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EFFECTS OF AXIAL FORCE ON THE FLUTTER OF HIGH ASPECT RATIO AEROFOIL BLADES

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Abstract

The effect of axial force on the flutter characteristics of high aspect ratio aerofoil blades are investigated using the finite element method and unsteady aerodynamics in two dimensional flow. Beam and lumped mass elements are used in the structural representation of the blade whereas the validity of strip theory is assumed in forming the aerodynamic matrix. Flutter characteristics of a uniform cantilever blade under both tensile and compressive loads are first investigated. A parametric study is then undertaken by altering the basic data to demonstrate the effects of axial force on flutter. Results are obtained for a realistic rotating blade and the significances of axial-force effects are discussed and commented on. The investigation confirms the predictable accuracy of an aeroelastic program currently under development.

1. INTRODUCTION

Flutter is perhaps the most serious of all aeroelastic phenomena and its consideration has become a standard feature in any aircraft design procedure right from the very beginning of aviation to today. In the late forties and early fifties, numerous papers appeared on the flutter of aircraft wings at low speeds and these achievements were systematically organized and reported in two excellent survey papers [1,2]. The present work stems from the fact that the author felt that even today flutter analysis at low speed is still very relevant in the context of rotating blades such as wind turbine blades and it appears that the method available for fixed wing aircraft can be suitably turned to advantage for flutter analysis of rotating blades. However an important parameter, the axial force which results from the rotating action of the aerofoil blade will have to be accounted for as it can change the natural frequencies and mode shapes of the blade in bending vibration. (Obviously this did not preoccupy the mind of the bygone aeroelasticians because spanwise axial force along the length of the wing for a fixed wing aircraft is negligible or almost nonexistent.) Against the above background, this paper sets out to investigate the effects of axial force on the classical bending-torsional flutter characteristics of high aspect ratio aerofoil blades using finite element method and unsteady aerodynamics in two dimensional flow given by Theodorsen [3]. Flutter problem is formulated using an approach which implements normal modes and generalized coordinates [4,5]. Beam and lumped mass elements are used in the structural representation of the blade in order to obtain the normal modes whereas the validity of strip theory (as applicable to high aspect ratio) is assumed in the aerodynamic idealization. Flutter characteristics of a uniform blade (which can also be thought of as a wing) under both tensile and compressive loads are first investigated. A parametric study is then undertaken by altering the basic stiffness data of the blade, to demonstrate the effect of axial force on flutter. Results are obtained for a 12m wind turbine blade with cantilever end condition and the effects of axial load (resulting from the centrifugal force) are discussed in detail.

2. THEORY

Use of generalized coordinates and normal modes in flutter analysis is well established; the details of the method can be found in Refs [4,5]. From a structural point of view, experience has shown that for high aspect ratio blades (or wings) beam and lumped mass element idealization gives sufficiently accurate results on natural frequencies and mode shapes. Ground resonance testing on a glider wing has earlier confirmed this accuracy [4]. On the other hand, the validity of strip theory and Theodorsen expressions [3] for unsteady lift and moment in two dimensional flow when applied to high aspect ratio wings at low speed, has also been previously verified [6] to a high degree of accuracy using a lifting surface theory [7] and a corresponding computer program [8]. Based on these earlier results, existing theory is assembled and applied to the present problem. Thus the blade flutter problem is treated exactly in the same way as wing flutter except for the effect of axial force which can alter only the bending frequencies and the bending modes of the blade.

As a preliminary step, the natural frequencies and mode shapes of the blade in both bending and torsional vibration are first calculated from beam element idealization in the finite element method. Source codes from a previously published computer program BUNVIS-RG [9] which uses exact member theory for an axially loaded Timoshenko beam are taken out and implemented in a short, compact and self-contained aeroelastic package called CALFUN [10] currently under further development. Thus axial force effects are accounted for. Modes are then selected for flutter analysis (of course, the fundamental bending and torsional modes are included). Using the selected modes the mass, stiffness and aerodynamic matrix of the blade are expressed in terms of the generalized coordinates. The flutter matrix is formed by algebraically summing the genalized mass, stiffness and aerodynamic matrices.

The solution of flutter determinant is a complex eigenvalue problem because the determinant is primarily a complex function of two unknown variables, the airspeed and the frequency. The method used selects an airspeed and evaluates the real and imaginary parts of the flutter determinant for a range of frequencies. The process is repeated for a range of airspeeds until both the real and imaginary part of the flutter determinant (hence the flutter determinant) vanish completely.

3. RESULTS

A uniform aerofoil blade with cantilever end condition at the root is shown in Fig.1. The following input data of the blade are required [10] to compute its flutter speed: (1) bending rigidity (EI), (2) torsional rigidity (GJ), (3) mass per unit length (ρA), (4) polar inertia per unit length (ρI_p), (5) length of the blade (L), (6) axial force (P, compression positive), (7) semi-chord (b), (8) location of the elastic (or flexural) axis (ba_h) and (9) location of the mass axis (ba_g). In the input system of CALFUN [10], the first six of the above data items are considered as structural data and the remaining three as aerodynamic data. Also a non-uniform blade is idealised as an assemblage of uniform blade elements rigidly joined together at the nodes. In this case all nine data items mentioned above are to be supplied for each uniform portion representing the blade. However in obtaining the numerical results the basic data file was created for a straight uniform blade with $EI = 10^6\ Nm^2$,
$GJ = 4 \times 10^5\ Nm^2$, $\rho A = 10.0$ kg/m, $\rho I_p = 0.25$ kgm, L = 10 m, P = 0,
b = 0.5 m, $a_h = a_g = -0.05$ (i.e. 5% of the chord and forward, see Fig.1). As the axial force effects are considered to be the most pertinent study the elastic axis and mass axis are considered to be coincident in the

analysis to reduce the number of parameters involved and hence reducing the number of computer runs. (When elastic axis and mass axis are coincident flutter is mainly effected by aerodynamic coupling. Ref.11 gives results for a rigid wing (i.e. an aerofoil section of unit span resting on a translational and rotational spring) with mass centre and shear centre coincident). The flutter speed for the above blade is located at 123.2 m/s and the corresponding flutter frequency is established at 75 rad/s. Only the fundamental bending and torsional modes are included in all analyses. Fig.2 shows the method of solution for the above problem where the loci of the zeros of the real and imaginary parts of the flutter determinant are plotted and the point of intersection as shown marks the flutter speed. The unloaded case is further investigated and only the stiffness data (EI and GJ) of the blade are altered so as to alter the frequencies. Fig.3 illustrates the variation of flutter speed against frequency ratio in a non-dimensional plot for a practical range of frequency ratios.

Axial force is expected to change only the bending frequency and the exact computer program BUNVIS-RG [9] is used to investigate the effect. Fig.4 shows the effect of axial force on the fundamental bending frequency of a uniform cantilever beam. The axial force is non-dimensionalized in terms of the elastic critical buckling load of the cantilever beam ($P_{cr} = \pi^2 EI/4L^2$). The frequency reduces to zero at buckling as expected. An inspection of the figure indicates that the bending frequency is reduced by 35% for a compressive axial load which equals 60% of the critical buckling load. Also a corresponding tensile force of same magnitude increases the bending frequency by 24%. So a load level of 60% of critical buckling load on either way (compression or otherwise) seems to be quite significant and therefore is taken to be the reference load in obtaining the subsequent results. Although the chosen load level makes a significant difference in the frequency, the corresponding mode shapes for the cantilever are not significantly altered as indicated by Fig.5.

Results for flutter speed and flutter frequency of the uniform blade are obtained with and without the axial force. The first row of Table 1 shows the result for the basic data file. The stiffness data are then altered (keeping other parameters constant) to generate the comprehensive results given in Table 1.

Following the results obtained for the uniform cantilever blade, an investigation is carried out to study the flutter behaviour of a 12 m long wind turbine blade manufactured by Vølund A/S and O.L. Boats [12]. The structural, aerodynamic and other details of the blade required for analysis are given in Table 2. Bending in one plane (the plane which is perpendicular to the plane of rotation) only is considered. The fundamental bending and torsional modes of the blade with cantilever root condition and in the absence of centrifugal force are shown in Fig.6. The flutter speed and frequency are established at 218 m/s and 62.3 rad/s respectively. Based on mass variation data given in Table 2, the centrifugal force in the blade is worked out at a rotating speed of 60 RPM. The distribution of centrifugal force from root to tip is shown in Fig.7. The centrifugal force altered the bending frequency from 15.07 rad/s to 18.74 rad/s but did not make any appreciable difference in the flutter speed and flutter frequency.

4. CONCLUSIONS

Within the most practical range of interest (where the torsional frequency is much higher than the bending frequency) the axial force does not seem to have any significant effect on the classical bending-torsion flutter of high aspect ratio blades. Although the flutter speed is virtually unaltered, the axial force has some marginal effect on flutter frequency (see Table 1). A compressive load reduces the flutter frequency whereas a tensile load increases it as expected from the fact that the bending and torsional frequencies coalesce at flutter speed. The flutter of the 12 m long wind turbine blade occurs at a high airspeed which is well above the normal wind speed. This ensures a safe design. Further investigation needs to be carried out to study the effects of axial force from the point of view of contribution of normal modes to flutter mode.

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Table 1. Effects of axial force on the flutter speed and flutter frequency of uniform cantilever blade.

Data		$P/P_{cr} = 0$			$P/P_{cr} = 0.6$ (compression)			$P/P_{cr} = -0.6$ (tension)		
EI Nm^2	GJ Nm^2	Frequency Ratio (ω_h/ω_α)	Flutter speed (m/s)	Flutter Frequency (rad/s)	Frequency Ratio (ω_h/ω_α)	Flutter speed (m/s)	Flutter Frequency (rad/s)	Frequency Ratio (ω_h/ω_α)	Flutter speed (m/s)	Flutter Frequency (rad/s)
1.0×10^6	4.0×10^5	0.056	123.2	75.5	0.036	123.2	74.6	0.069	123.2	76.5
1.0×10^6	2.0×10^5	0.079	87.1	54.2	0.051	87.1	53.0	0.098	87.1	55.3
1.0×10^6	1.0×10^5	0.112	61.7	39.1	0.072	61.7	37.5	0.139	61.7	40.0
4.0×10^6	1.0×10^5	0.224	61.9	43.6	0.145	61.8	40.0	0.277	61.9	46.7
8.0×10^6	1.0×10^5	0.317	62.2	48.5	0.204	61.9	42.5	0.392	62.2	53.6

Table 2. Structural and aerodynamic details of 12m wind turbine blade.

Station from root (m)	EI (Nm^2)	GJ (Nm^2)	ρA (kg/m)	ρI_p (kgm)	semi chord(b) (m)	Shear Centre a_h	Mass Centre a_g
0.0	2.2101×10^7	5.1483×10^6	112	21.80	0.90	-0.573	-0.403
1.0	1.7802×10^7	4.1789×10^6	104	18.10	0.85	-0.572	-0.400
2.0	1.3872×10^7	3.3405×10^6	96	14.90	0.80	-0.570	-0.396
3.0	1.0787×10^7	2.6000×10^6	88	12.10	0.75	-0.567	-0.392
4.0	0.8126×10^7	2.0020×10^6	80	9.60	0.70	-0.566	-0.387
5.0	0.6012×10^7	1.5065×10^6	72	7.50	0.65	-0.560	-0.377
6.0	0.4026×10^7	1.0426×10^6	62	5.40	0.60	-0.558	-0.377
7.0	0.2578×10^7	0.6956×10^6	52	4.05	0.55	-0.556	-0.358
8.0	0.1547×10^7	0.4271×10^6	42	2.55	0.50	-0.558	-0.368
9.0	0.0864×10^7	0.2544×10^6	34	1.75	0.45	-0.553	-0.356
10.0	0.0451×10^7	0.1408×10^6	26	1.10	0.40	-0.545	-0.310
11.0	0.0188×10^7	0.0666×10^6	18	0.65	0.35	-0.537	-0.245
12.0	0.0058×10^7	0.0223×10^6	10	0.35	0.30	-0.533	-0.133

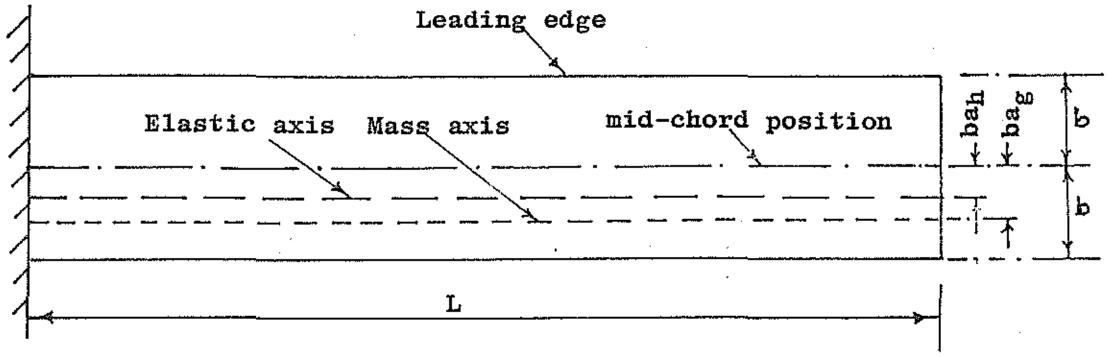

Fig.1 A uniform aerofoil blade with cantilever end condition

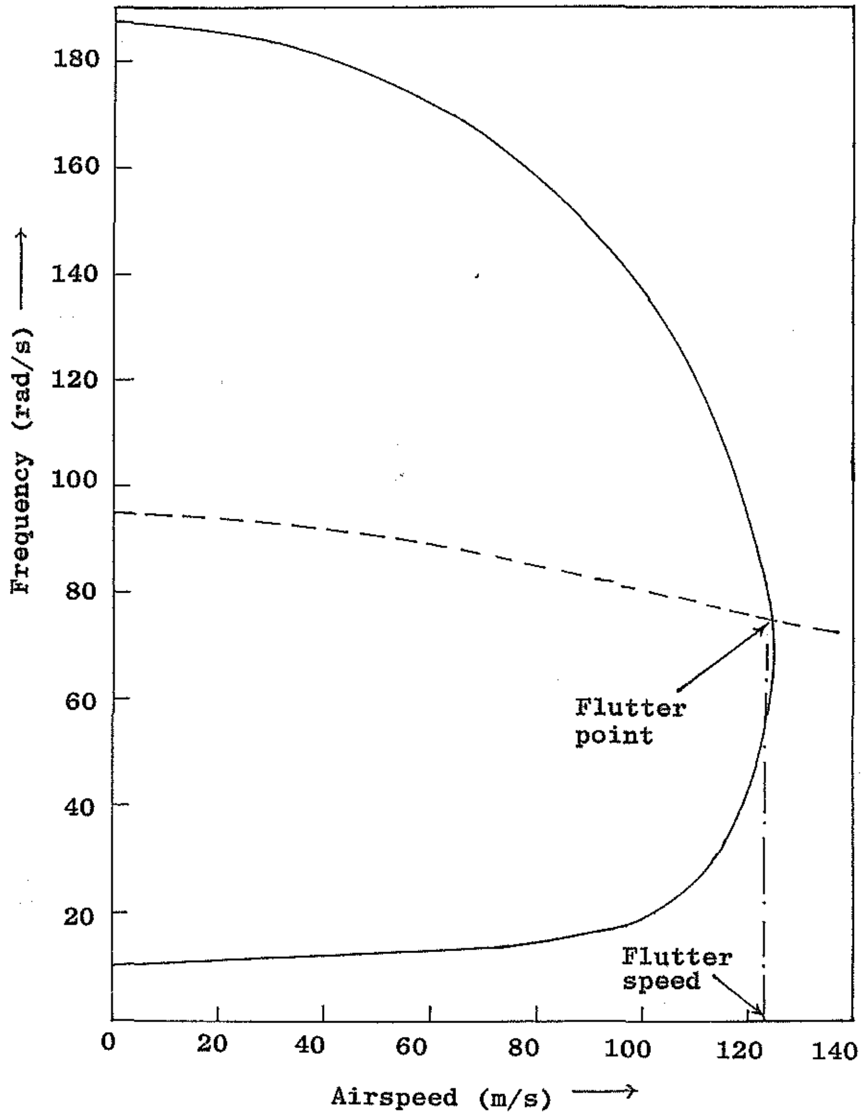

Fig. 2 Zeros of real and imaginary parts of flutter determinant , ——— roots of real part; ---- roots of imaginary part.

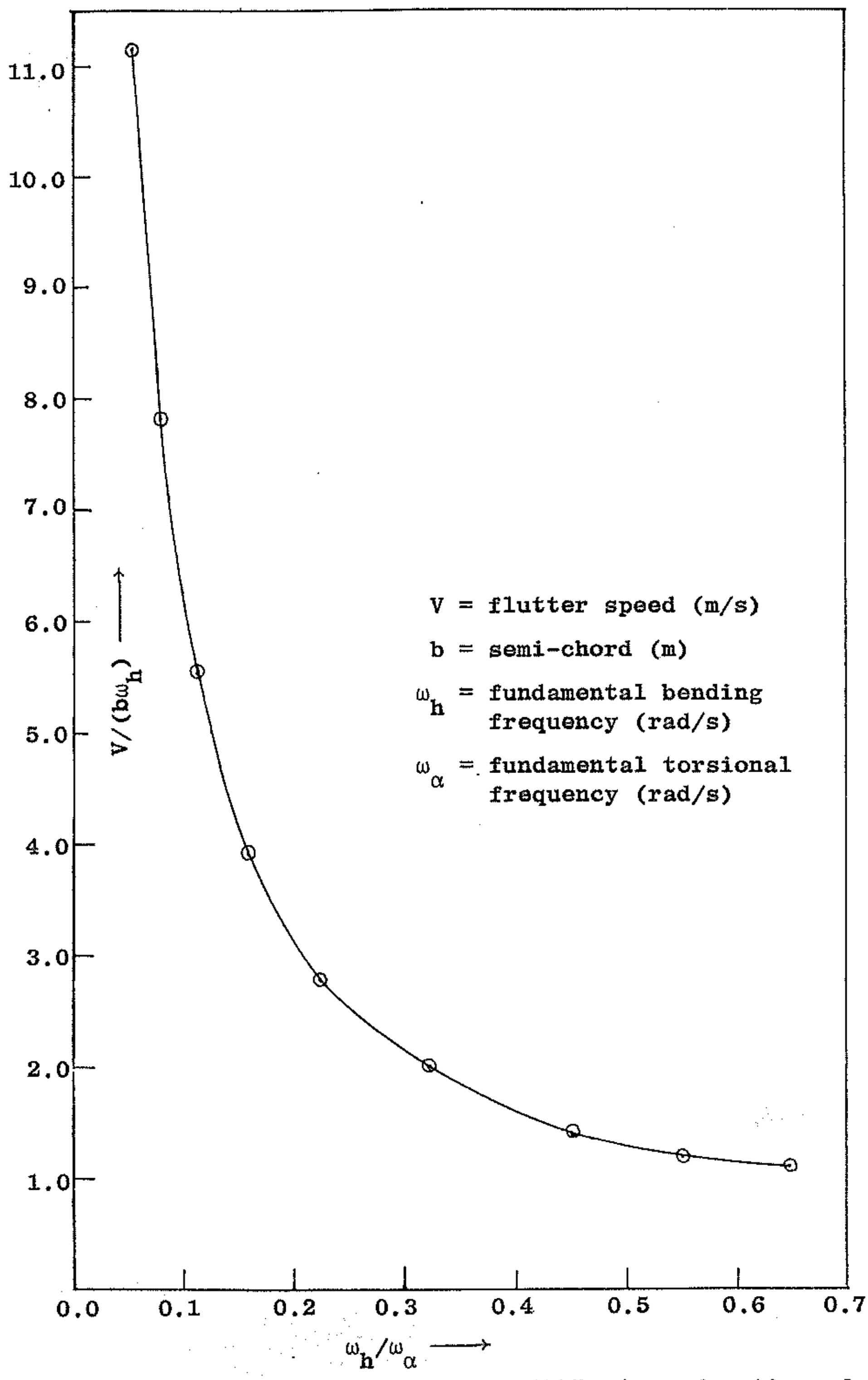

Fig.3. Flutter speed coefficient $V/(b\omega_h)$ as function of frequency ratio ω_h/ω_α of cantilever blade.

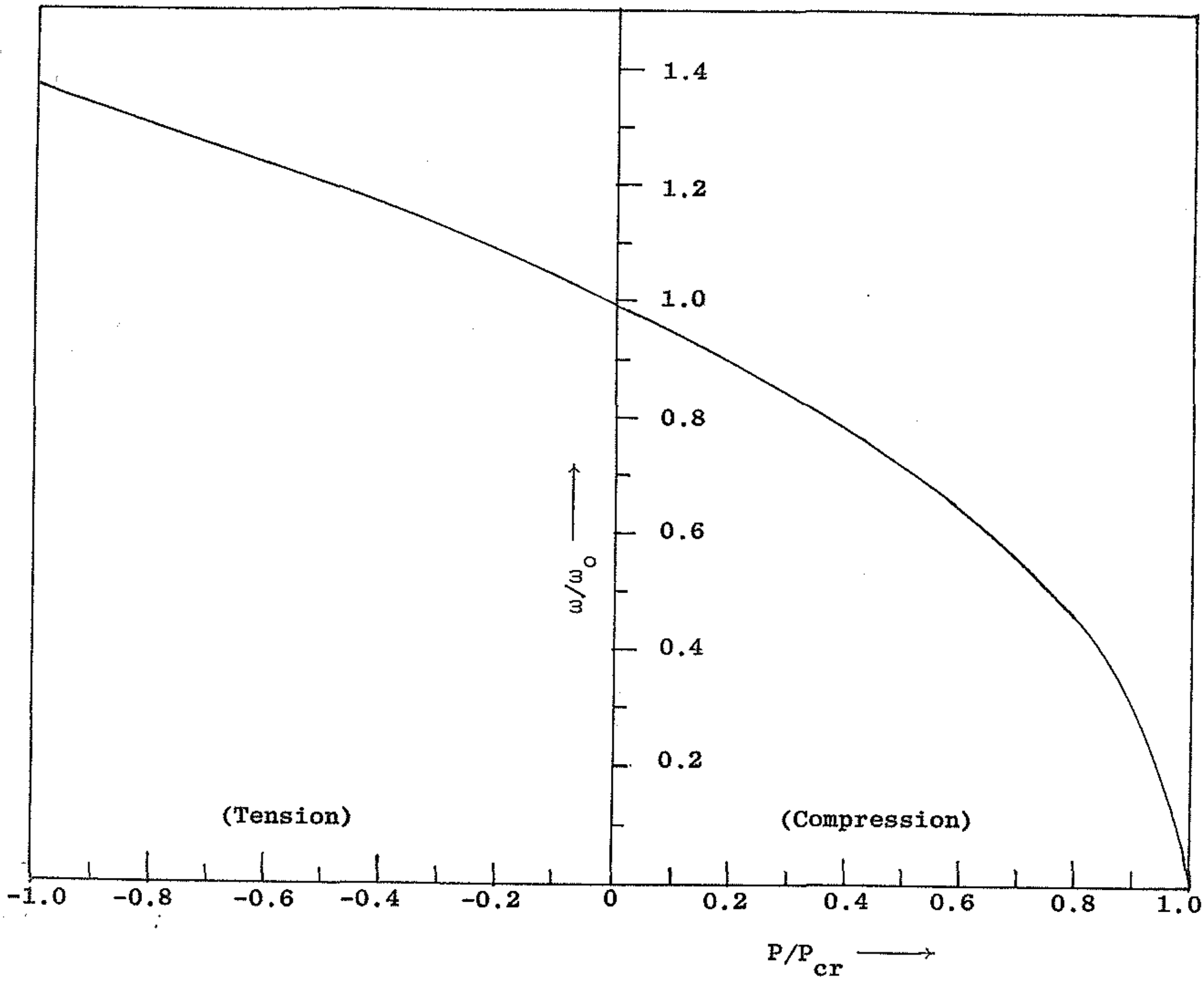

Fig.4. Effect of axial force (P) on the fundamental bending frequency (ω) of a uniform cantilever beam (ω_o = frequency for the unloaded case; P_{cr} = Euler critical buckling load = $\pi^2 EI/4L^2$)

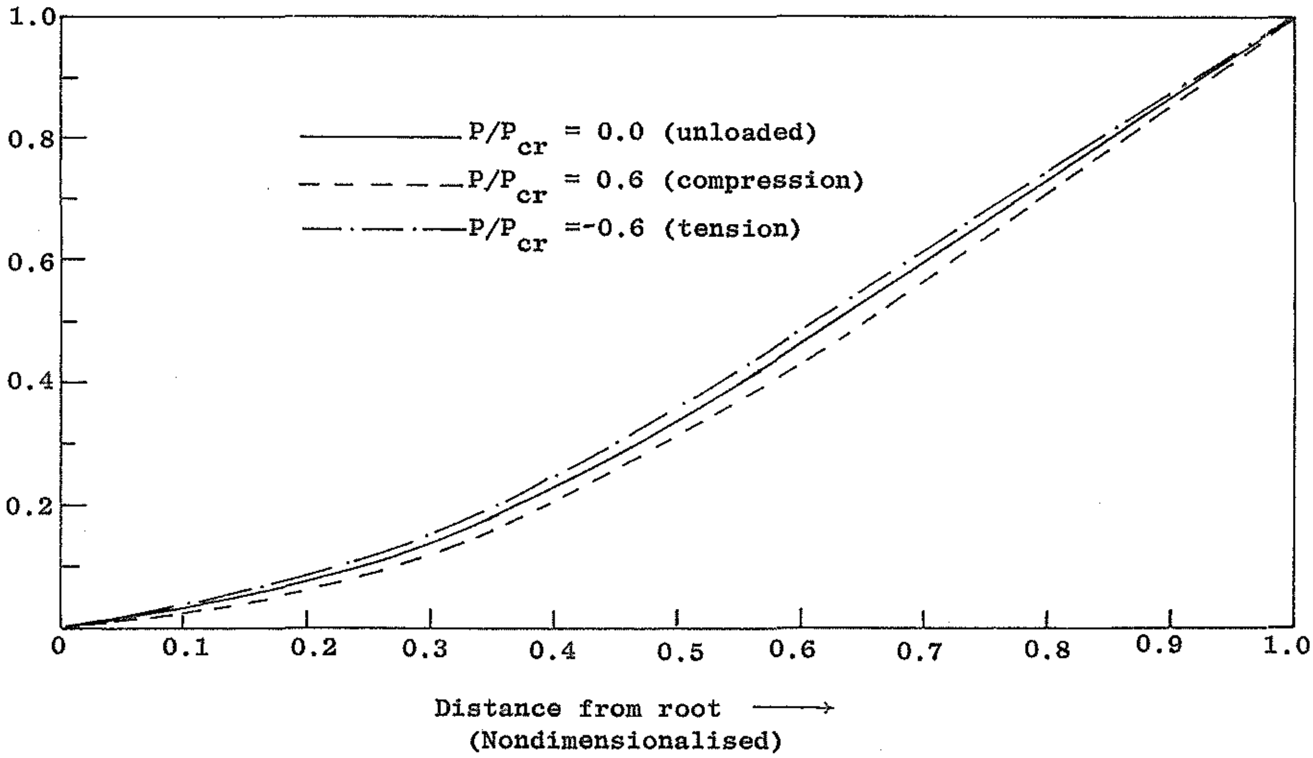

Fig.5. Effect of axial force on the fundamental bending mode of a cantilever beam (P_{cr} = Euler critical buckling load = $\pi^2 EI/4L^2$)

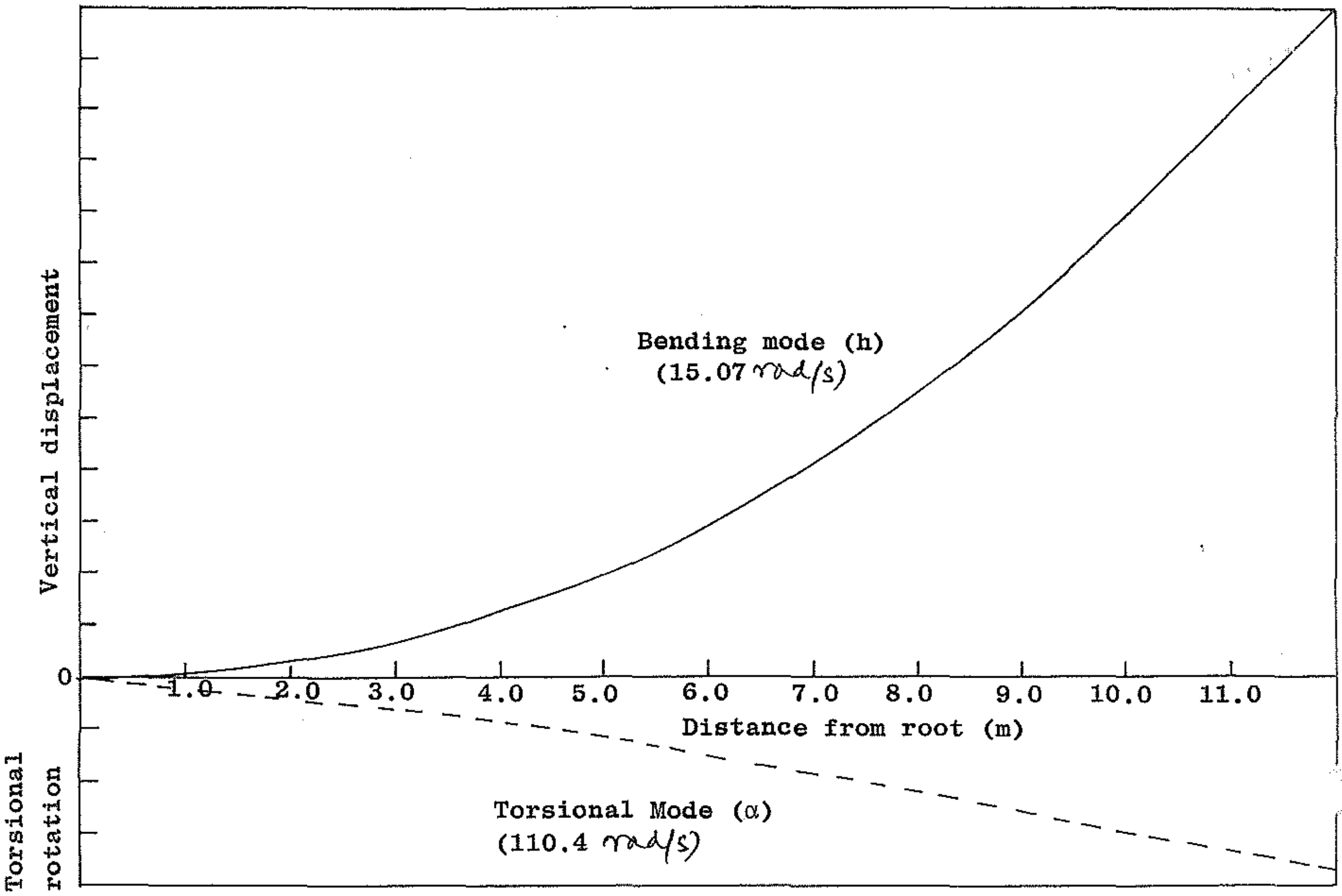

Fig.6. Fundamental bending and torsional (uncoupled) modes of 12m turbine blade.

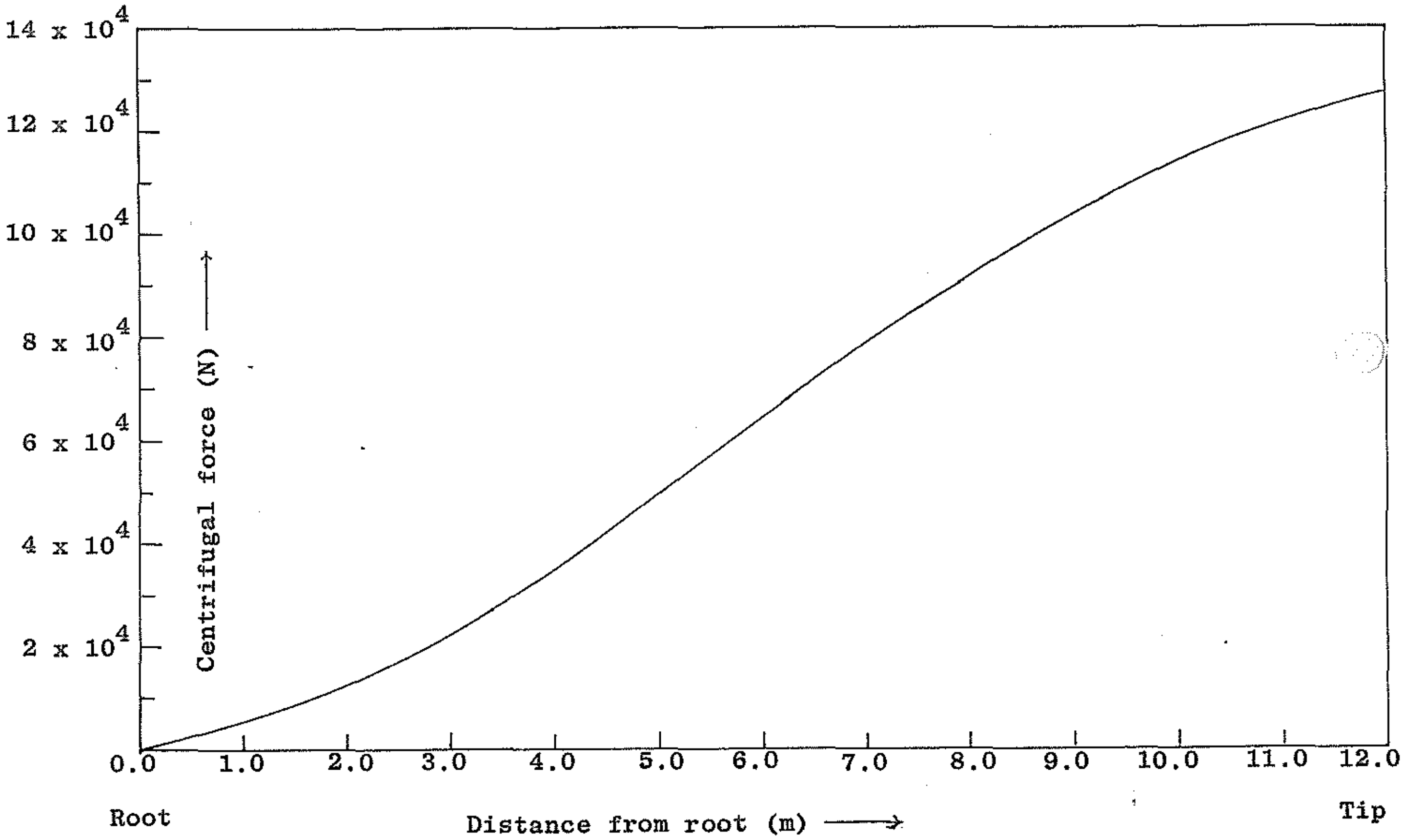

Fig.7. Distribution of centrifugal force along the 12m blade length at 60 RPM