor hub. Main results are discussed below.

* Ground resonance :

Mechanical stability analysis of the Triflex hub fitted on a Gazelle helicopter indicated that the 1^{st} drag natural frequency positioning was such that ground resonance is not likely to occur.

But during the bench tests, lag damping has been found weaker than predicted and this may have an adverse effect on rotor stability. In fact, during the first tests, the aircraft being on the ground, a weak tendency to ground resonance has been observed. This tendency is weaker when collective pitch is increased ; this fact is consistent with the result found during the bench tests showing the favourable effect of collective pitch on rotor damping.

Installation of a landing gear hydraulic damper has been very efficient in solving the problem, allowing the flight tests to proceed on.

* Air resonance :

During the first flights, a vibratory phenomenon, characterized by 4.1 Hz lag loads on the rotor and 2.2 Hz loads on the MGB and MGB support structure, has been identified.

It did not affect flight safety, as oscillation level remained constant and no sudden build up has been encountered. But the vibration level in the cabin was much increased.

To find an explanation and to help solving the problem, a stability analysis was made involving the following vibration modes :

- blade first lag mode.
- four rigid body modes : lateral and longitudinal translation and roll and pitch motion.
- two MGB suspension modes (pitch and roll).
- one engine lateral mode.

Results shown on figure 18 indicate that there is an instability occurring at a rotor speed slightly above the nominal rotor RPM. The vibration modes involved are the blade first lag mode and the engine lateral mode.

Actions found to have a favourable effect on damping are :

- raising the blade 1^{st} lag frequency. Nevertheless, this has an adverse effect on ground resonance.
- increasing the blade lag damping.
- modifying the engine mount stiffness.

In fact, it has been found during the flight tests, that when the MGB suspension is locked longitudinally in position, the lag excitation is sufficiently attenuated to permit the flights to proceed on. (See figure 19).

*** Handling - qualities of the Gazelle equipped with the Triflex hub :**

The flight envelope has been limited due to occurrence of control system jack stall. This problem was anticipated before the tests, the control system being that of the basic Gazelle equipped with the drag - rigid (NAT) rotor, though control system loads are higher.

Nevertheless, maximum speed of 275 km/h and maximum load factor of 2.50 at 220 km/h has been achieved and a good study of the Triflex hub impact on handling qualities has been possible.

The Triflex rotor hub affects mainly the aircraft controllability : its flapping restraint results in a good control power, and the Gazelle equipped with the Triflex hub is well located in the NASA diagram given on figure 20. The only handling problem noticed is associated with the phase offset of the hub response to cyclic input (this characteristic was already identified during the design phase and documented during the bench tests).

With the non modified control system of the Gazelle, there is a cross coupling between roll and pitch response to pure longitudinal or lateral stick movement. This effect is quantified on figure 21, both in hovering and in forward flight for a longitudinal step of the cyclic stick. This coupling effect can easily be decreased and even zeroed by a proper phasing of the cyclic control. (See figure 22). However, this phase offset must be limited to avoid a pronounced left positioning of the cyclic stick in cruise flight.

7 - CONCLUSION

A hingeless Triflex rotor hub has been successfully flight tested on a Gazelle helicopter, hence demonstrating the feasability of the concept. In particular, no stability problems specific to this type of rotor hub have been encountered, and the flying qualities of Gazelle fitted with the Triflex hub was good.

However, the rotor lag damping has been found to be weak, and must be improved. We think that this can be achieved by selecting an elastomeric matrix incorporating structural visco elastic damping.

Then, the next phase of the Triflex hub development will concentrate on material selection. Other improvements will be studied also, with a major concern on optimizing the manufacturing process. In this regard, a reduction in the number of roving yarns is contemplated.

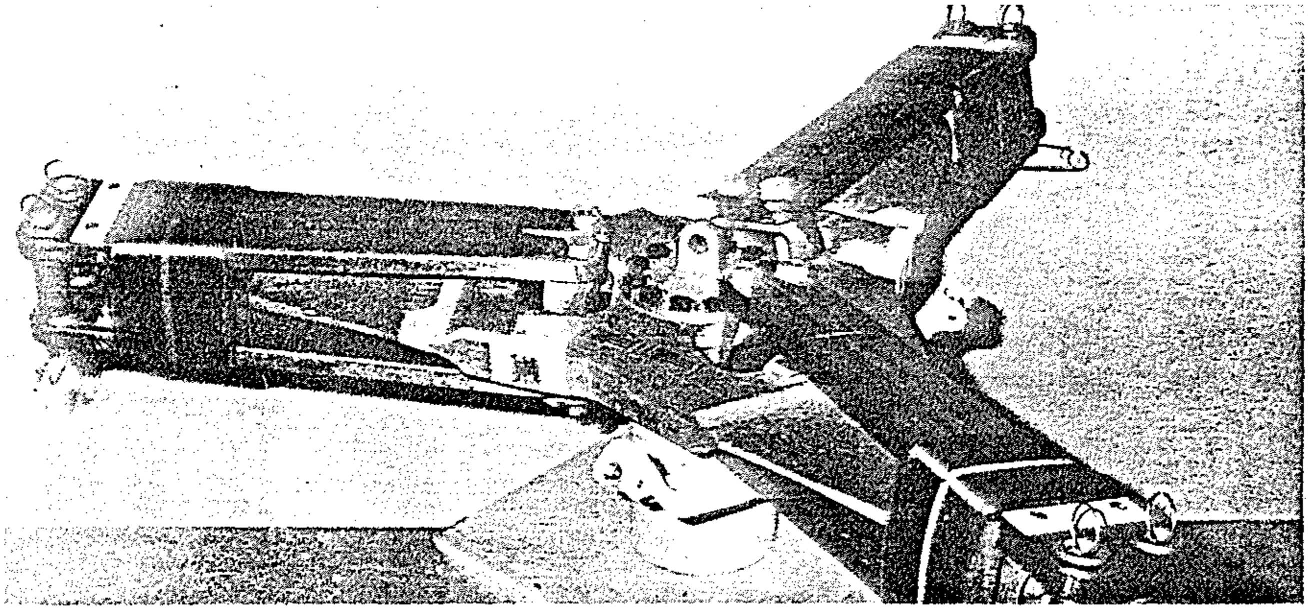


FIG 1 STARFLEX ROTOR HEAD

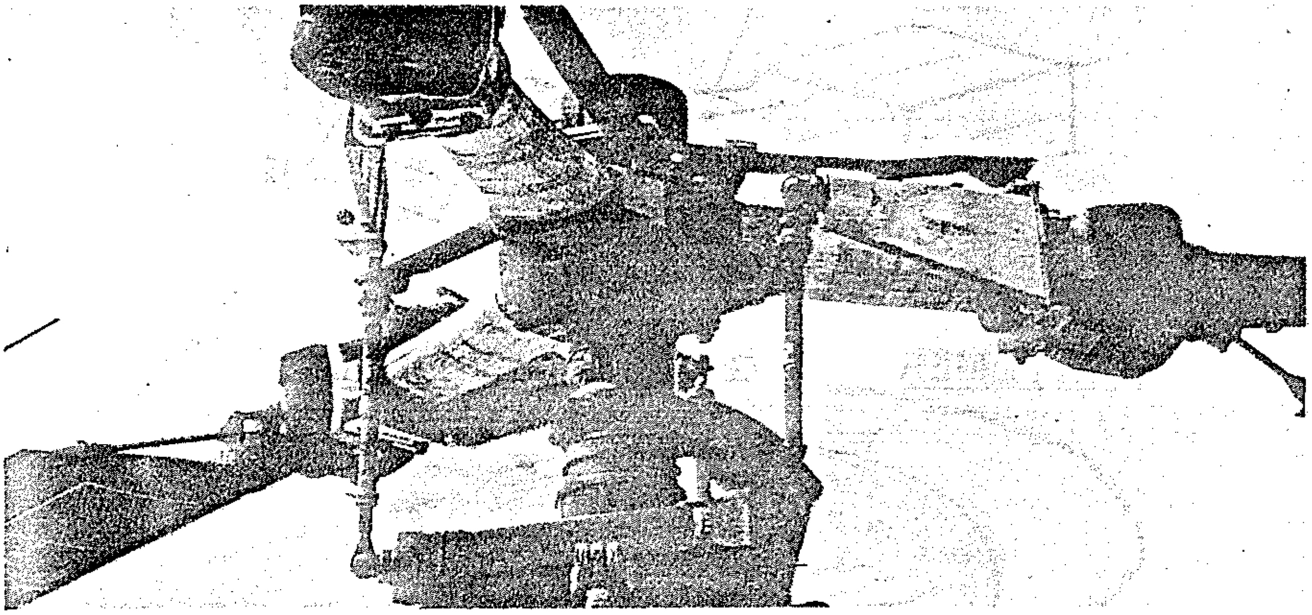


FIG 2 TRIFLEX ROTOR HEAD

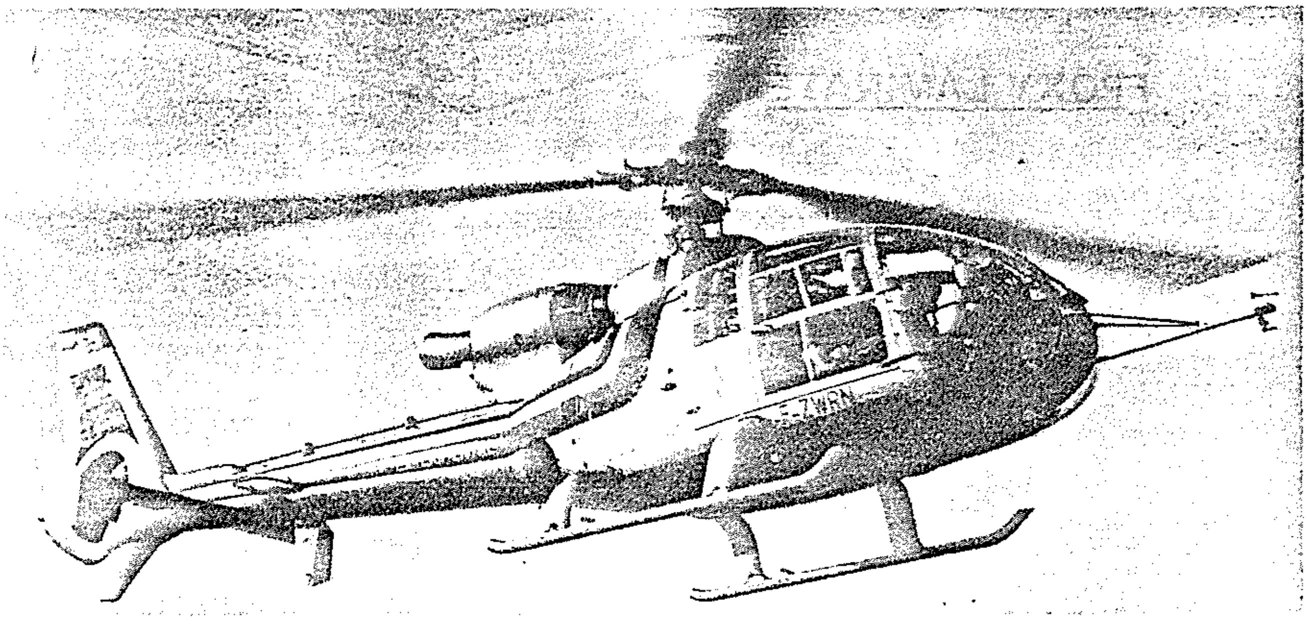


FIG 3 GAZELLE HELICOPTER

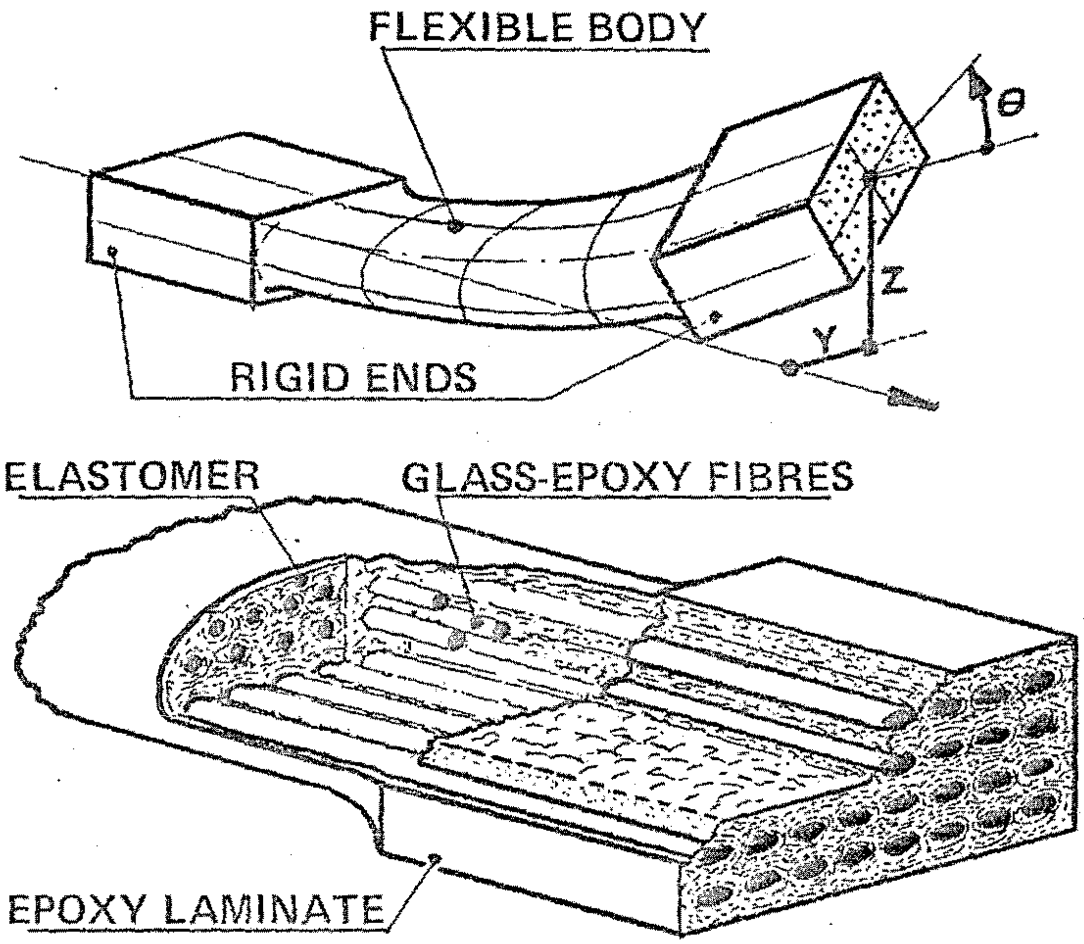


FIG 4 TRIFLEX HUB CONSTRUCTION

TRIFLEX HUB DESIGN CRITERIA

- RESISTANCE TO FLIGHT LOADS
- RESISTANCE TO STATIC GROUND LOADS
- AEROELASTIC AND MECHANICAL STABILITY OF THE ROTOR SYSTEM
- LOADS TRANSMITTED TO THE HELICOPTER AIRFRAME

FIG 5 TRIFLEX HUB DESIGN CRITERIA

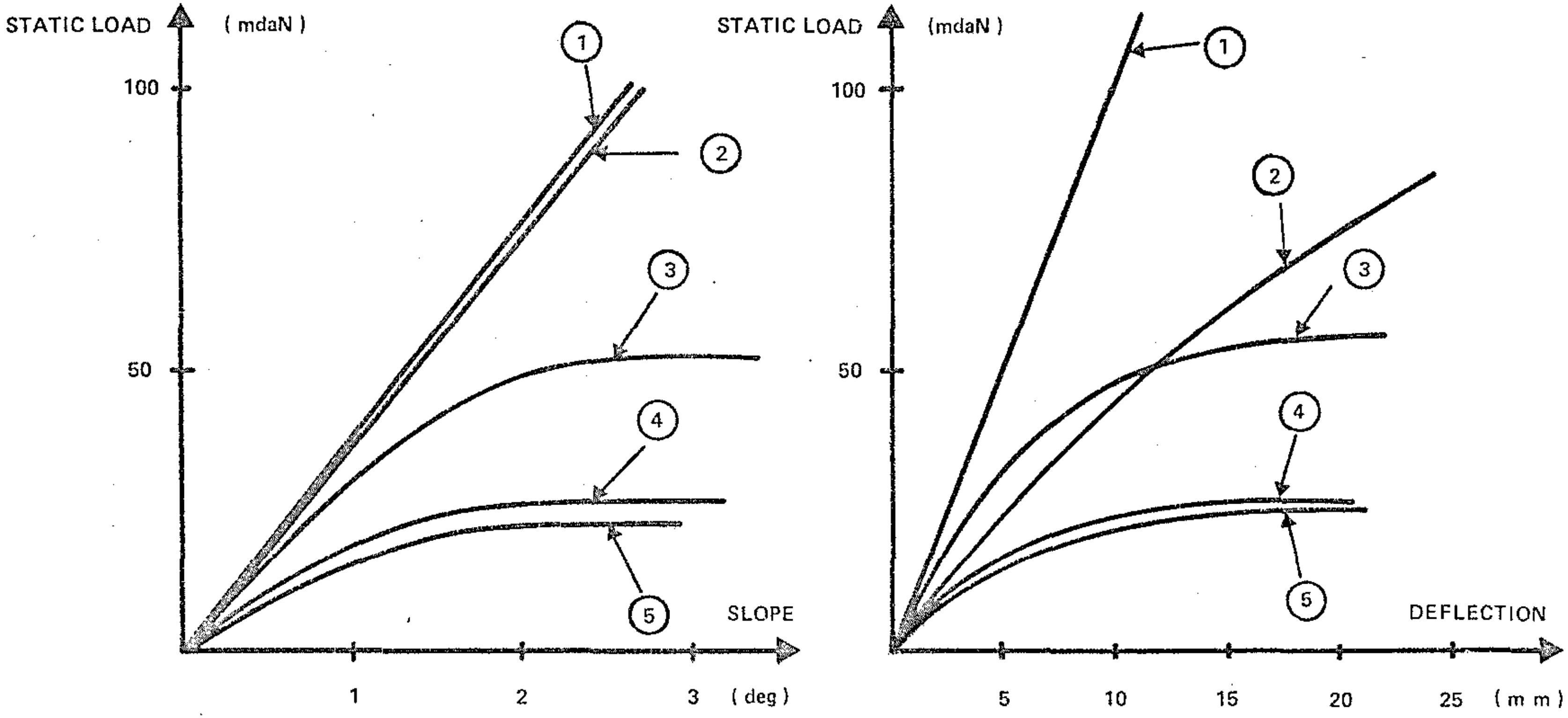
TRIFLEX HUB DESIGN PARAMETERS

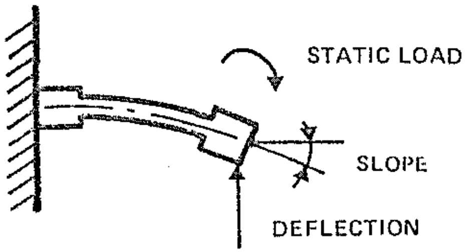
- TRIFLEX ARM CONSTITUTION
  - ROVING YARNS DIAMETER
  - NUMBER OF ROVING YARNS
- TRIFLEX ARM LENGTH
- YARNS SPACING
- TRIFLEX ARM CROSS SECTION SHAPE
- ELASTOMER CHARACTERISTICS
- PITCH ARM LOCATION
- HUB PRECONE AND BLADE LAG OFFSET

FIG 6 TRIFLEX HUB DESIGN PARAMETERS

EFFECT OF ELASTOMER ON TRIFLEX ARM

STATIC DEFLECTION





1	ELASTOMER	HARDNESS	80
2	ELASTOMER	HARDNESS	35
3	ELASTOMER	HARDNESS	70
4	ELASTOMER	HARDNESS	35
5	NO ELASTOMERIC MATRIX		

FIG 7

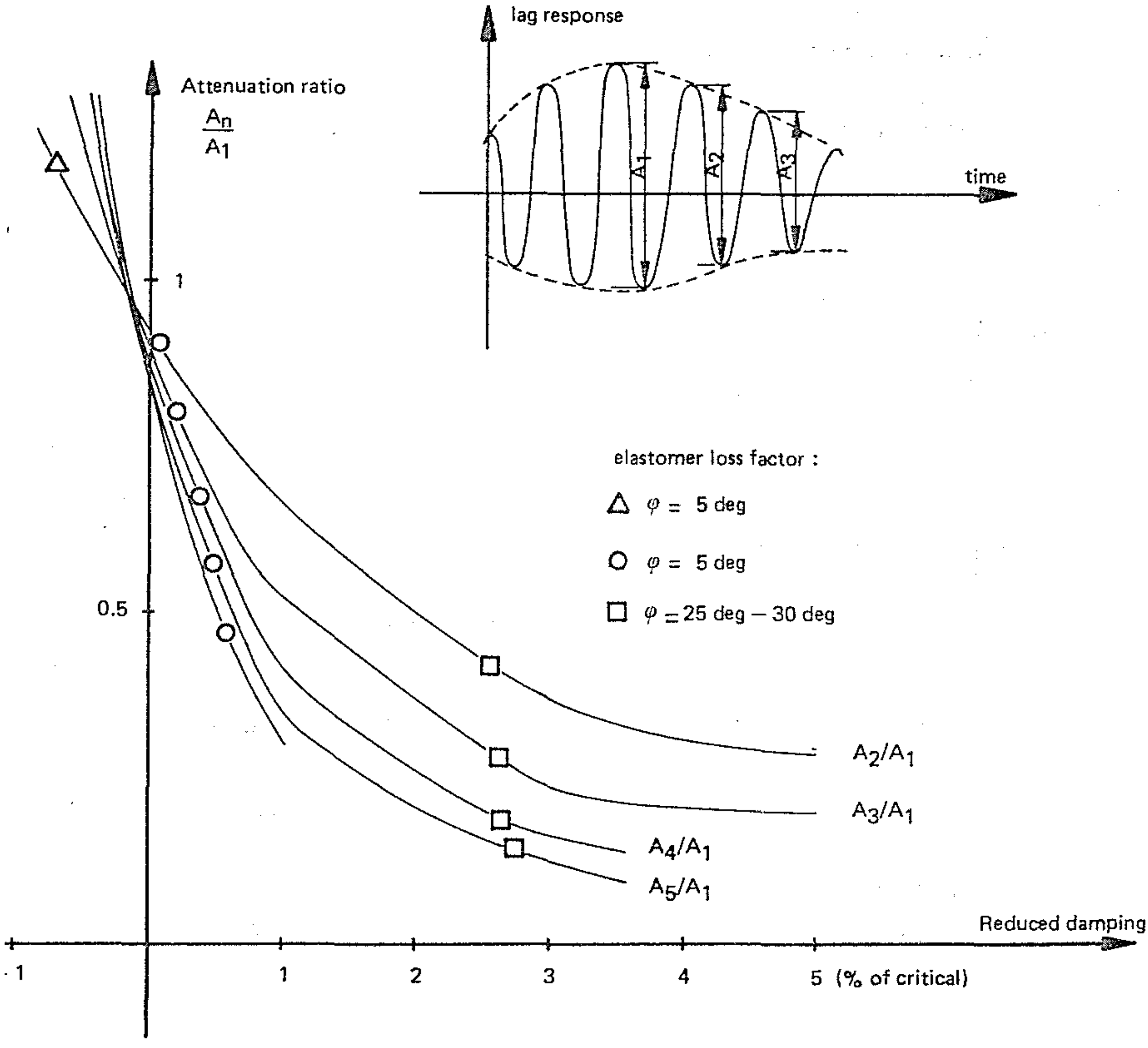


FIG 8 EFFECT OF ELASTOMER ON TRIFLEX HUB LAG DAMPING (AS DEDUCED FROM BENCH TESTS).

TABLE 1

TRIFLEX ROTOR LEADING CHARACTERISTICS

* Triflex arm characteristics

— length	:	0.24 m
— elliptical section	:	0.031 x 0.0465 m x m
— number of roving yarns	:	1200
— yarns diameter	:	1,6 mm

* Lag offset : 18 mm

* Hub precone : 2.5 deg

* Blade dimensional characteristics

— number of blades	:	3
— radius	:	5,20 m
— chord	:	0.35 m

* Rotor speed : 40 rad/sec

*Blade natural frequencies (fully coupled including aerodynamic effect)

Modes	Frequencies (Hz)	Reduced frequencies
1st drag	4.2	0.66
1st flap	8.2	1.29
2nd flap	18	2,83
1st torsion	19.2	3.02
2nd drag	24.5	3.85

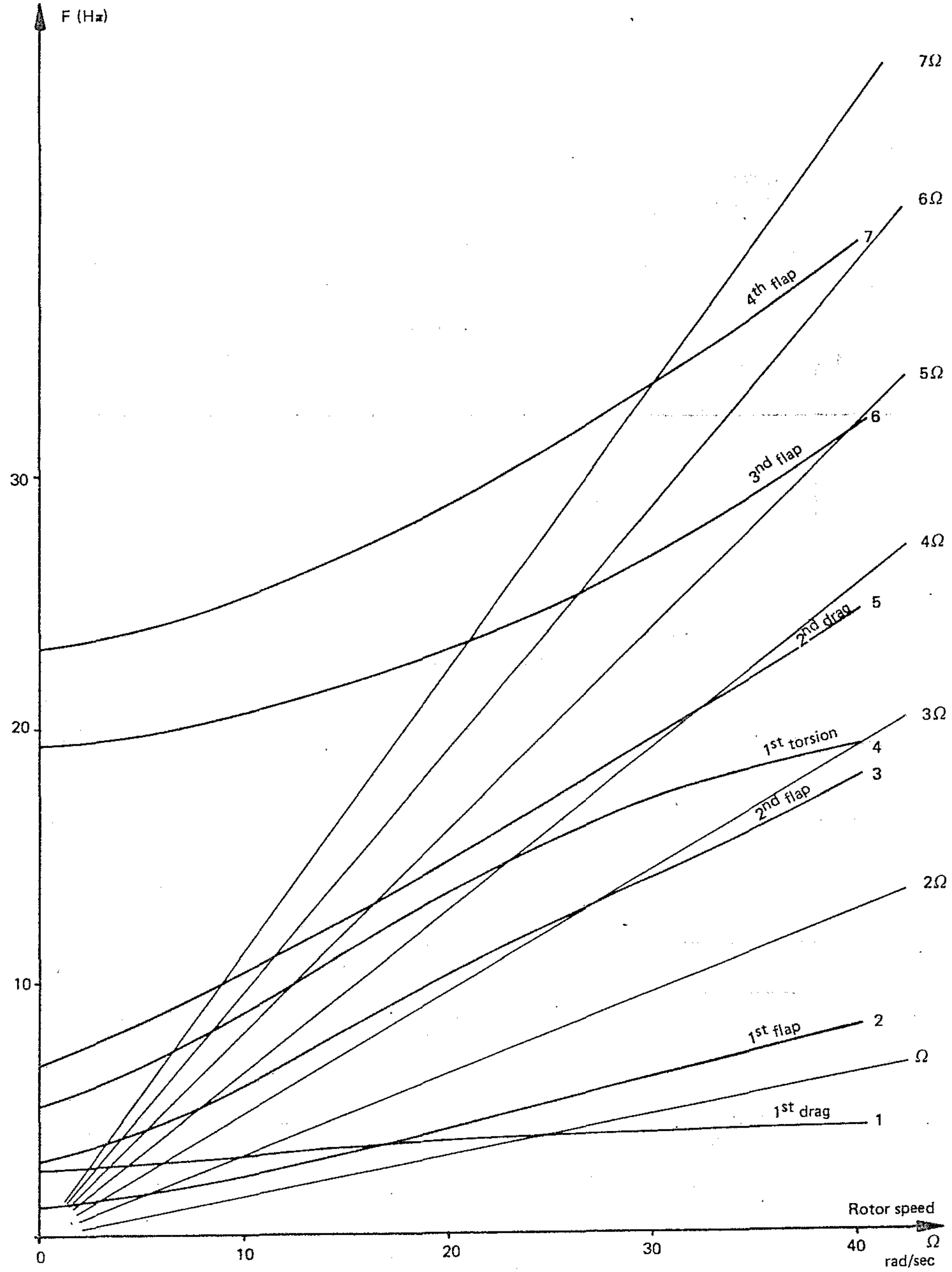


FIG 9 PREDICTED FULLY COUPLED NATURAL FREQUENCIES FOR TRIFLEX MAIN ROTOR SYSTEM

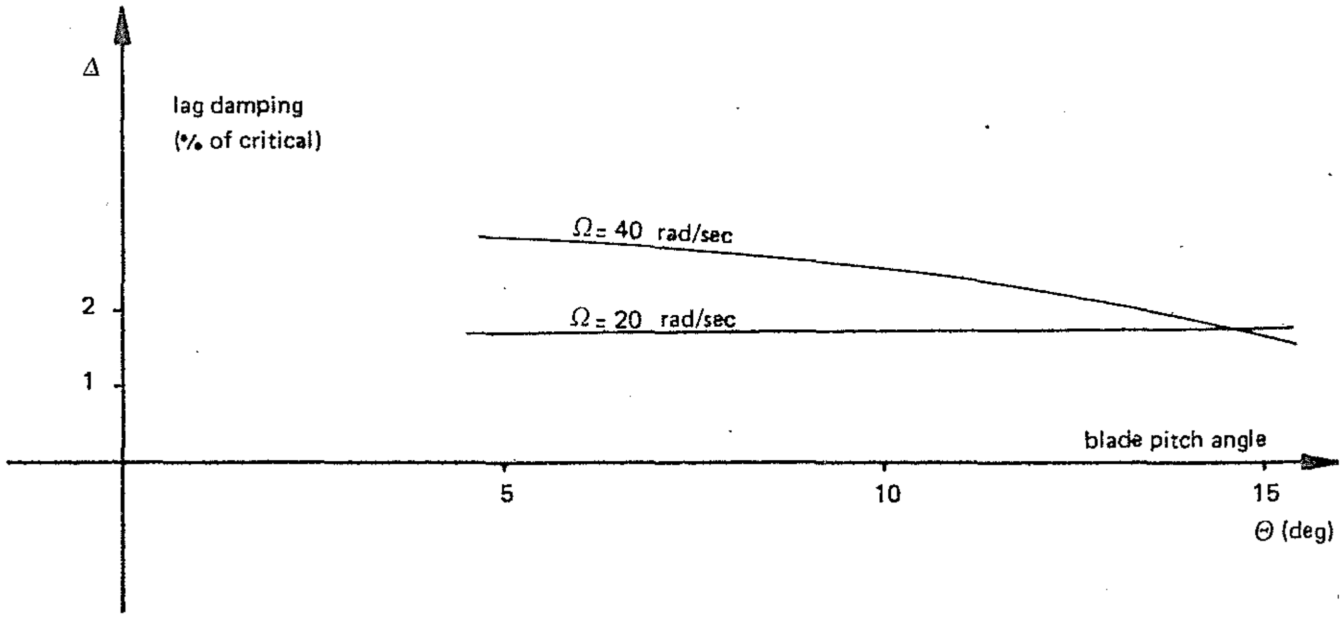


FIG 10 ROTOR DAMPING IN LAG (PREDICTION)
(545 TRIFLEX HUB)

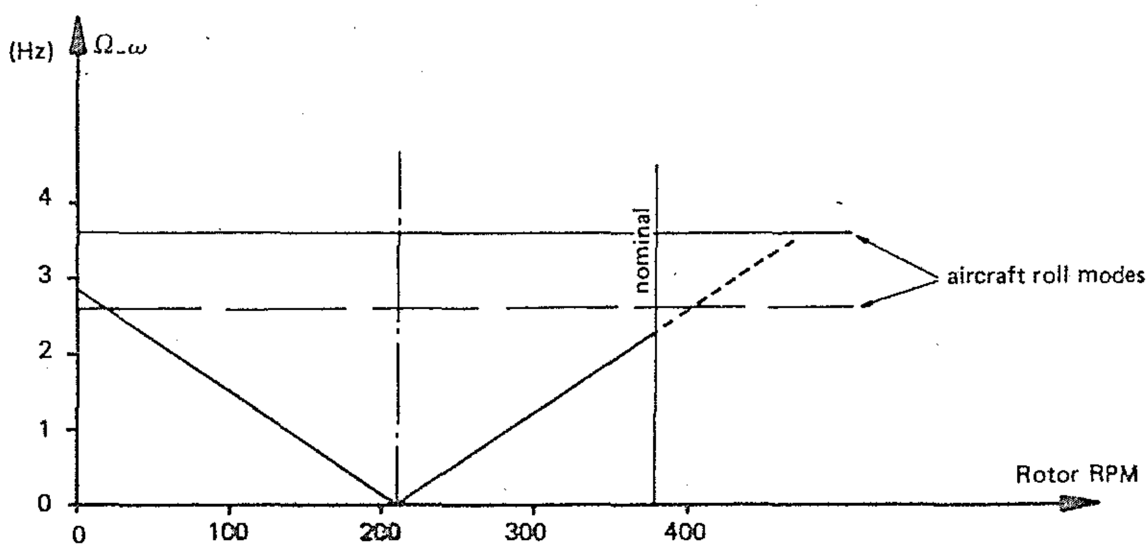


FIG 11 GROUND RESONANCE DIAGRAM

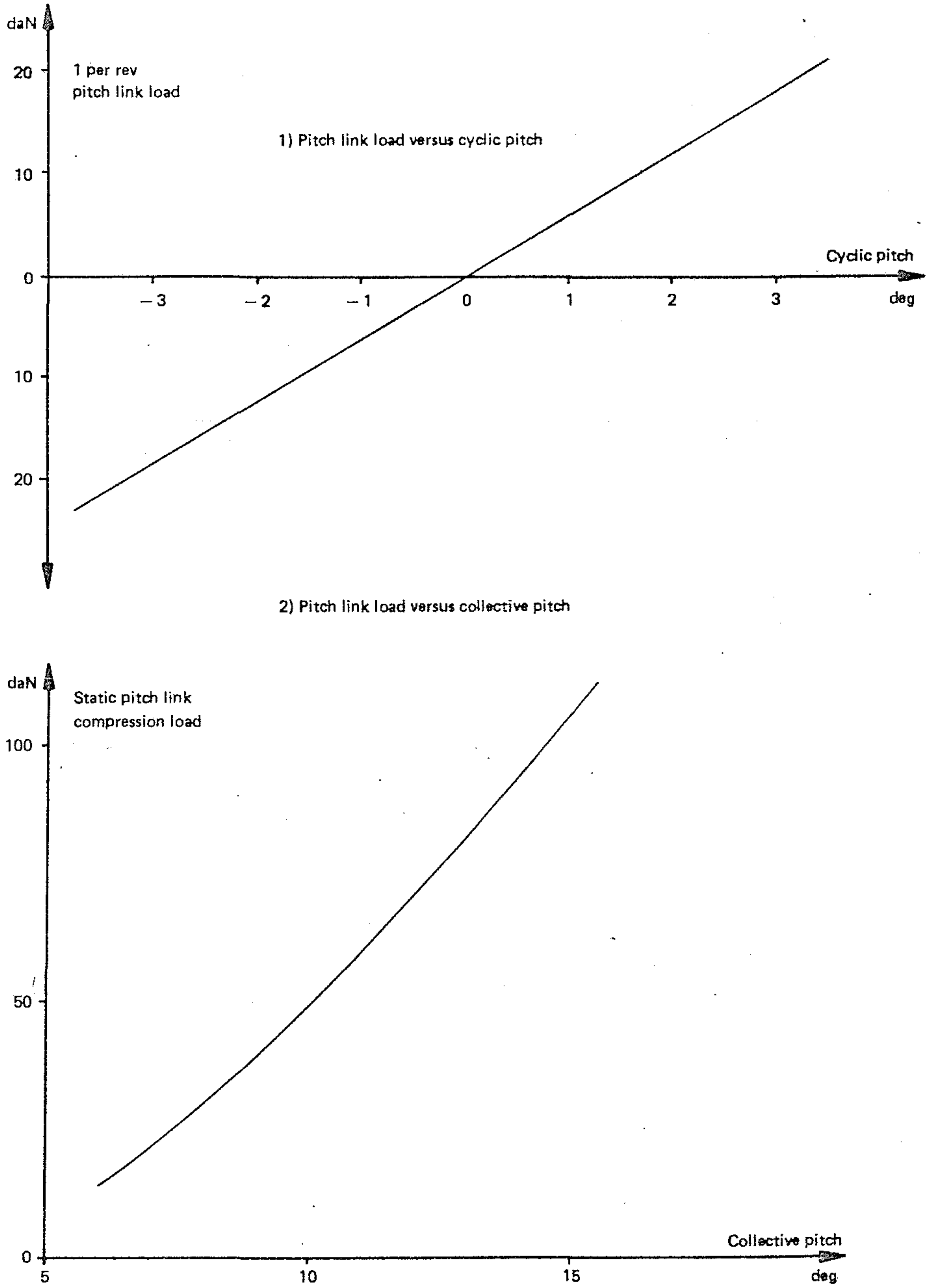


FIG 12 TRIFLEX HUB CONTROL SYSTEM LOADS
(RECORDED DURING BENCH TESTS)

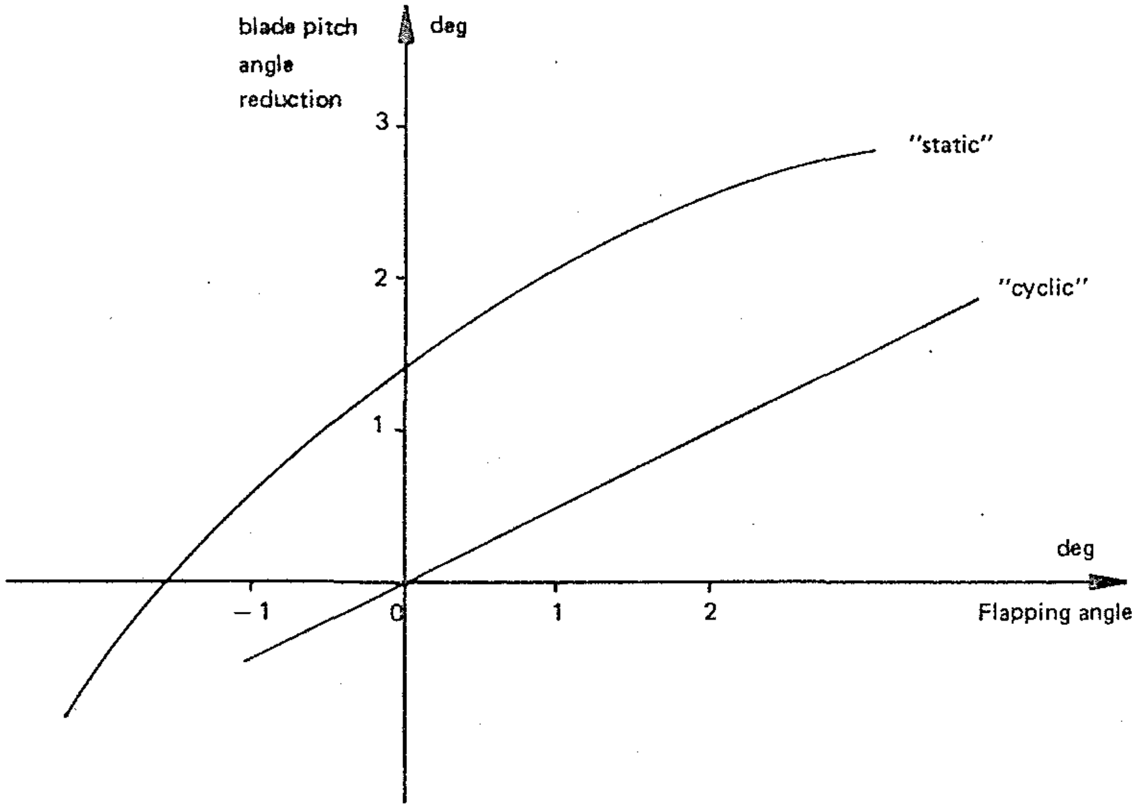


FIG 13 TRIFLEX HUB δ_3 EFFECT

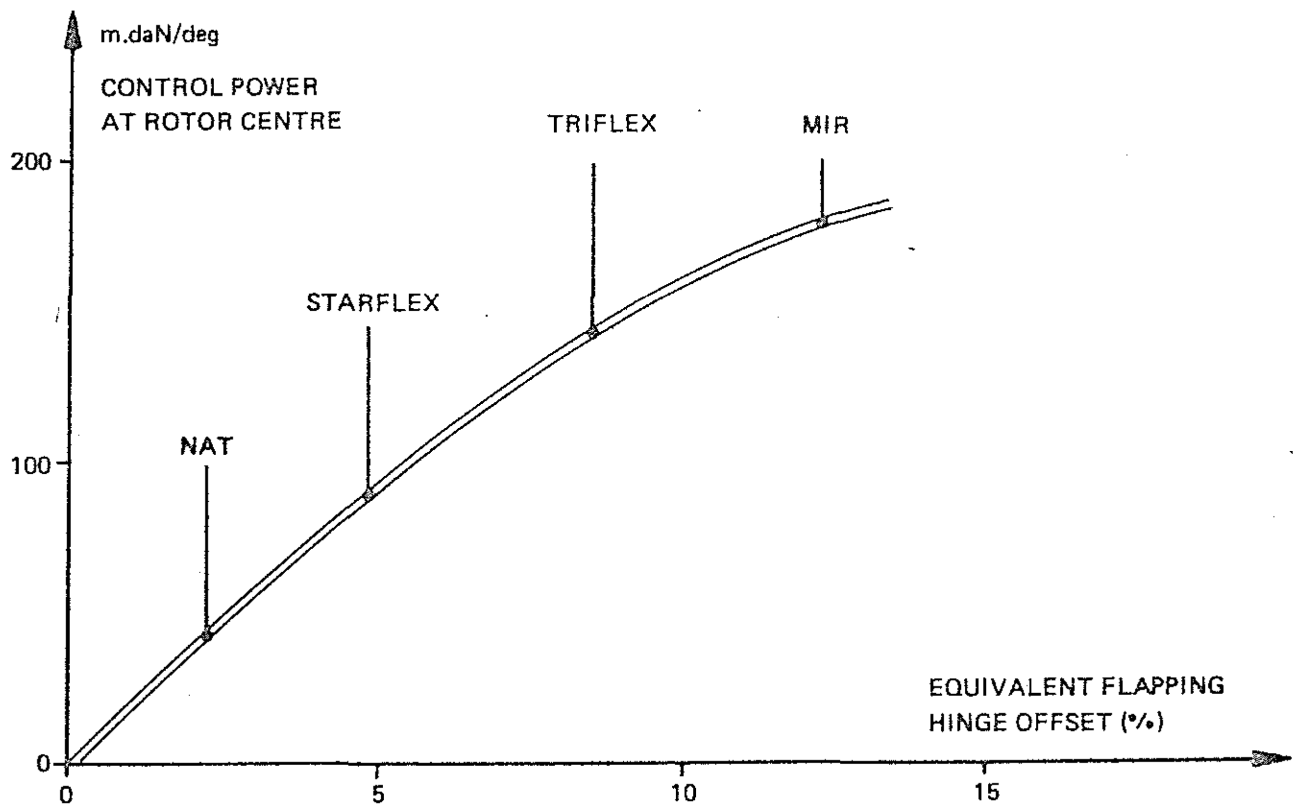
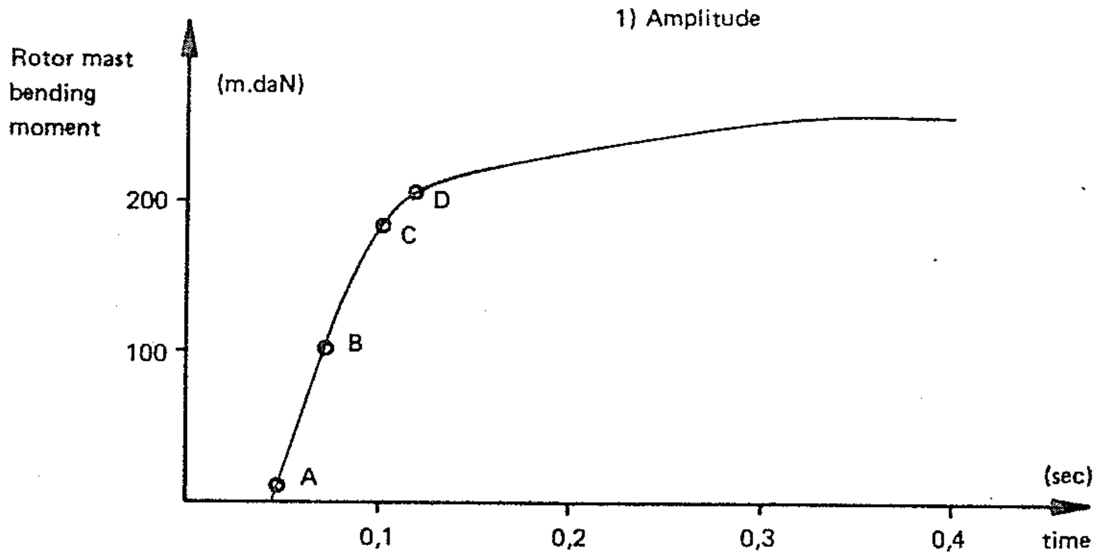


FIG 14 CONTROL POWER



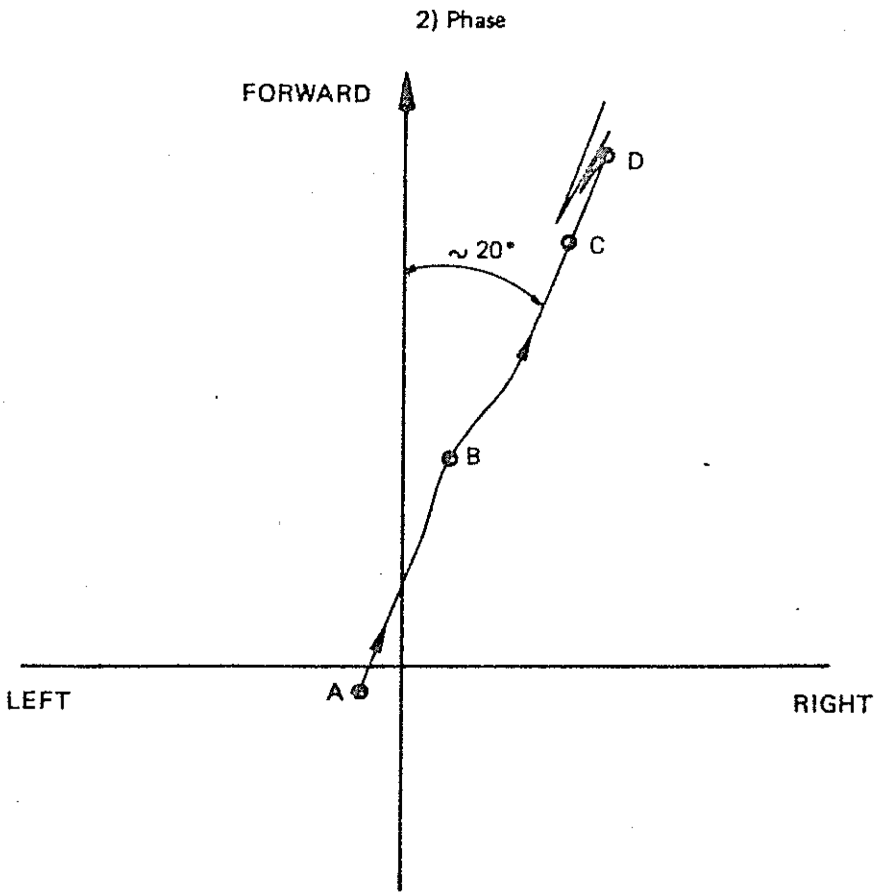
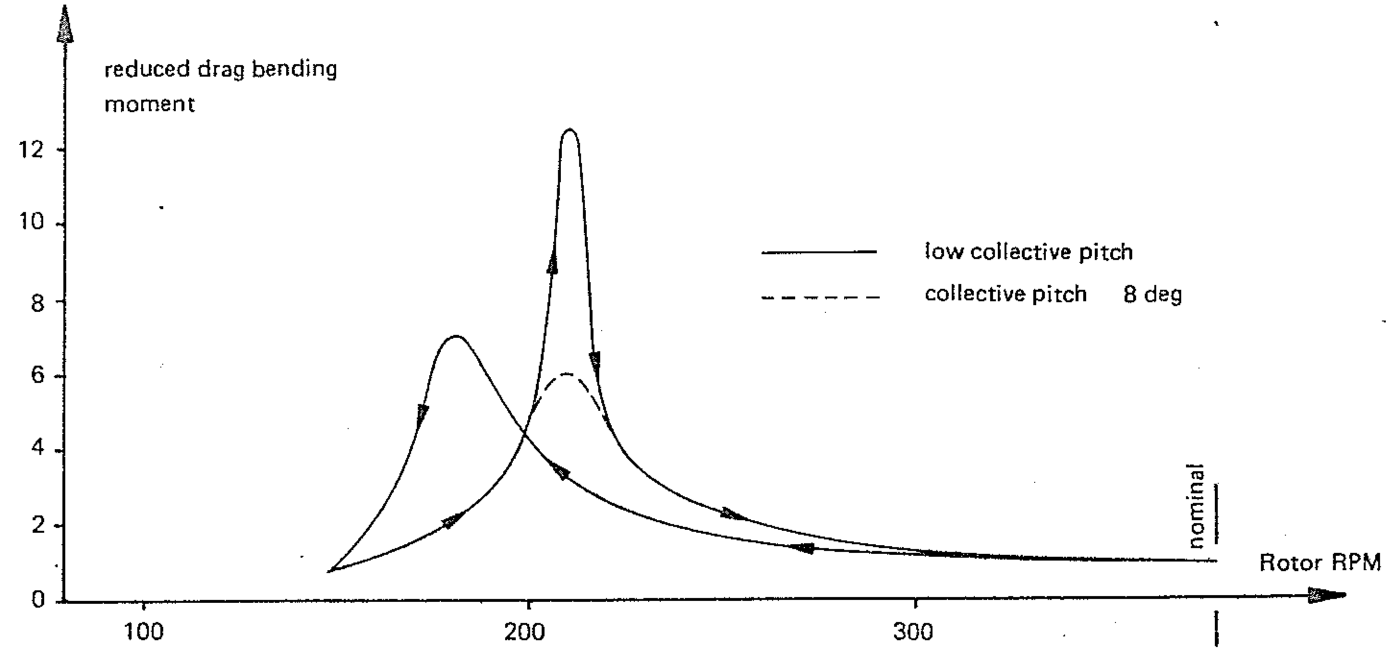


FIG 15 TRIFLEX ROTOR RESPONSE TO CYCLIC PITCH STEP INPUT (LONGITUDINAL STEP INPUT)



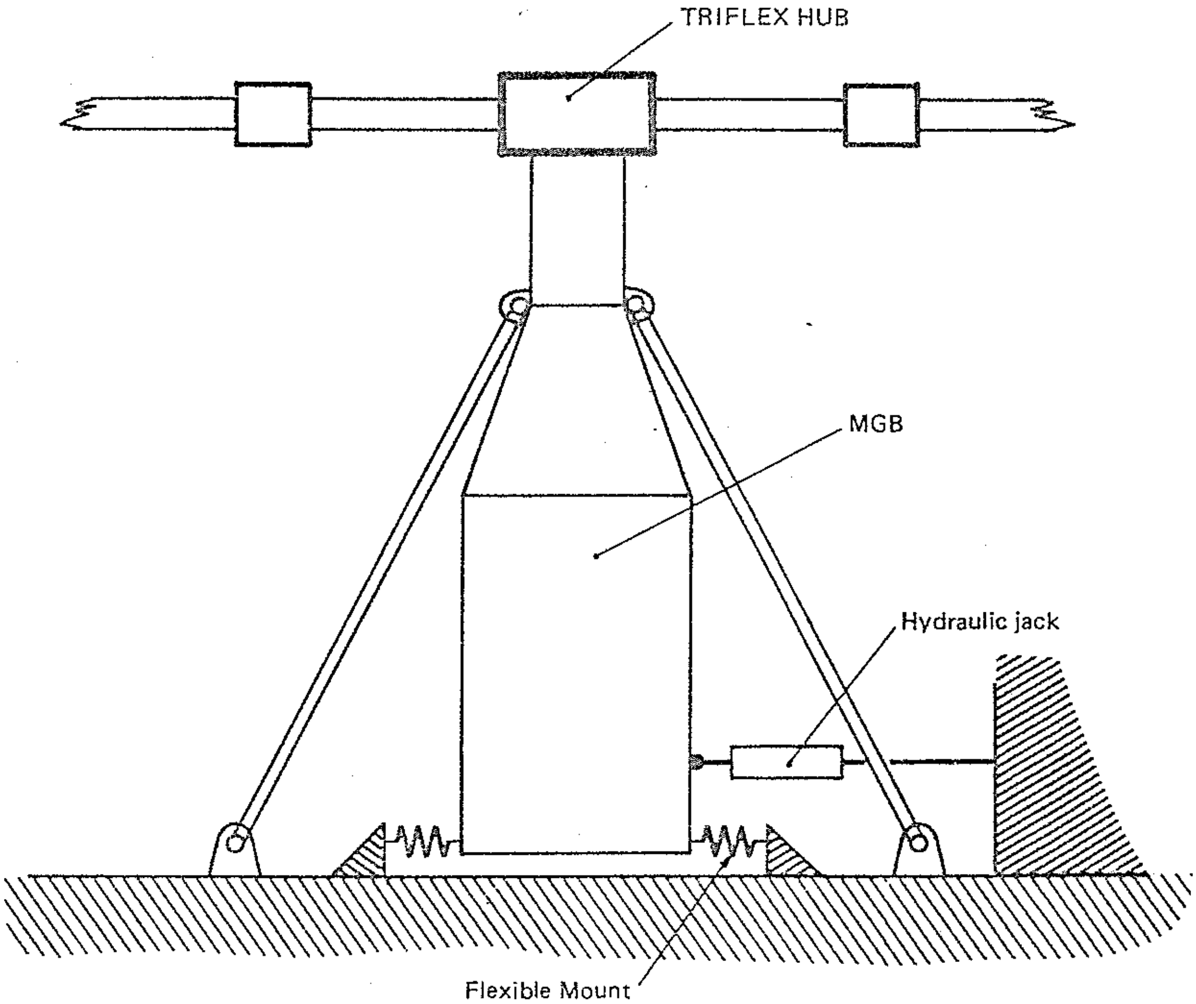


FIG 16 VARIATION OF CREST TO CREST HUB DRAG MOMENT DURING ROTOR START UP AND SHUT DOWN

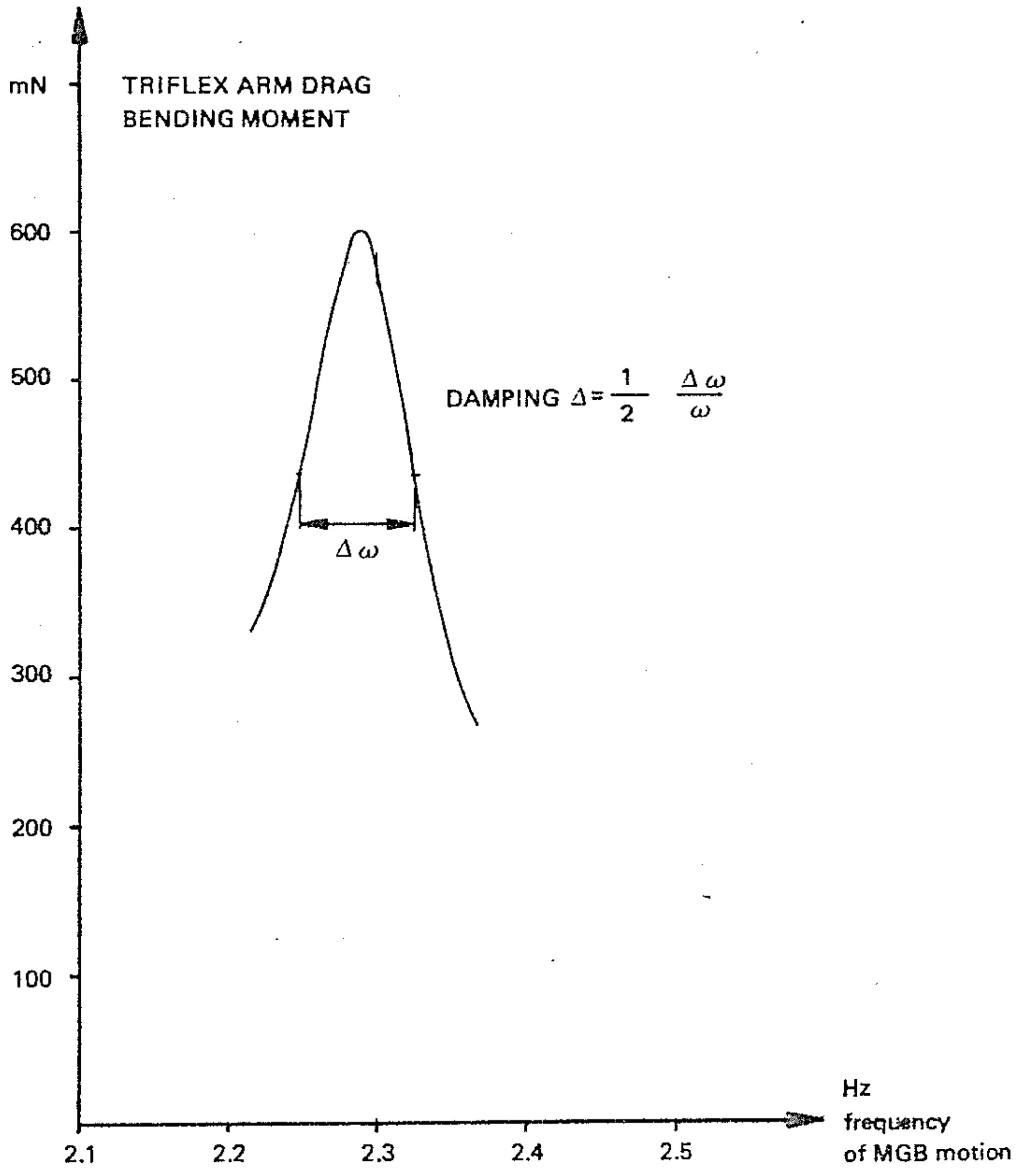


FIG 17 VARIATION OF TRIFLEX ARM DRAG BENDING MOMENT WITH MGB EXCITATION FREQUENCY

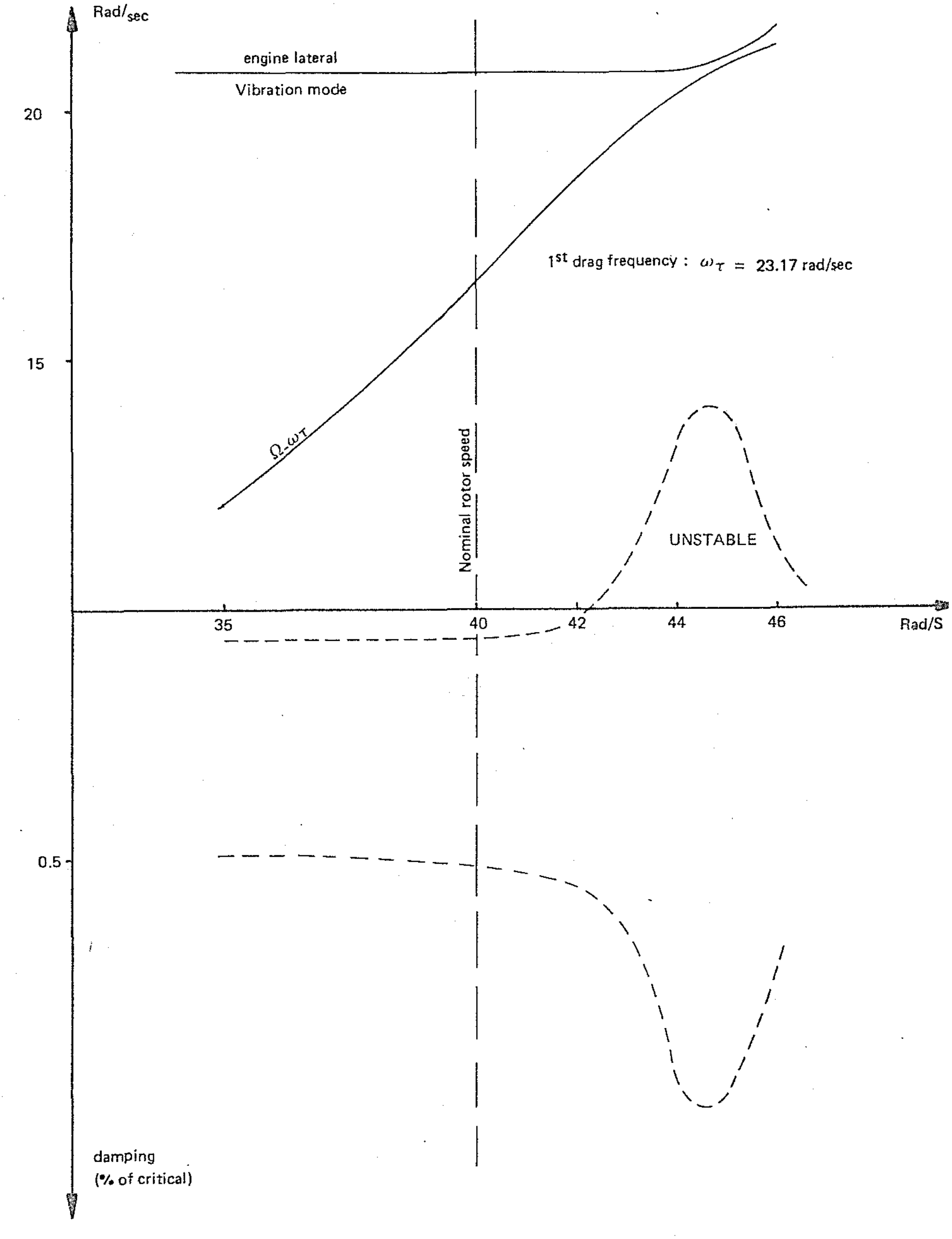


FIG 18 AIR RESONANCE DIAGRAM

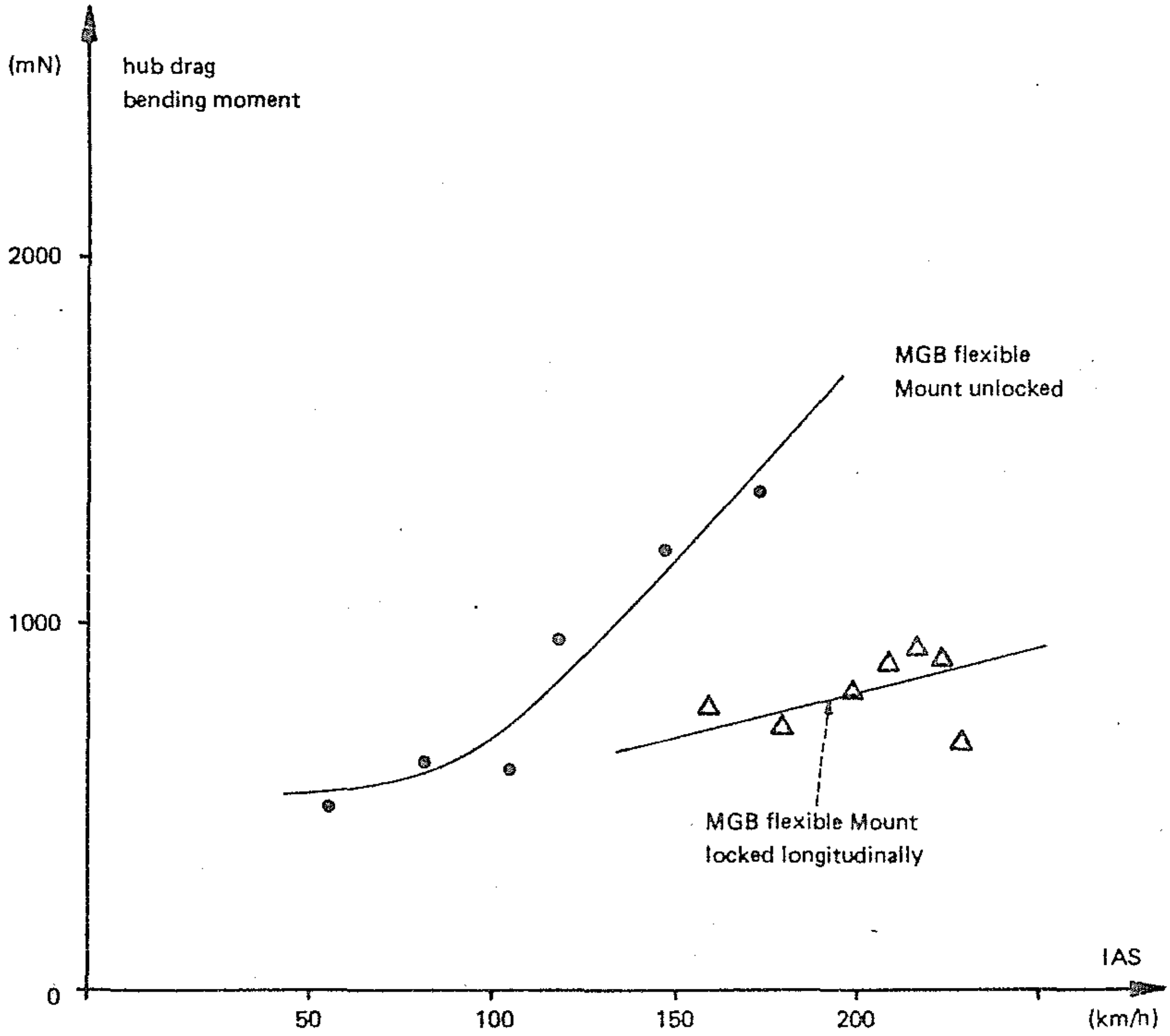


FIG 19 AIR RESONANCE : HUB DRAG BENDING MOMENT
(f 4.2 Hz)

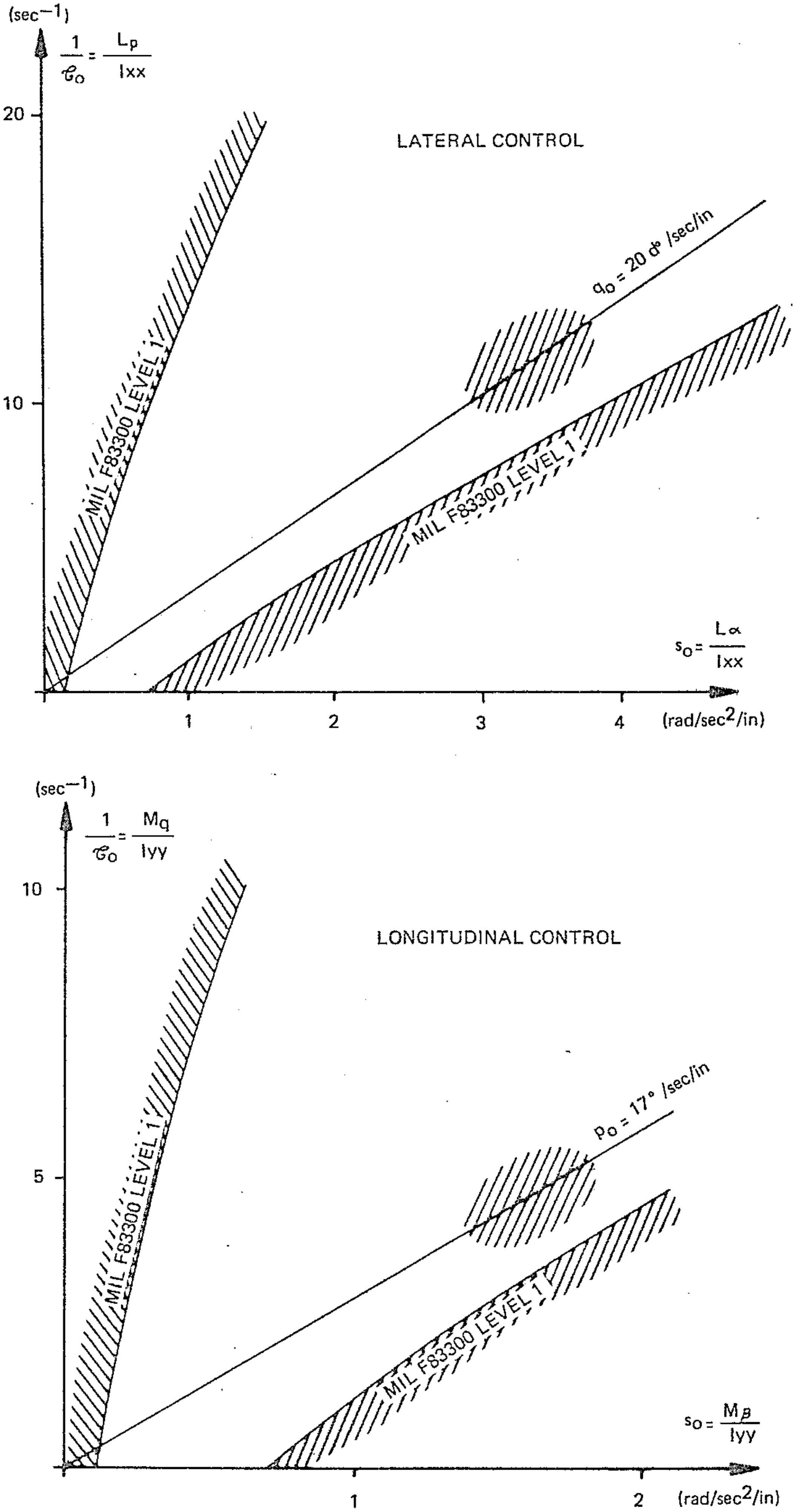


FIG 20 LATERAL AND LONGITUDINAL CONTROL IN LEVEL FLIGHT (250 KM/H) (SA 341 WITH TRIFLEX HUB)

(RESPONSE TO LONGITUDINAL CYCLIC STEP INPUT)
(stick travel $\simeq$ inch)

	MAX. PITCH RATE	MAX. ROLL RATE	CROSS-COUPLING
HOVER	20 deg/sec	12.3 deg/sec	62 %
CRUISE FLIGHT	13.3 deg/sec	19.3 deg/sec	145 %

FIG 21 PITCH - ROLL CROSS - COUPLING

(RESPONSE TO LONGITUDINAL CYCLIC STEP INPUT)

CONTROL SYSTEM PHASING	HOVER	CRUISE FLIGHT
0 deg	62 %	145 %
10 deg	39 %	91 %
20 deg	19 %	44 %
30 deg	0 %	0 %

FIG 22 - 1 EFFECT OF CONTROL SYSTEM PHASING ON PITCH - ROLL CROSS - COUPLING

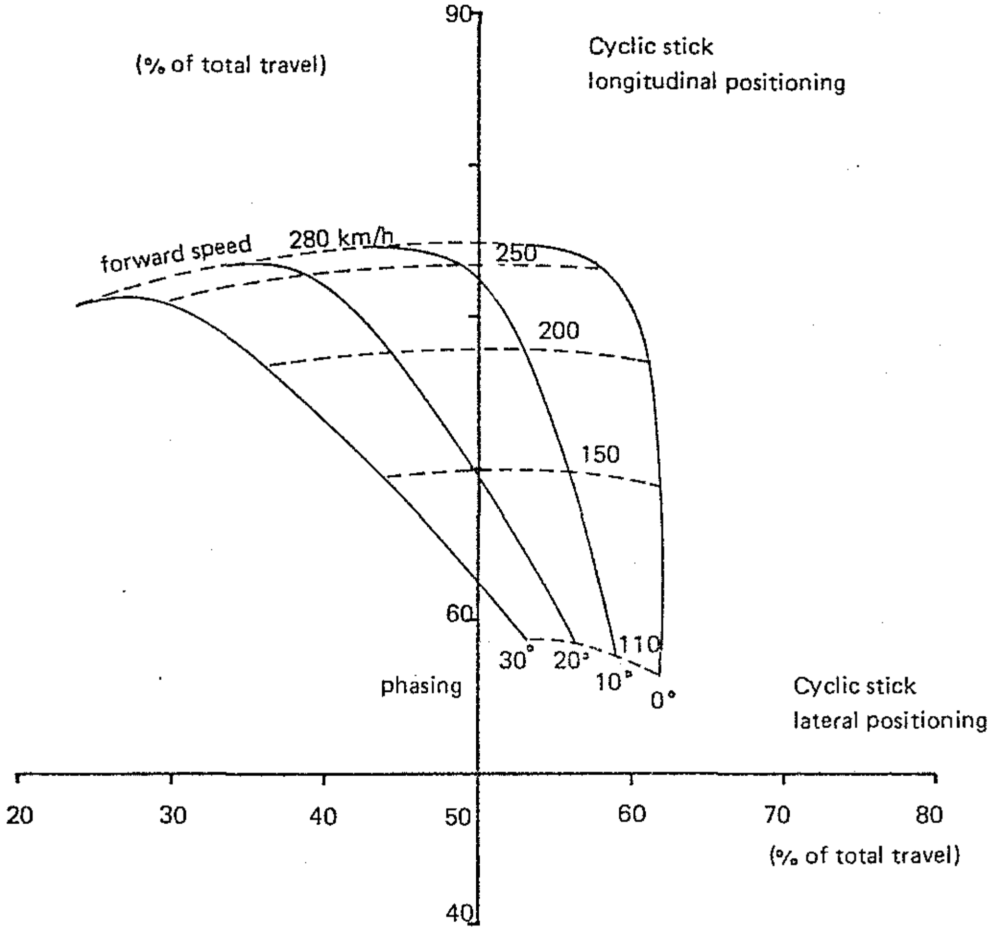


FIG 22 EFFECT OF CONTROL SYSTEM PHASING ON CYCLIC STICK POSITIONING