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A THEORETICAL MODEL FOR PREDICTING THE BLADE SAILING BEHAVIOUR OF A SEMI-RIGID ROTOR HELICOPTER

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Abstract

A theoretical aeroelastic model has been developed for determining the blade flapwise motion of a helicopter rotor during rotor engagement and disengagement, particularly in high wind conditions during operation from the flight deck of a ship. A computer program has been written and results from it are presented for a Lynx helicopter. Details of the flow state over a typical flight deck are provided by wind tunnel tests of a 1/120th scale model of a ship of the Rover class of the Royal Fleet Auxiliary.

Introduction

The operation of a helicopter requires the rotor to be spun up to operating speed from rest at the beginning of the sortie and its subsequent deceleration to rest at the end of the mission. An obvious statement, it is true, but there is a danger in treating it in a matter of fact way and assume that rotor engagement and disengagement are mundane and housekeeping exercises.

Rotor flapping behaviour is determined by the relative magnitudes of aerodynamic forcing and centrifugal stiffening, and pilot control via collective and cyclic pitch presents no difficulty at normal operating rotor speeds. Under calm atmospheric conditions aerodynamic forcing and centrifugal stiffening both vary with the rotor speed in the same manner and so as the rotor speed varies during run up or down the balance of the forcings on the blade are maintained. Should the atmospheric conditions surrounding the rotor be adverse with high winds then such balance of forcings is destroyed and large blade excursions can take place. It is not difficult to see that the rotor blade is in danger predominantly at low rotor speed where due to the low dynamic head over the blades the pilots controls are of minimal effect. This virtually uncontrollable blade behaviour is known as blade sailing and although of major importance to helicopter operators, particulary on board ships or oil rigs, seems to be limited in published works. The author has conducted a literature survey and only two references have emerged, one concerned some early work done on a Westland Whirlwind (reference 1) and secondly the problems of operating a Chinook from an oil rig caused by cliff edge effects (reference 2).

The importance of the blade sailing phenomenon can be gauged by problems recounted to the author during the study. This can vary from:

(i) An air sea rescue in severe gales required the rotor engagement and disengagement to be performed <u>within</u> a hanger and at normal rotor speed the aircraft was taxied in and out of the protection of the building.

(ii) When subjected to catabatic winds in excess of 70 knots the rotor could not be safely shut down and until the wind abated the rotor was kept turning with crew changes when necessary.

Consequently the dangers of blade sailing are present when helicopters are operated in severe atmospheric conditions and for this reason the present study of this phenomenon is taking place. This paper discusses the investigation into the semi-rigid rotor of the Westland Lynx and follows from reference 3. The extension of the theory of to an articulated rotor will be discussed in a following paper.

Description of the Theory

In order to predict the blade flapping behaviour during the engagement and disengagement of the rotor a theoretical model of the hub was constructed. The analysis has to address the fact that the rotor speed would be varying throughout which renders invalid several assumptions which can be justified for a rotor at normal operating rotor speed. These are listed below:

(a) The existence of gravity - With normal rotor speeds the Lynx blade tip is pulling 760 g and the effect of gravity can be sensibly neglected. With a rotor speed variation including zero the effect of the weight of the blade on the blade flapping must be included.

(b) Blade Tension - The blade position is to be defined by a series of modes which must apply to a specific rotor speed. The change in blade tension away from the reference rotor speed values will require extra terms in the analysis to correct for these differences at all other rotor speeds.

(c) Small angle approximations - A 70 knot incident wind on a Lynx at full rotor speed corresponds to an advance ratio of 0.16. The reverse flow region is very small for this condition and inflow angles will follow suit. At very low rotor speeds the advance ratio can increase without limit and the reverse flow region can extend to cover the entire retreating half of the disc. With very low tangential speeds possible the inflow angles and in consequence the incidences will take all possible values. Therefore the small angle approximations used in normal situations must be discarded and the aerodynamic model must be capable of handling a blade in deep stall.

The blade position is to be defined as a degenerate combination of spatial mode shapes together with their associated timewise responses.

$$Z(r,t) = \zeta_n(t) g_n(r) \tag{1}$$

where Z is the flapwise deflection at radius r
g_n is the nth (flapwise) mode shape
ζ_n is the timewise response of g_n

Use of expression (1) leads to the equation of motion for ζ_n

$$I_n \ddot{\zeta}_n + \rho_n^2 I_n + \left(\Omega^2 - \Omega_N^2\right) C_{mn} \zeta_m = F_n \tag{2}$$

where I_n is the nth modal inertia $\int_0^R M g_n^2 \, dr$ (2a)

ρ_n is the nth modal frequency
Ω_N is the reference rotor speed for the modes
Ω is the rotor speed at time t.
M is the blade mass distribution.
R is the rotor radius.

$$C_{mn} = \int_0^R Tg_m' g_n' dr \qquad (2b)$$

Where

$$T = \int_r^R M\eta \, d\eta \qquad (2c)$$

T is the local tension in the blade and the third term of equation (2) is the correction term required for the variation in blade tension at any rotor speed different from Ω_N (the reference rotor speed for the mode shapes). This term vanishes when the rotor speed Ω equals the reference rotor speed Ω_N.

The term on the right hand side of (2) is the forcing of the nth mode and is given by

$$F_n = \int_0^R \left(L - MG\right) g_n \, dr$$

Where L is the lift distribution and G is the gravitational acceleration.

To solve (2) analytically would require far reaching assumptions to be made and as described earlier simplifying assumptions must be removed rather than retained or added to the method. The non linear nature of the wind conditions, the rotor speed variation and the aerodynamic characteristics of the blade section make a numerical integration of equation (2) as the only course available if physical reality is to be retained. A fourth order Runge Kutta scheme was used for this.

The variation of rotor speed was investigated using a simple model for the dynamics of the rotor system. For acceleration the engine torque was considered constant and for deceleration this was assumed for the rotor brake torque. For both engagement and disengagement the rotor torque consumption was assumed to vary with the square of the rotor speed.

For engagement the solution of the equation of motion gave a rotor speed variation which required an infinite time to reach the operating value. The variation was fixed by specifying a time at which the rotor speed had reached 99% of its final value.

For disengagement the rotor speed variation and hence the solution of the equation of motion requires three separate phases each with its own solution. Firstly a settling period is allowed to enable the rotor blades to adopt the initial periodic motion prior to slowing the rotor. (For the engagement condition the initial position of the blade is easily determined. This is not the case for disengagement however and the settling period is the most convenient way of setting the correct initial conditions for the rotor blades). The second period is the rotor slowing under aerodynamic drag only to a given rotor speed, when the rotor brake is applied. From this point, under braking, the third phase takes the rotor to its eventual stopping.

To apply the rotor brake at the outset would require a heavier and more substantial installation otherwise severe overheating would occur with a possible outbreak of fire, whilst the absence of a brake would mean an unacceptably long running down period. The two slowing phases of disengagement is the necessary compromise.

The aerodynamic model used was developed in reference 4 and caters for a section which has the stall characteristics of a trailing edge separation. The data available for this quasi-static model is that for the NACA 0012 aerofoil. The

Westland Lynx blade is based on the NPL 9615 section which was developed from NACA 0012 to provide better high mach number characteristics. As the greatest blade deflections were anticipated to be at low rotor speed and where the aerodynamic characteristics of both are close use of this data is considered justified. The collective pitch angle was used to cater for the change in no lift angle between the sections.

The induced velocity is set to zero, which is not considered unreasonable as the rotor is usually run up or down at nominally zero thrust.

Modal Torsion

The model uses the flapping degree of freedom only. However each flapping mode has a degree of torsional deflection in it and this has been included in the aerodynamics with the facility for appropriate factoring.

Wind Tunnel Testing

References 3 and 4 detail the experimental testing of the flow conditions surrounding the helicopter flight deck of a Rover class Royal Fleet Auxiliary ship both at full scale and at model scale in the 7' x 5' Southampton University Wind Tunnel.

The data from these tests are used as input to the theory. The three velocity components were measured using a triple axis hot wire anemometer which was positioned at thirteen points above the deck of the model. These were twelve points at the representative position of 75% rotor radius with equal azimuth spacing of 30° with the thirteenth point at the rotor centre. All points were at the correct height above the deck as that of a Lynx rotor with the helicopter in contact with the deck.

This was repeated for five wind/ship aligments equally spaced at 45° from ahead to astern. The hot wire anemometer has a cone of acceptance for reliable readings and problems were encountered with the conditions of ahead and 45° whereby the turbulence was of an order to cause a high proportion of the data points to be rejected because they were outside the cone of acceptance. Because of this it was decided to restrict the investigation of the blade motion to the rearward three ship headings, namely with the wind direction abeam from starboard, 135° to starboard and astern.

The data was statistically analysed giving a mean and standard deviation for each point, component, and ship heading (i.e. 117 in total).

From this data the wind and turbulence were simulated using a NAG pseudo - random number generator to recreate the wind data with the appropriate statistical properties.

The calling of this generation routine was controlled so as to provide the correct Strouhal number scaling to full scale.

Alternative Gust Specification

A simpler method of specifying the wind behaviour, other than use of the wind tunnel test results, was developed. Initially it was to enable development of the theory whilst the wind tunnel data was unavailable, however after comparison of the two sets of data it enables more efficient and quicker computation of particular wind conditions. The concept is to specify the three wind components relative to the aircraft with the option of factoring these separately for the advancing and retreating sides of the disc. This was primarily for the abeam wind condition with the helicopter aligned with the nose pointing to the ships bow.

The factoring was to simulate, in particular, the upflow and downflow through the rotor disc on the windward and leeward side of the ship respectively where the cliff edge effect will be felt. The vertical gust factoring was thus of opposite sign on each half of the disc and two options were available. In the simplest gust the factor was constant over the whole of the appropriate half of the rotor disc. With the linear gust the factoring varies linearly across the disc in a lateral sense with zero value at the diameter of the disc lying along the centre line of the aircraft and the specified values at the disc periphery where the diameter at right angles to the aircraft centre line intersects it. The simple gust will have a discontinuous vertical velocity changes on the aircraft centre line whilst the linear gust will retain continuity.

Ship Motion

To evaluate the effect of the ships motion in roll a facility was added to the theory to enable the gust/wind components to be rotated about the rotor in a prescribed sinusoidal manner to model the rolling of the ship. As the roll centre is usually below the plane of the rotor the lateral velocity of the ships deck is also added. The rotation of the wind components does not take account of any rotor dynamic effects caused by rotor precession, however as the roll frequency of the ship was substantially lower than the rotor frequencies used in the program this was not felt to be an unreasonable approximation.

Aircraft Tipping

During the examination of the initial results the maximum tip deflections obtained caused comment from a pilot that this could cause a wheel to lift off the deck. The tip deflections are greatest at low rotor speeds where the bending moments on the rotor head are much reduced for a given disc tilt. However in order to assess the danger of fuselage tilting, particularly at low aircraft weight, a brief study was undertaken to examine such a possibility of occurrence. The tip deflections produced by the theoretical model were assumed to be for the fundamental mode only and from this a given disc tilt can be translated to an average head moment which is dependent on rotor speed. This coupled with the undercarriage geometry and aircraft weight will give the blade tip deflections required to lift a wheel.

Results

The input data used for the Westland Lynx main rotor is shown in Table 1. A summary of the results are shown in Table 2. The variation of rotor speed with time during a rotor run up or run down is shown in Figs 1 and 2, respectively.

The wind speed was standardised at 50 knots. Using information from the wind tunnel tests the blade flapping behaviour is shown in Figs 3 to 8. (The figures have elapsed time (in seconds) as abscissa and blade tip deflection (in inches) as ordinate). The most extreme downward blade deflection is indicated with the respective displacement written alongside.

Figs 3 and 4 show the blade behaviour during rotor run up and run down respectively with the wind at 180° to the ship heading, i.e astern. (The run down figures have three vertical markers which correspond to the one second settling period after which the deceleration commences, the time at which the rotor brake is applied and the time at which the rotor comes to rest).

Figs 5 and 6 present the similar results for the 135° wind heading and Figs 7 and 8 the 90° wind heading.

As can be seen the deflection increases from 180° to 90° heading reflecting the importance of the cliff edge effect. It should be noted that the lateral up flow and down flow variation created by this result in a longitudinal disc tilt which needs to be of the order of 75 inches in order to contact the tail boom.

As mentioned earlier a simpler specification for the ambient wind conditions was proposed as an alternative to the wind tunnel data for the purpose of efficient use of the complete program in investigating a parametric study of aircraft types and rotor characteristics.

The simple gust admits a discontinuous change in the vertical wind component at the aircraft centre line. The blade behaviour for this condition is shown in Figs 9 and 10. The gust factoring used is consistent with the 90° ship heading wind tunnel experiment results, which shows a 30% of free stream velocity vertical component upwards through the disc on the windward side of the ship, a 24% vertical component downward through the disc on the leeward side of the ship and a 19% supervelocity in the horizontal wind component laterally across the flight deck. Figs 11 and 12 shows the equivalent results for the linear gust model which allows a continuous variation of vertical wind component across the rotor disc .

Comparing with Figs 7 and 8 the linear gust model can be seen to produce a blade behaviour time history which is close to the equivalent wind tunnel results whilst the simple gust model provides a time history which is more adverse than the wind tunnel model and by about 25%. For this reason the linear model was adopted for any future analysis. The maximum deflections of Figs 9 and 10 relative to 7 and 8 are not identical but the wind tunnel results has the velocity components of turbulence above the mean level included whilst the linear gust model does not furnish this.

The previous results did not include any torsional effects in the analysis, however the modal data available included the blade torsion variation in the blade flap modes. The torsion in the fundamental mode is the greatest effect and this torsion distribution does not materially alter with rotor speed and so was considered constant for the computer produced time histories. (As an upward one inch tip deflection causes a nose up tip incidence change of .001 radians).

Figs 13 and 14 show the blade behaviour equivalent to Figs 11 and 12 with the torsional effects now included. A tip deflection increase of the order of 30% is indicated.

The run up variation of rotor speed with time was considered to be the most rapid rate feasible with good traction conditions between the undercarriage tyres and the ship's deck. To investigate the effect of a slower rotor speed run up Fig 15 shows the equivalent case to Fig 11 only with the rise time doubled from 10 to 20 seconds. Only a modest increase in blade deflection is predicted.

The investigation was extended to examine the effects of ship motion concentrating on rolling in an abeam wind as before. A roll of amplitude 7½° and a period of 10 seconds was chosen with the roll centre 30 feet below the ship's deck.

This was modelled by rotating the incident wind conditions about the rotor in the above prescribed sinusoidal manner.

The effect on run up and down is shown in Figs 16 and 17, torsion effects are included. The increase in tip deflection can be seen taking it to a value of 50 inches which corresponds to 67% of that required to contact the tail boom.

Fig 18 shows the run down with the ship roll motion one half period different to that of Fig 16. Inspection of Fig 16 showed that an even larger tip deflection may be possible with a different phase of ship rolling. That this did not occur is considered to be because of the high proportion of the blade being in stall.

The results of examining the possibility of the aircraft lifting a wheel is shown in Fig 19 for the rotor run up and run down.

Shown on the figures are the tip deflections required (fundamental mode only) to tip a wheel of an aircraft for a range of operational weights and rotor speeds. The results of Figs 13 and 14 are plotted on their respective figures and it is apparent that contrary to initial fears the aircraft is not liable to lift a wheel.

Conclusions

This paper describes the theoretical investigation conducted into the blade behaviour of a Westland Lynx main rotor when it is subjected to the ambient wind conditions in which it can be expected to operate from the flight deck of a Rover class Royal Fleet Auxiliary Ship.

The results are in the main a series of blade excursion time histories for rotor engagement and disengagement.

The comparison of the wind tunnel data with two simpler wind/gust models is favourable in one case allowing an efficient examination of the effects of a series of parametric changes to the rotor aeroelastic model and the operating regime of the ship.

The results survey the effect of:-

(i) Wind bearing.
(ii) Torsional effects in the flapwise model.
(iii) Ship rolling.
(iv) Possible tipping of the whole helicopter.

In the worst situation a tip deflection can be obtained which is 67% of that required to cause a blade strike on the tail cone.

Future work is planned for this research which comprises three main avenues.

(a) Extension of the theory to cater for an articulated rotor.
(b) Comparison of the method with data from a full size helicopter.
(c) A wind tunnel experiment on a model rotor for further comparison.

The results have shown that large blade excursions are possible and that the phenomenon of the blade sailing is a severe limitation on a helicopters operating envelope.

Acknowledgements

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References

1 M. A. P. Willmer. The Motion of Helicopter Blades at Low Rotor Speeds in High Winds. R.A.E. TM No. Naval 181. Sept. 1963.

2\. T. C. Porteous. Commercial Chinook - First Year of Operation. Paper No.5. Proceedings of the Twenty-Sixth Symposium. Society of Experimental Test Pilots. Sept 1982.

3\. D. W. Hurst and S. J. Newman. Wind Tunnel Measurements of Ship Induced Turbulence and the Prediction of Helicopter Rotor Blade Response. Paper 99. Eleventh European Rotorcraft Forum. Sept. 1985.

4\. S. J. Newman and D. W. Hurst. Helicopter Blade Sailing Characteristics - Final Report. AASU Memo 86/4. Feb. 1986.

Table 1

Lynx Main Rotor Data

Radius	21 ft.
Chord	15½ inches.
Twist	8° linear

Nominal rotor speed (100% NR) 34.167 rads/sec

4 Flap modes used.
Wind Speed 50 knots
Collective Pitch 4°
Cyclic Pitch 0°

Table 2

FIG	RUN	FLOW CONDITIONS	TORSION	RUN UP TIME	SHIP ROLL	MAX TIP DEF'N.
3	UP	Wind Tunnel 180°	No	10	0	28
4	DOWN	Wind Tunnel 180°	No		0	26
5	UP	Wind Tunnel 135°	No	10	0	34
6	DOWN	Wind Tunnel 135°	No		0	36
7	UP	Wind Tunnel 90°	No	10	0	36
8	DOWN	Wind Tunnel 90°	No		0	38
9	UP	Simple	No	10	0	40
10	DOWN	Simple	No		0	50
11	UP	Linear	No	10	0	32
12	DOWN	Linear	No		0	31
13	UP	Linear	Yes	10	0	41
14	DOWN	Linear	Yes		0	41
15	UP	Linear	No	20	0	33
16	UP	Linear	Yes	10	7½°	50
17	DOWN	Linear	Yes		7½°	46
18	DOWN	Linear	Yes		7½°	49

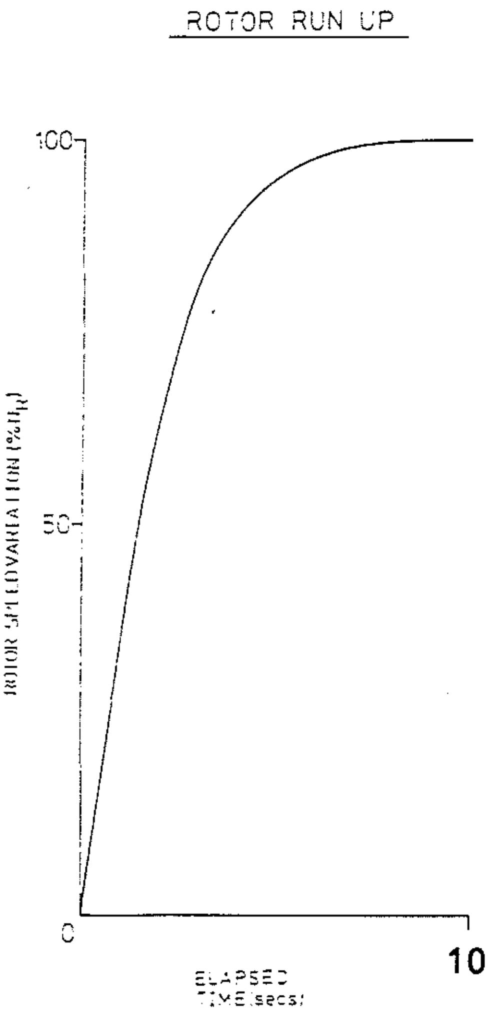


FIGURE 1

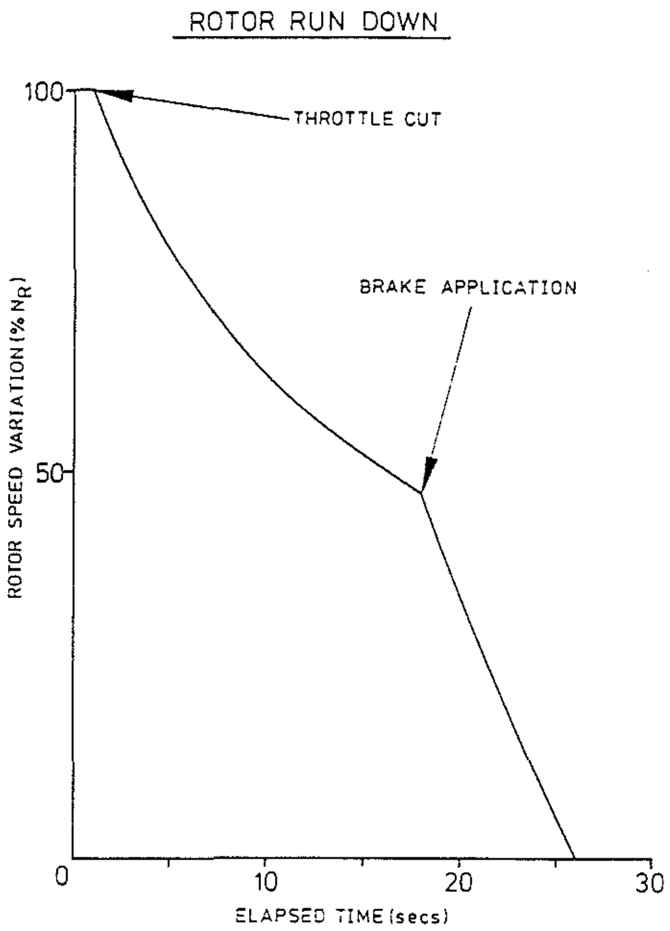


FIGURE 2

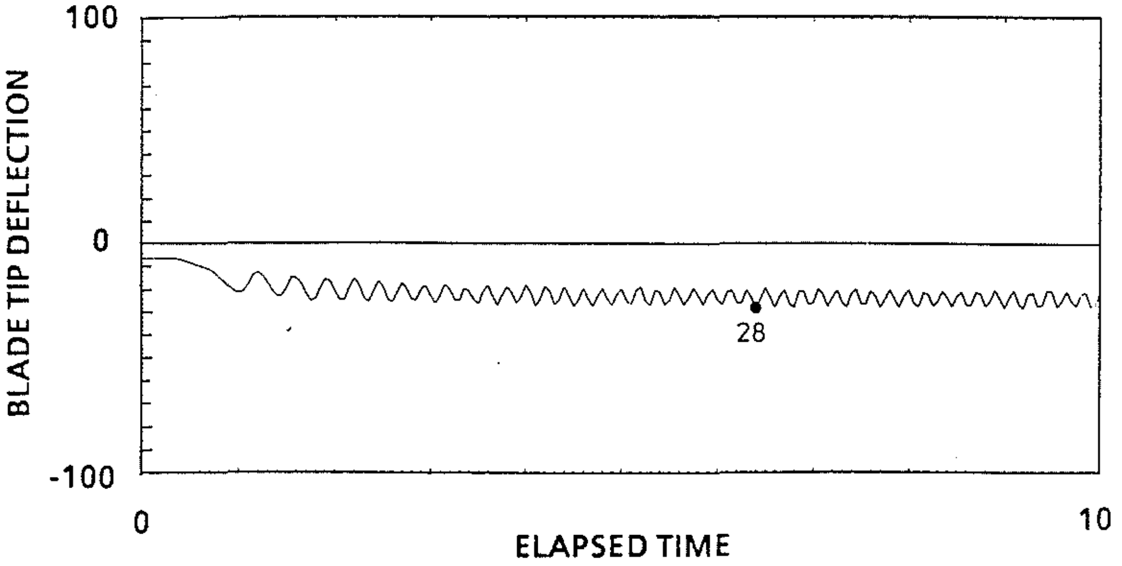


FIGURE 3

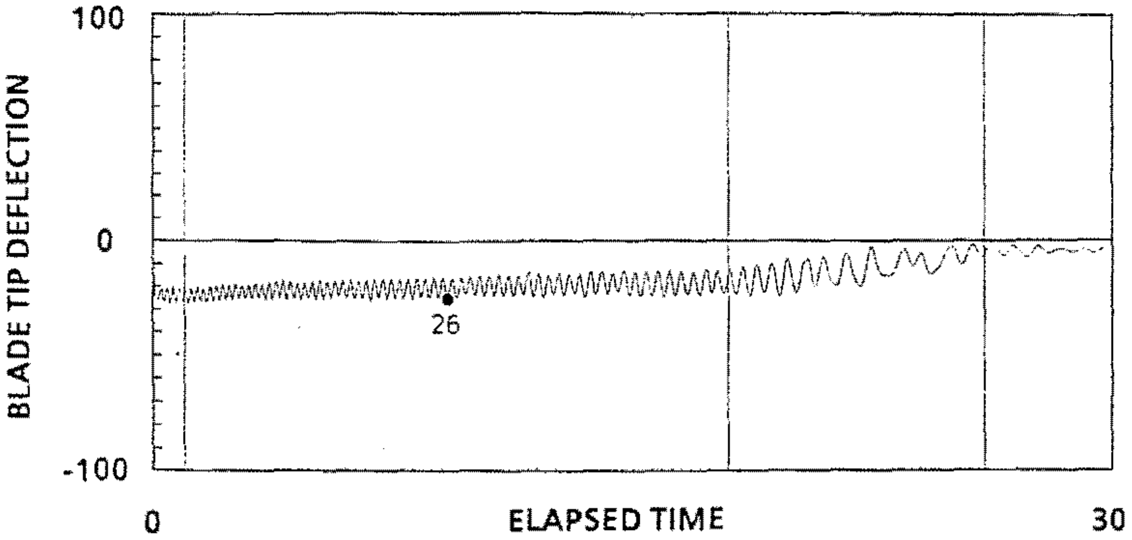


FIGURE 4

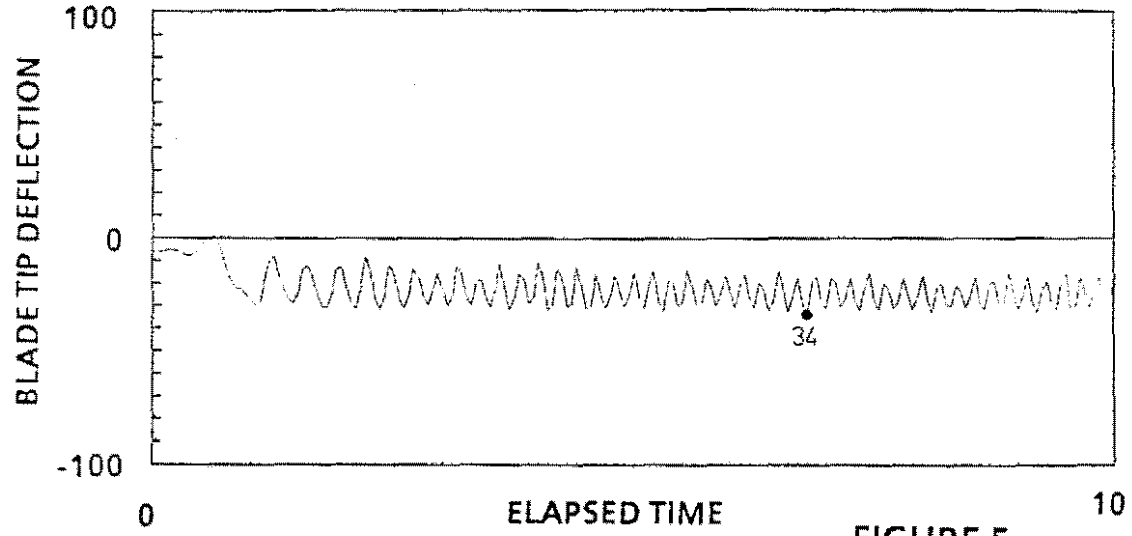


FIGURE 5

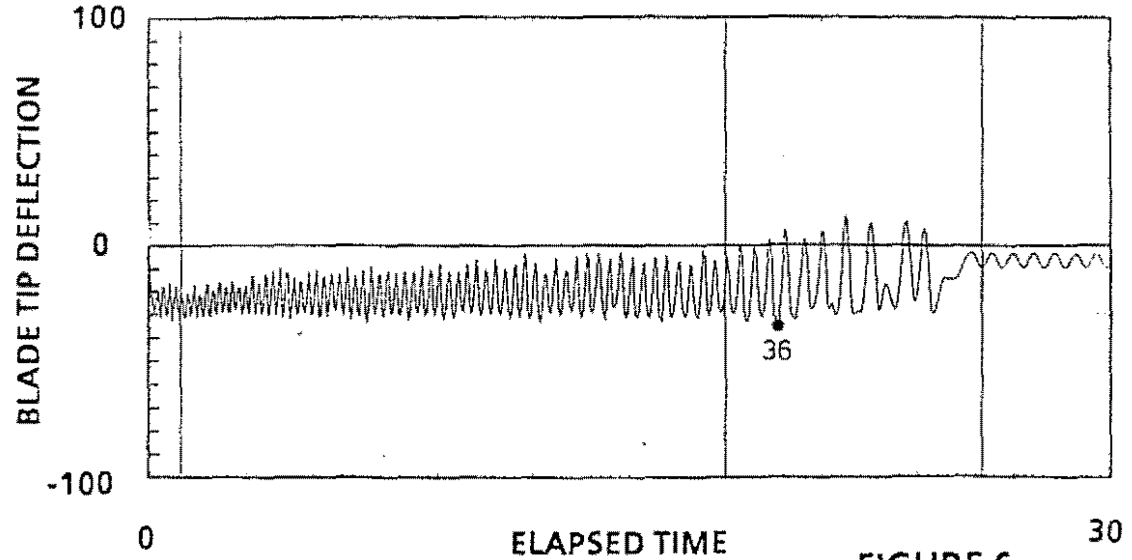


FIGURE 6

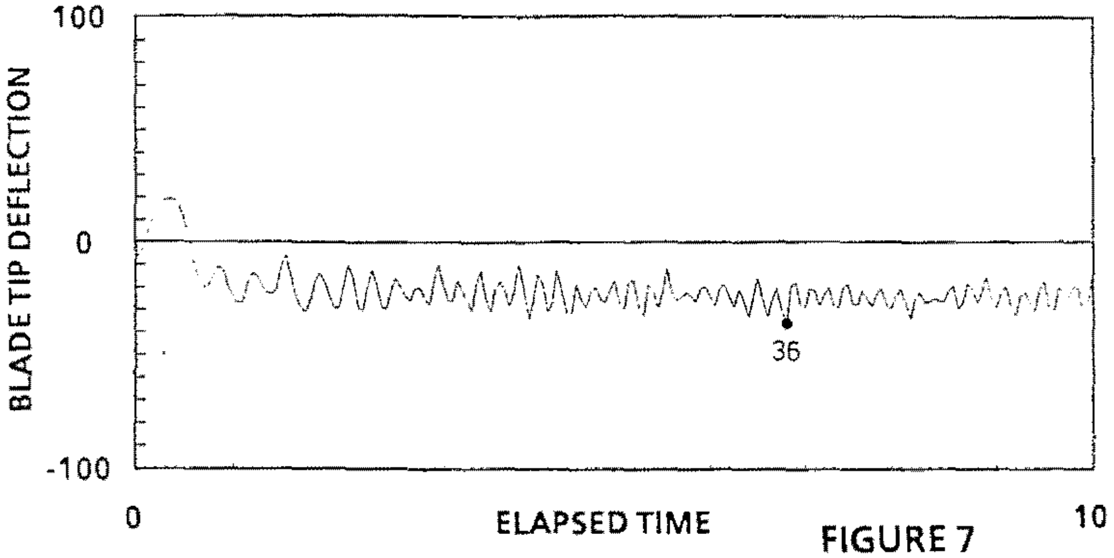


FIGURE 7

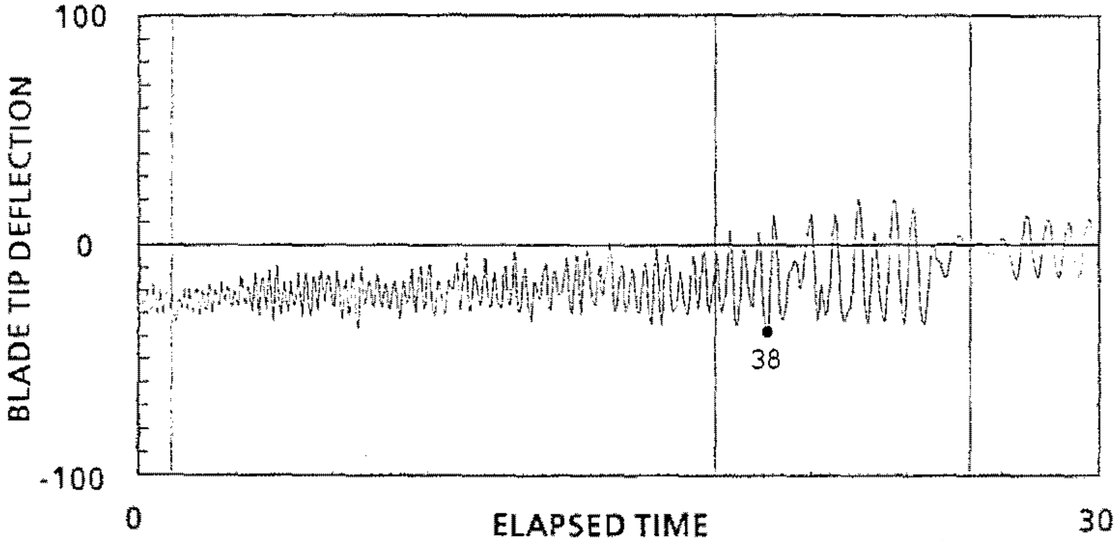


FIGURE 8

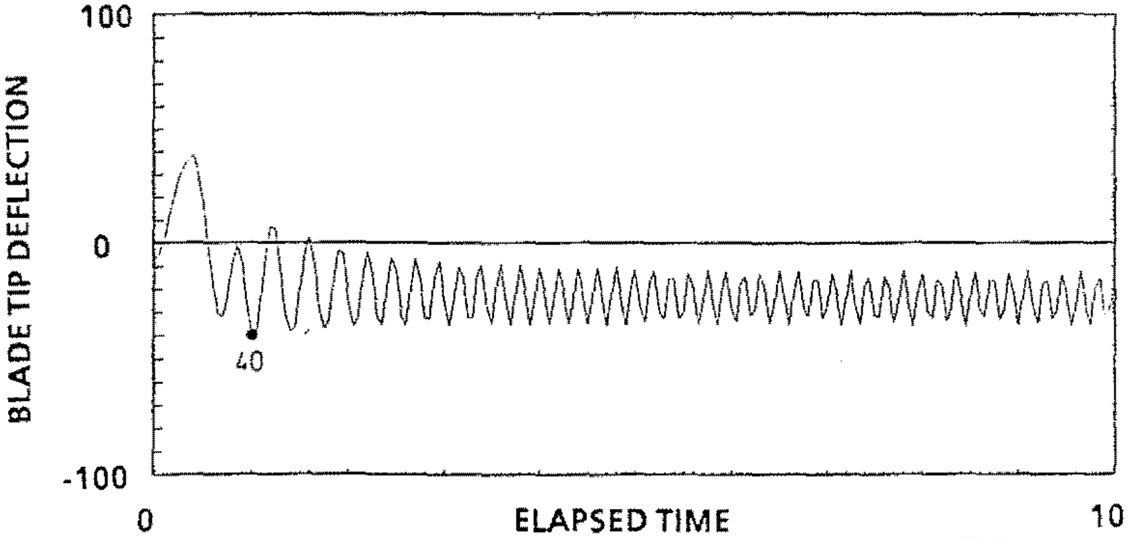


FIGURE 9

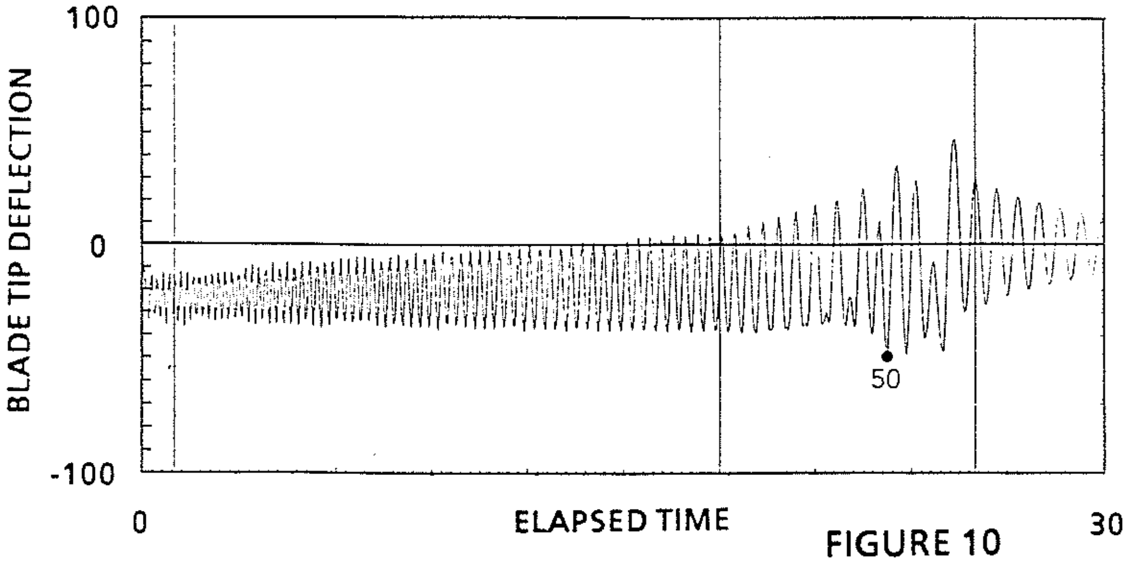


FIGURE 10

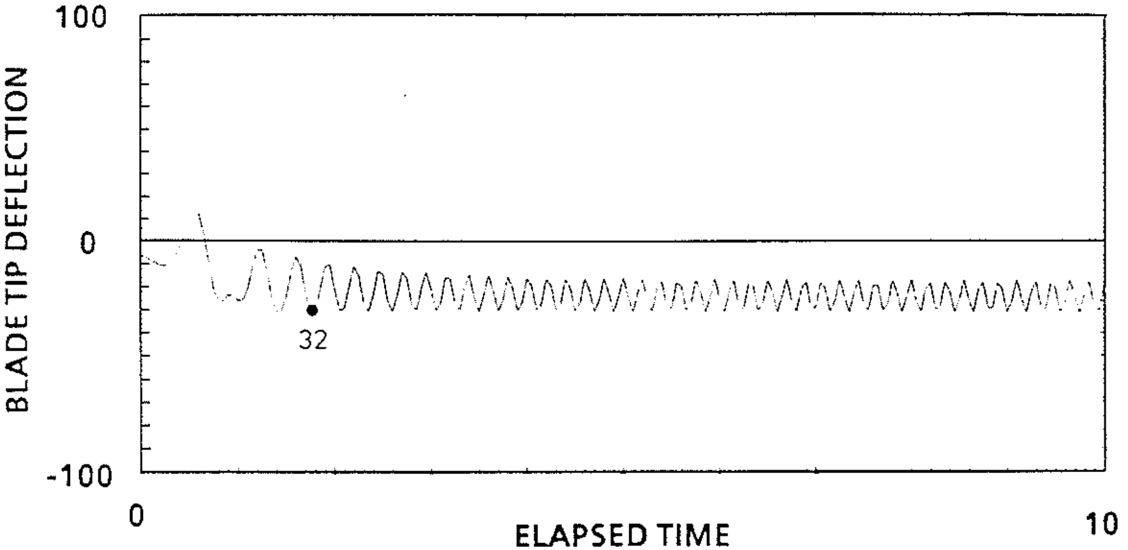
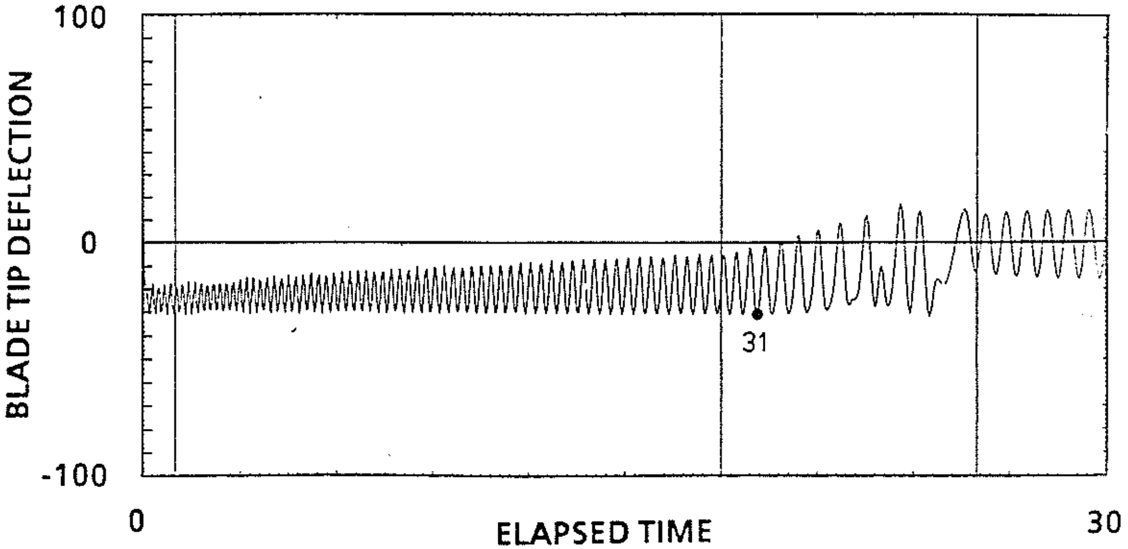


FIGURE 11



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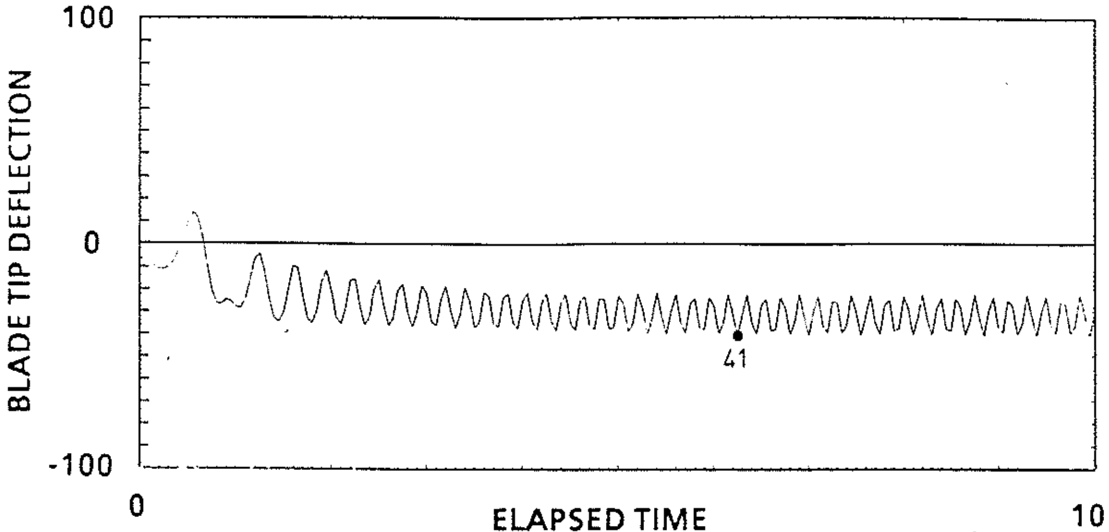

FIGURE 13

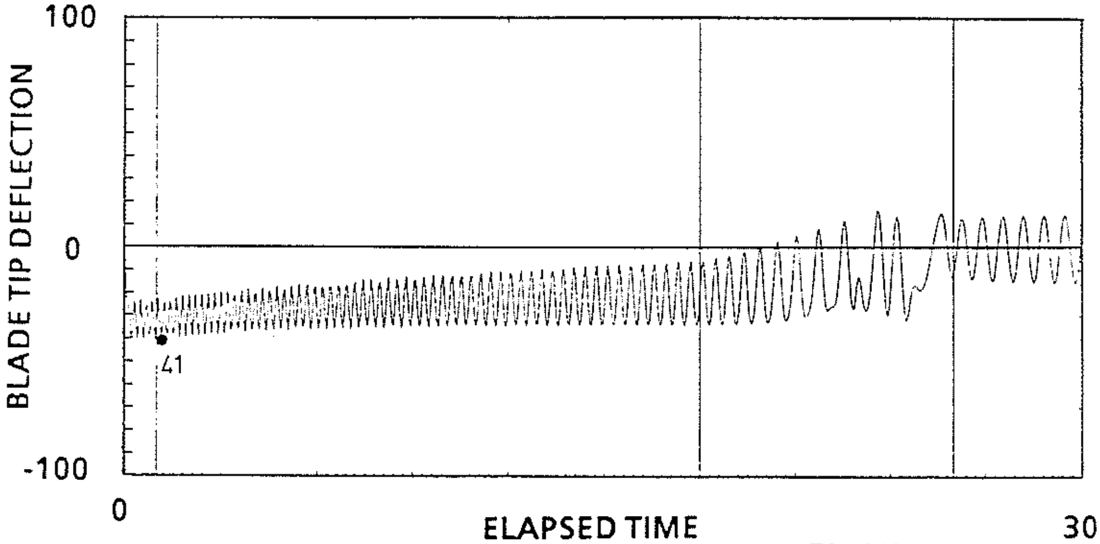

FIGURE 14

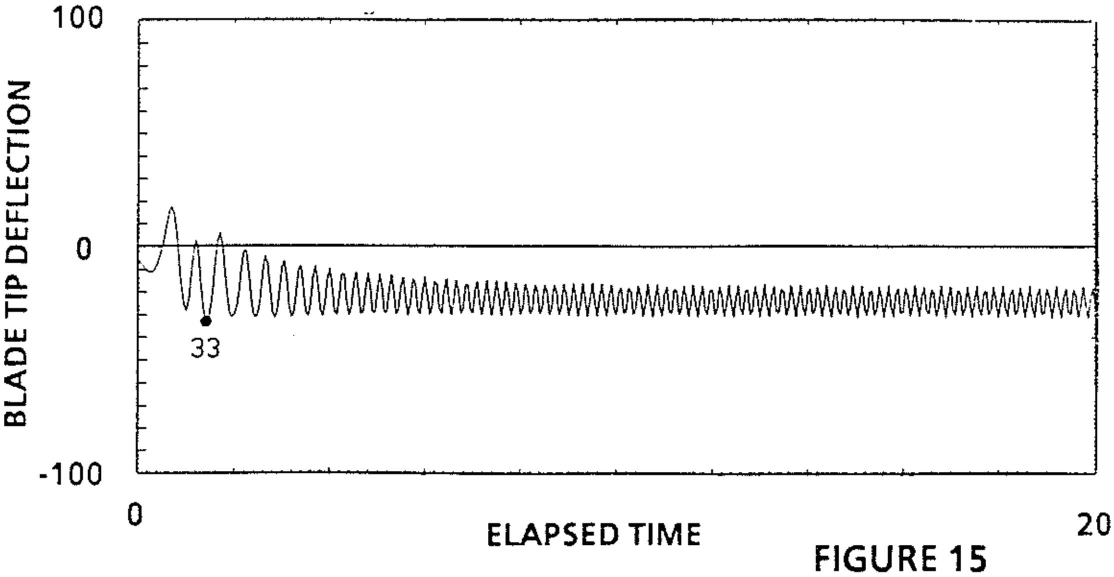

FIGURE 15

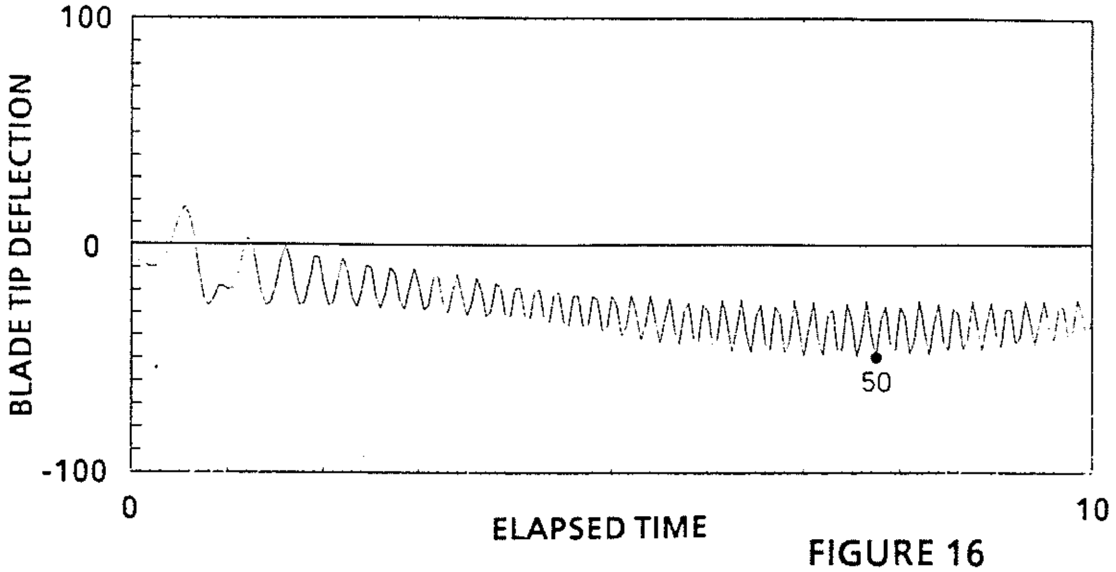

FIGURE 16

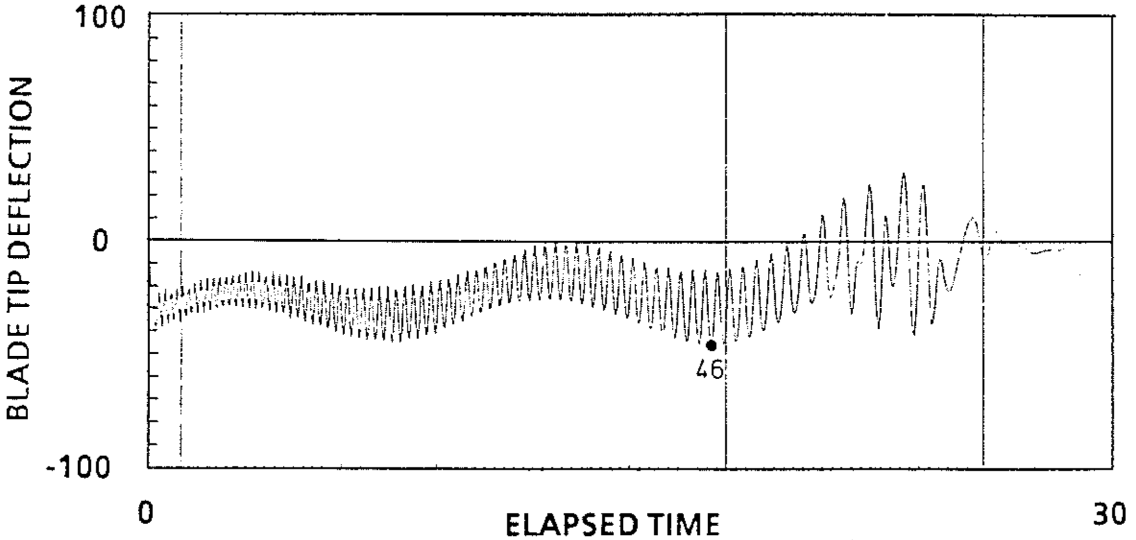

FIGURE 17

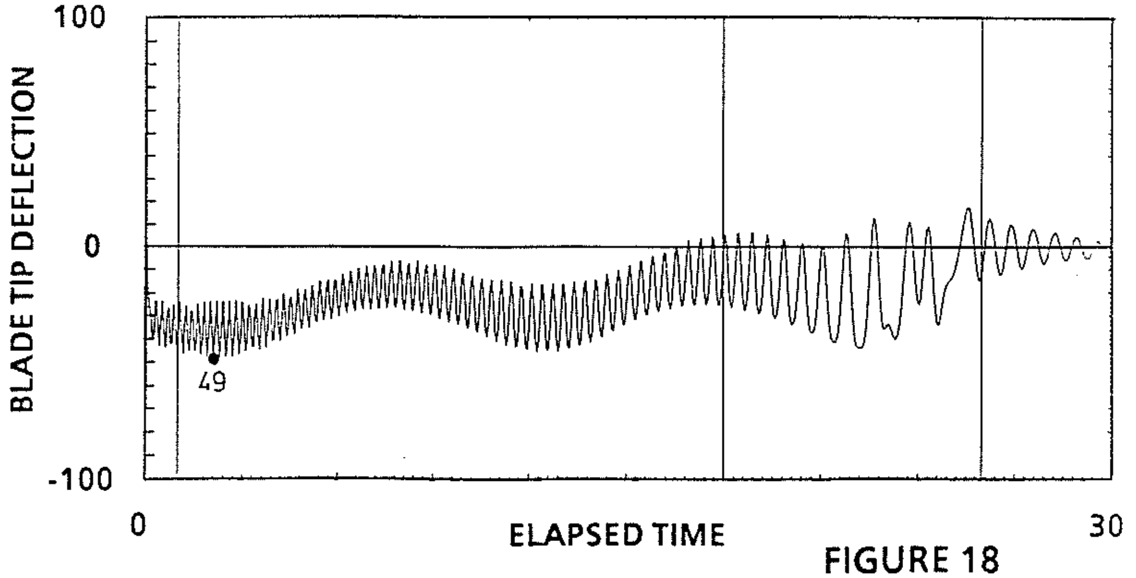

FIGURE 18

TIP DEFLECTION TO TIP AIRCRAFT

NAVAL LYNX

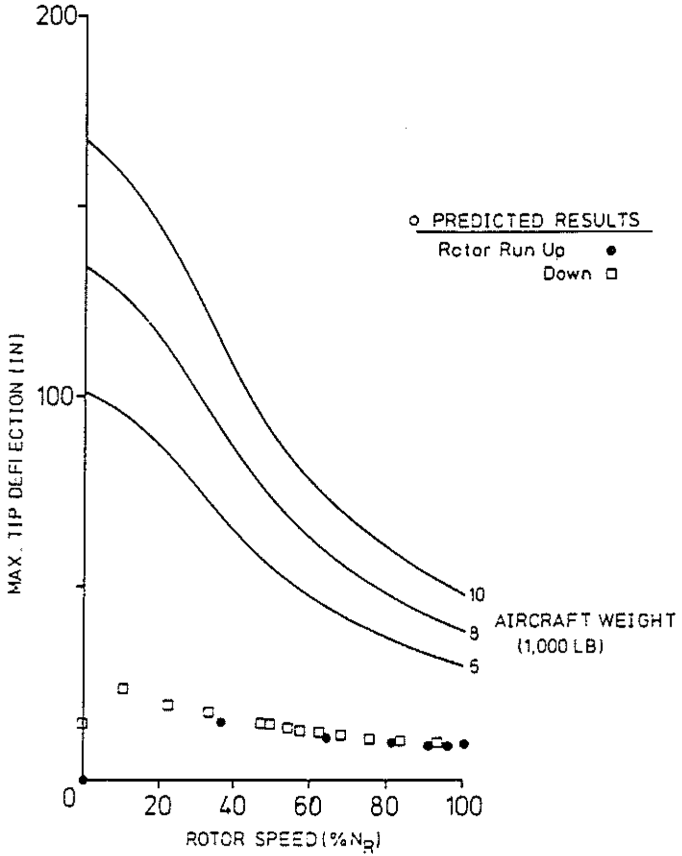

FIGURE 19