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Summary.—This report describes comparative flutter tests on two, three, four-and five-blade Duralumin propellers with the same blade design. The tests were made on the No. 3 spinning tower, Royal Aircraft Establishment. Strain-gauges were used for determining the vibratory stresses and the phase relations between the blades. A wide range of blade angles above and below the stalling region was explored. Stalling flutter was the only form encountered. The phase relation of the blades was found to be dependent on number of blades and speed of rotation, and to influence the amplitude of the vibratory stresses. It is shown that no direct comparison of the flutter characteristics of the two, three, four and five-blade propellers can be made.

1. *Introduction.*—Experiments on wooden propellers have shown that both classical and stalling flutter may be encountered within the running range[1], and that the type and severity of the flutter depend on the number of blades as well as on the blade design.

The present report describes experiments on two, three, four and five-blade propellers with paddle-type Duralumin blades of the same design. The blades were originally designed for a five-blade $12\frac{3}{4}$ ft diameter propeller for the Tempest-Centaurus aircraft. Only one set of five blades was used and from these blades the two, three, four and five-blade propellers were assembled. The tests were made on the No. 3 Spinning Tower at R.A.E. Strain-gauges were used to measure the vibratory stresses and to determine the flutter frequency and modes of vibration, with particular reference to the phasing of the blades.

A wide range of blade angles above and below the stalling region was explored; only torsional stalling flutter was encountered and the flutter frequency corresponded to the fundamental torsional frequency of the blades.

When flutter occurred, the vibrations in any pair of blades were found to have a definite phase relationship, which did however vary with rotational speed. The stress at any speed varied with blade angle to an extent which was dependent on the number of blades. The greatest stresses occurred on the four and five-blade propellers.

The results show that it is not possible to make a direct comparison of the stalling characteristics of two, three, four or five-blade propellers, of the same blade design.

* R.A.E. Report Structures 18—received 29th April, 1948.

2. *Method of Test.*—2.1. *Gauge Type and Arrangement.*—Wire-resistances train-gauges, each of 2400 ohms resistance, were fixed to the pressure faces of the blades to measure torsion and flexure as described in R. & M. 2472[2]. The distribution of the gauges on each of the five blades was as follows:

Blade number 1: Torsion and flexure gauges at 0·3, 0·45, 0·6, 0·75 and 0·9 radius stations.

Blades numbers 2, 3, 4: Torsion and flexure gauges at 0·6 and 0·75 radius stations.

Blade number 5: No gauges.

The electrical circuit was similar to that used in previous tests[2], and four-channel equipment was used for recording the vibratory stresses. A voltage of 24 was supplied to the blade system, giving a current of 5 mA per gauge. Calibration was made by recording a known alternating current (a.c.) voltage.

2.2. *Range of Tests.*—The blades were assembled as two, three, four and five-blade propellers, the fully-strain-gauged blade (number 1) being used in all the tests. Tests were made at blade angles of 12, 16, 20, 24, 28 and 32 deg measured from the flat face at the 0·7 radius up to a maximum speed of 1600 r.p.m. at the lower angles, and speeds dependent on the power limitations of the spinning plant at the higher angles. The speed range corresponds to Mach numbers of 0·45 to 0·75 and values of the frequency parameter ($\lambda = 2\pi \times$ frequency $\times$ chord/wind speed) of 1·5 to 0·9, the reference section being the $0{\cdot}8R$ station in each case. Recordings were made, at most angles, at intervals of approximately 50 r.p.m. and the traces were visually examined over the entire speed ranges.

2.3. *Recordings.*—The records taken at each speed enabled the following measurements to be obtained:

(1) The relative amplitudes of the stresses measured by the torsion and flexure gauges along the blade.
(2) The phasing between torsional and flexural modes of vibration.
(3) The phrasing between blades of the propeller.
(4) The frequencies of the vibrations.
(5) The maximum recorded stress.

In addition to the spinning tests, static tests were made to determine the fundamental torsiona and flexural frequencies of blade number 1, together with the frequencies of the first four flexura overtones.

3. *Test Results.*—3.1. *General.*—Throughout the tests, only stalling flutter was encountered, *i.e.* the flutter was a purely torsional vibration. At low incidences, even at the highest rotational speed, no evidence of flutter was found. Flexural stresses of considerable amplitude were recorded when the fundamental and overtone flexural frequencies of the blades resonated with propeller orders, due presumably to buffeting off the spinning tower structure. These vibrations were not accompanied by the noise normally associated with propeller flutter and they have not been considered in this report. Simultaneously, recordings from the torsion gauges sometimes showed the presence of vibrations of the same frequencies but of lower amplitude; these, too, have been omitted.

At blade angles of 12 and 16 deg no flutter was encountered (up to 1600 r.p.m.) and the recorded vibrations were very irregular except where a resonance with a propeller order occurred.

3.2. *Frequencies, and Blade Stress Distribution.*—The following figures were obtained from the static vibration tests on blade number 1.

Fundamental torsional frequency	= 155 c.p.s.
Fundamental flexural frequency	= 18 c.p.s.
1st flexural overtone	= 45 c.p.s.
2nd flexural overtone	= 61 c.p.s.
3rd flexural overtone	= 105 c.p.s.
4th flexural overtone	= 195 c.p.s.

The flutter frequency measured during the spinning tests in each case corresponded exactly with the fundamental torsional frequency; this result agrees with previous tests[2]. Further, the relative amplitudes of the stresses measured at the various gauge stations were independent of the number of blades, the blade angle and the rotational speed. Thus the frequency and mode of vibration in each blade were constant throughout. Fig. 2 shows the curve of relative amplitude of stress plotted against blade radius, with the maximum, which is slightly in-board of the 0·75 radius, taken as unity.

3.3. *Inter-blade Phasing*.—In recording the phasing between blades, it was found that at any particular condition of flutter, there was a fixed and regular phase difference between blades. For a propeller with N blades the phase angle ε between the vibration in any blade and that in the next preceding blade, is given by $\varepsilon = 2\pi p/N$, where $p = 0, 1, 2, \ldots$; only solutions of this equation will give symmetry of phasing between all the blades. The records show that p increased with increasing r.p.m. As p changed value, there was a transition from one phase relationship to the next, accompanied by a change in the wave-form from a sinusoidal trace to an irregular vibration of smaller amplitude. Figs. 3 to 6 show stress plotted against r.p.m. at constant blade angles for two, three, four and five-blade propellers. The full lines denote the regular sinusoidal vibration and dotted lines the regions of phase change. The r.p.m. at which phase changes take place appear to vary only slightly with angle of attack (and also blade angle) for a particular propeller; this is indicated in Fig. 7 which shows the phase areas for an angle of attack range of $\alpha = 10 \cdot 4$ to $21 \cdot 8$ deg for the two-blade propeller, and $8 \cdot 1$ to $17 \cdot 4$ deg for the five-blade, where α is measured from the no-lift angle at the 0·8 radius.

3.4. *Comparison of Stress Levels*.—The variation of stress with r.p.m. depends to such an extent on blade phasing that a detailed comparison of stress for two, three, four and five-blade propellers cannot be made. The r.p.m. at which phase changes occur vary with the number of blades, and for a given r.p.m. a peak in the stress curve for one propeller may coincide with a phase change (and consequently a lower stress) for another. It is, therefore, advisable to compare only the general stress levels.

For the three, four and five-blade propellers, the greatest stress was recorded at a blade angle of 24 deg; the greatest for the two-blade propeller was somewhat lower and was recorded at a blade angle of 20 deg. At blade angles below and above 24 deg, the level of stress for the four and five-blade propellers decreased rapidly with angle, and for the three blade rather less rapidly. The stresses for the two blade fell off very little from the maximum at 20 deg. Comparing the stresses on the basis of angle of attack, it is found that as the number of blades is increased, the greatest stresses at a given r.p.m. occur at progressively lower values of α, except in the regions of phase change.

3.5. *Discussion*.—The tests described have been made at blade angle intervals of 4 deg in order to cover a wide range of angles. An analysis of the results shows that stalling flutter occurred on the propellers at angles of attack greater than about 8·5 deg calculated from the no-lift angle at the 0·8 radius. At a blade angle of 20 deg, the angle of attack for the five blader (which did not flutter) was 8.2 deg and that for the four blader (which did flutter) was 8·8 deg. This angle of transition of 8·5 deg from the coupled flutter region to the region of stalling flutter compares with angles of 10·5 deg and 11 deg for somewhat thicker wooden blades[1]. The thickness/chord ratio of the wooden blades at the 0·8 radius was 7·8 per cent, compared with 6·25 per cent for the present blades.

The results show that the testing of a two-blade propeller in order to obtain flutter data for a three, four or five-blade propeller of the same design has little value apart from a very rough indication of stress level.

Subsequent tests have indicated that the phase pattern described in section 3.3 does not necessarily occur in all propellers. It has been noted that during tests on two, three, four and five-blade propellers assembled from a second set of five blades that the flutter frequency of the blades may differ due to a difference in static fundamental torsional frequencies. When this occurs phasing is impossible. The production tolerance of blades may well permit a variation in natural frequencies.

4. *Summary of Conclusions.*—(1) The flutter encountered during the tests was stalling flutter of a purely torsional mode, the onset occurring at an angle of attack of 8·5 deg.

(2) For a given propeller assembled from this set of blades, with constant blade angle and running in a region where flutter was encountered, a variation in the vibratory stresses was recorded which was dependent on the phase relation between the blades. This phase relation obeyed the general law $\varepsilon = 2\pi p/N$, (where ε is the phase angle between the vibration in any blade, and that in the next preceding blade, N is the number of blades and $p = 0, 1, 2 \ldots$); p was found to increase, with increasing rotational speed.

(3) The rotational speeds at which the phase changes occurred varied slightly with blade angle for a given propeller. A change in phase was accompanied by a decrease in stress level in which the vibration was irregular and of low amplitude and which was followed by an increase to the maximum stress in the new mode of vibration.

(4) The maximum vibratory stresses recorded were encountered on the five and four-blade propellers at angles of attack of 10·7 deg and 11·6 deg respectively; for angles above and below these values the stress level fell sharply. The rate of decrease of stress with angle was less for the three-blade propeller; the maximum vibratory stress being recorded at an angle of attack of 12·6 deg, while for the two-blade propeller the maximum stress remained reasonably constant over the range where flutter was encountered.

(5) The frequency and mode of vibration in any particular blade were constant and were independent of the number of blades, blade angle and rotational speed. The frequency of the flutter was 155 c.p.s. which corresponds to the measured fundamental torsional frequency of the blades.

(6) No direct comparison of the stalling flutter characteristics of two, three, four and five-blade propellers can be made.

(7) When propellers are assembled from blades whose fundamental torsional frequencies are not nearly identical the stalling flutter characteristics do not follow the phase relationship described in this report.

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2	L. H. G. Sterne, H. G. Ewing and J. Kettlewell	Strain gauge investigation of propeller flutter. R. & M. 2472. January, 1947.

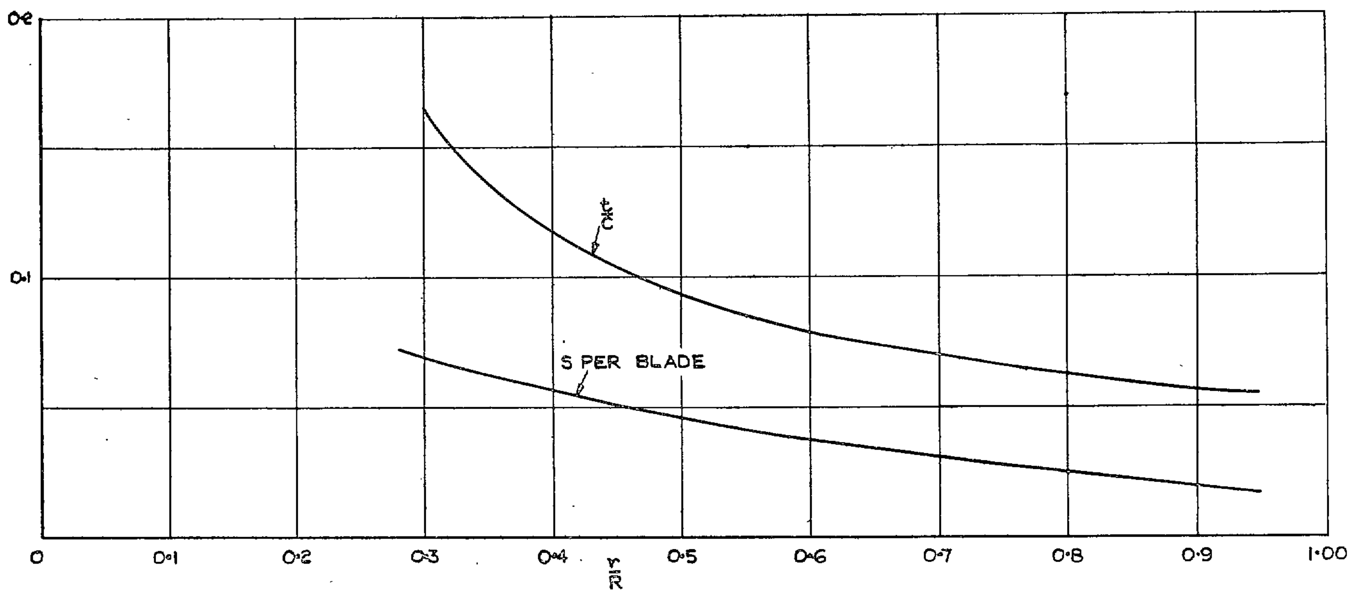

FIG. 1 Solidity per blade and thickness/chord ratios.

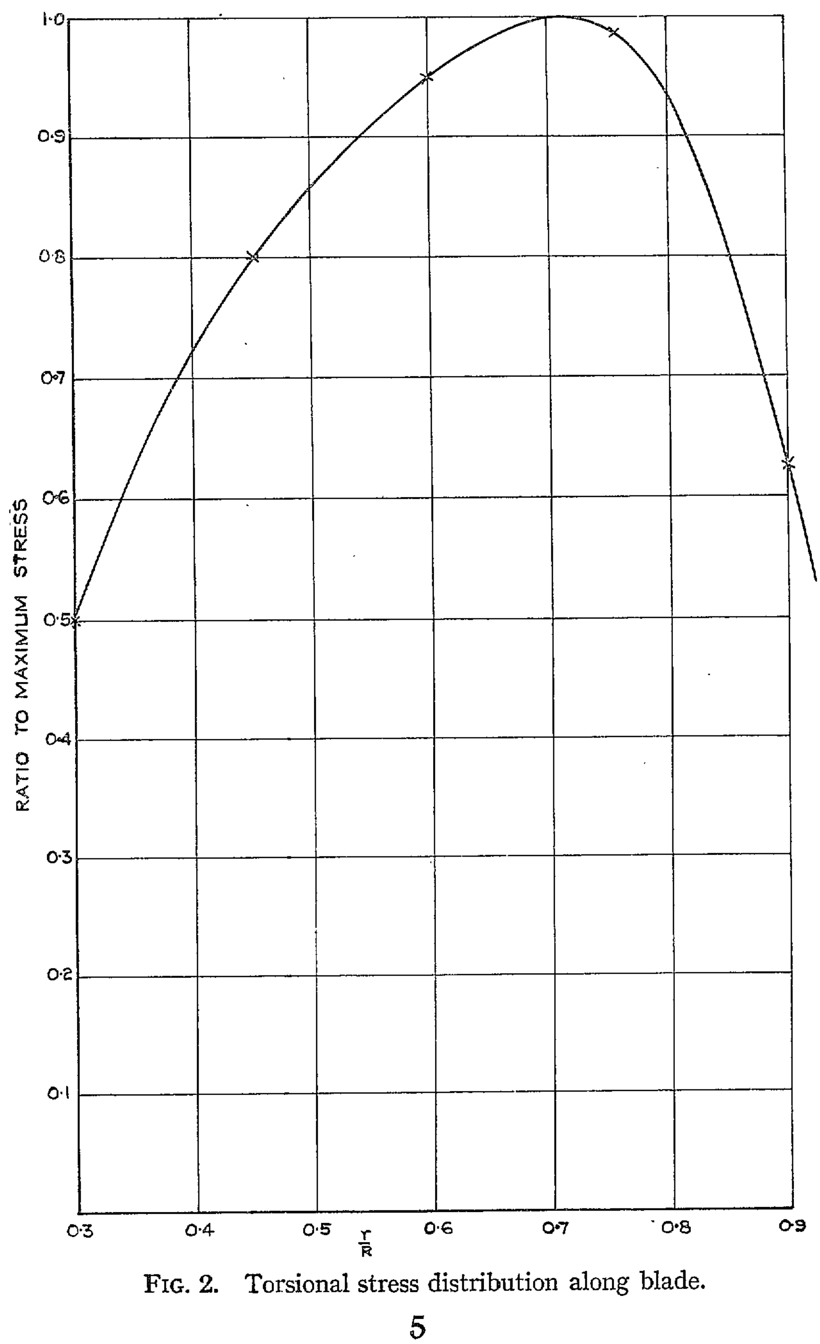

FIG. 2. Torsional stress distribution along blade.

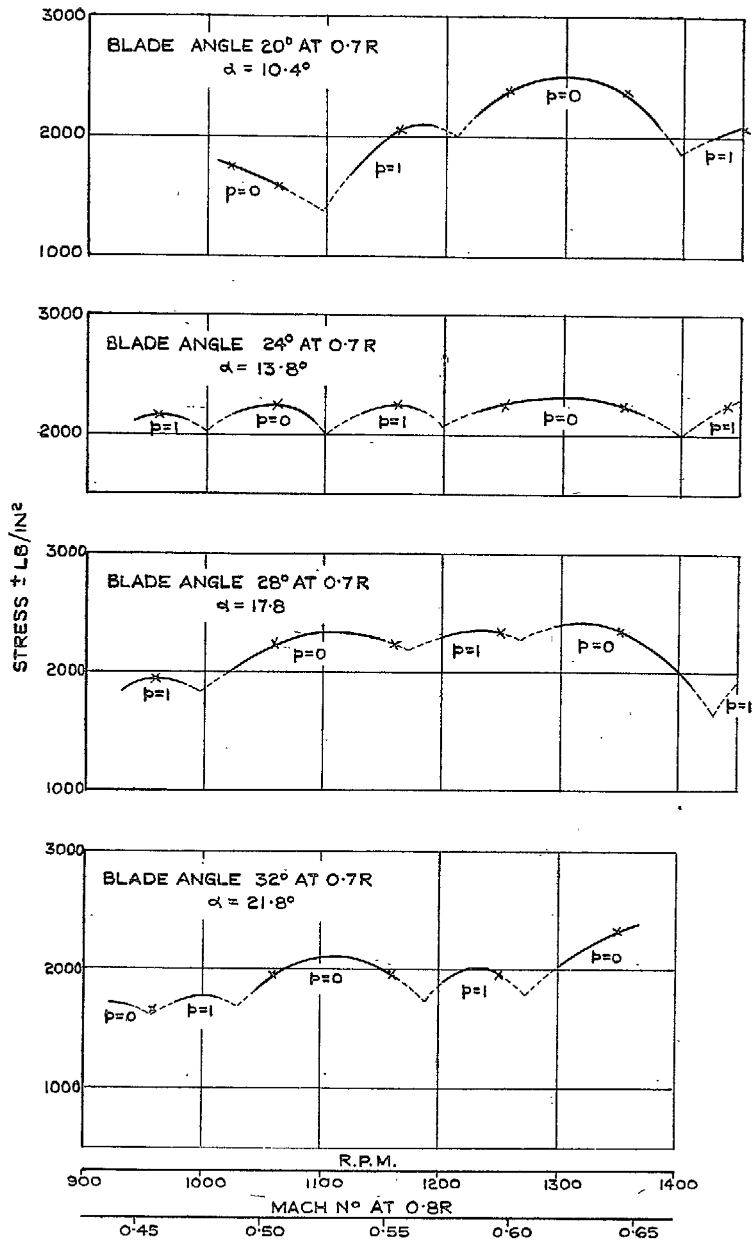

FIG. 3. Two-blade propeller. Torsional stress at $0 \cdot 75R$ and blade phasing.

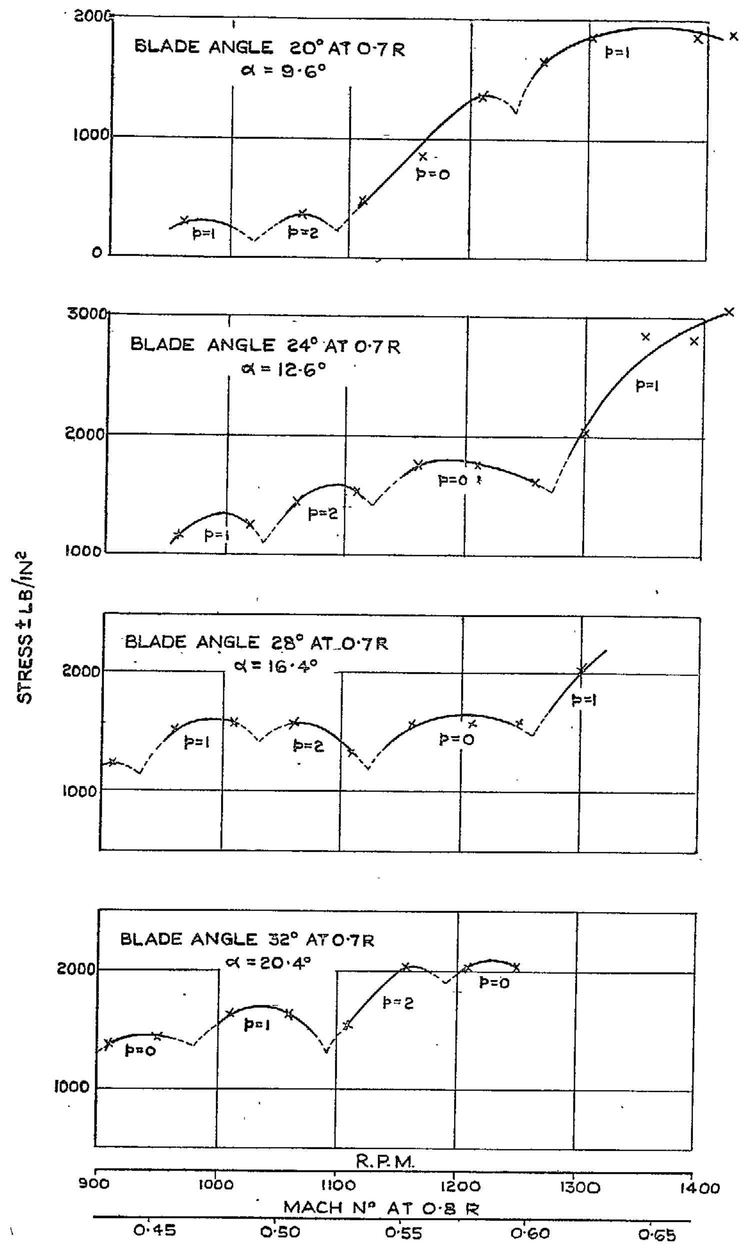

FIG. 4. Three-blade propeller. Torsional stress at $0 \cdot 75R$ and blade phasing.

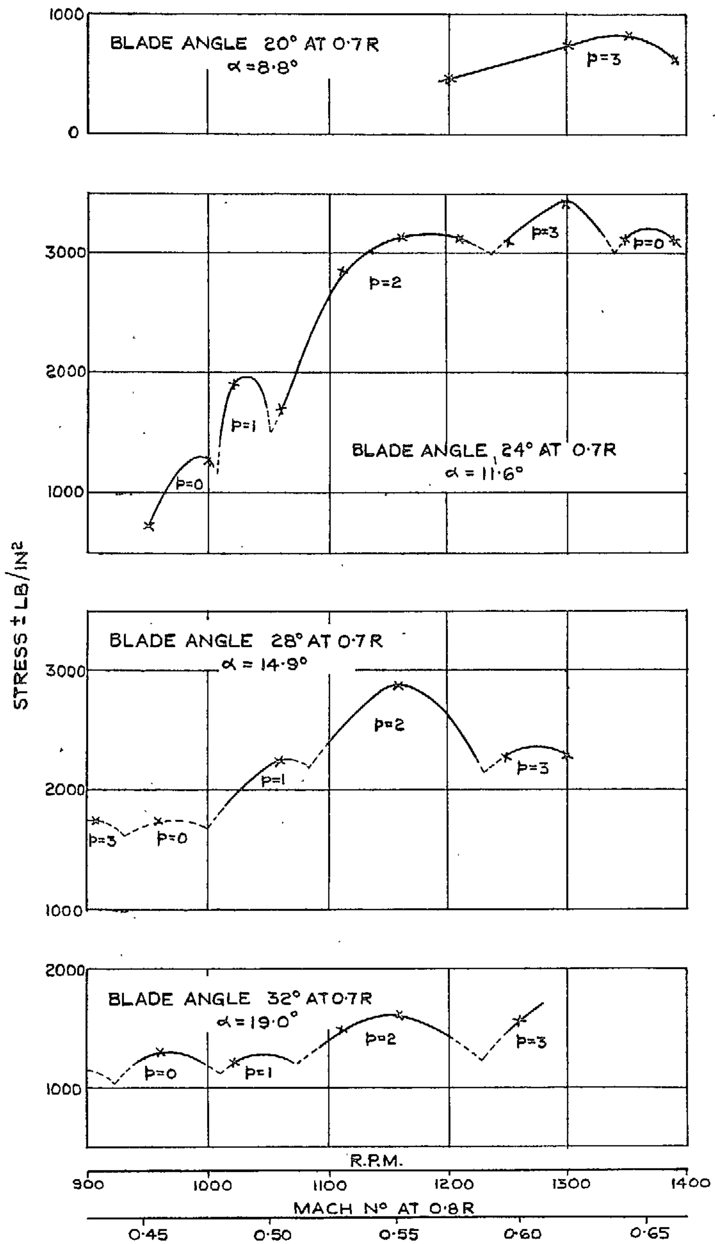

FIG. 5. Four-blade propeller. Torsional stress at $0 \cdot 75R$ and blade phasing.

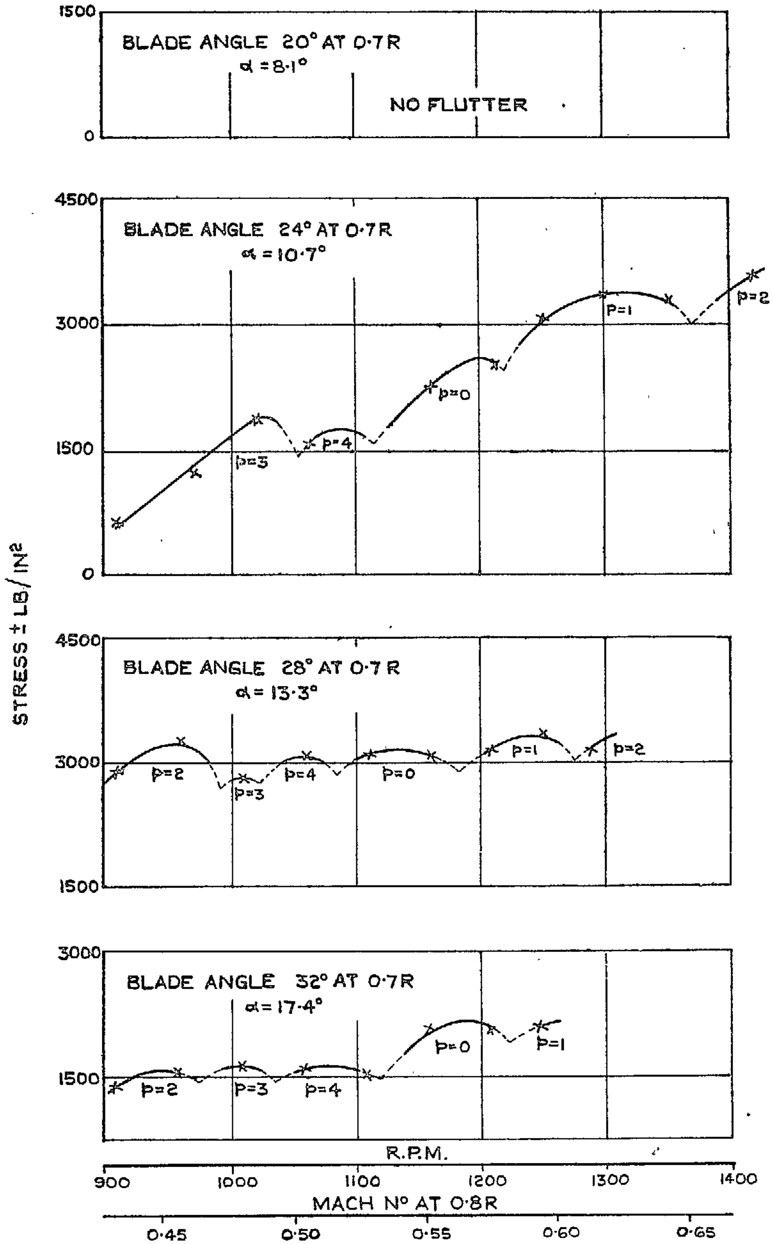

FIG. 6. Five-blade propeller. Torsional stress at $0 \cdot 75R$ and blade phasing.

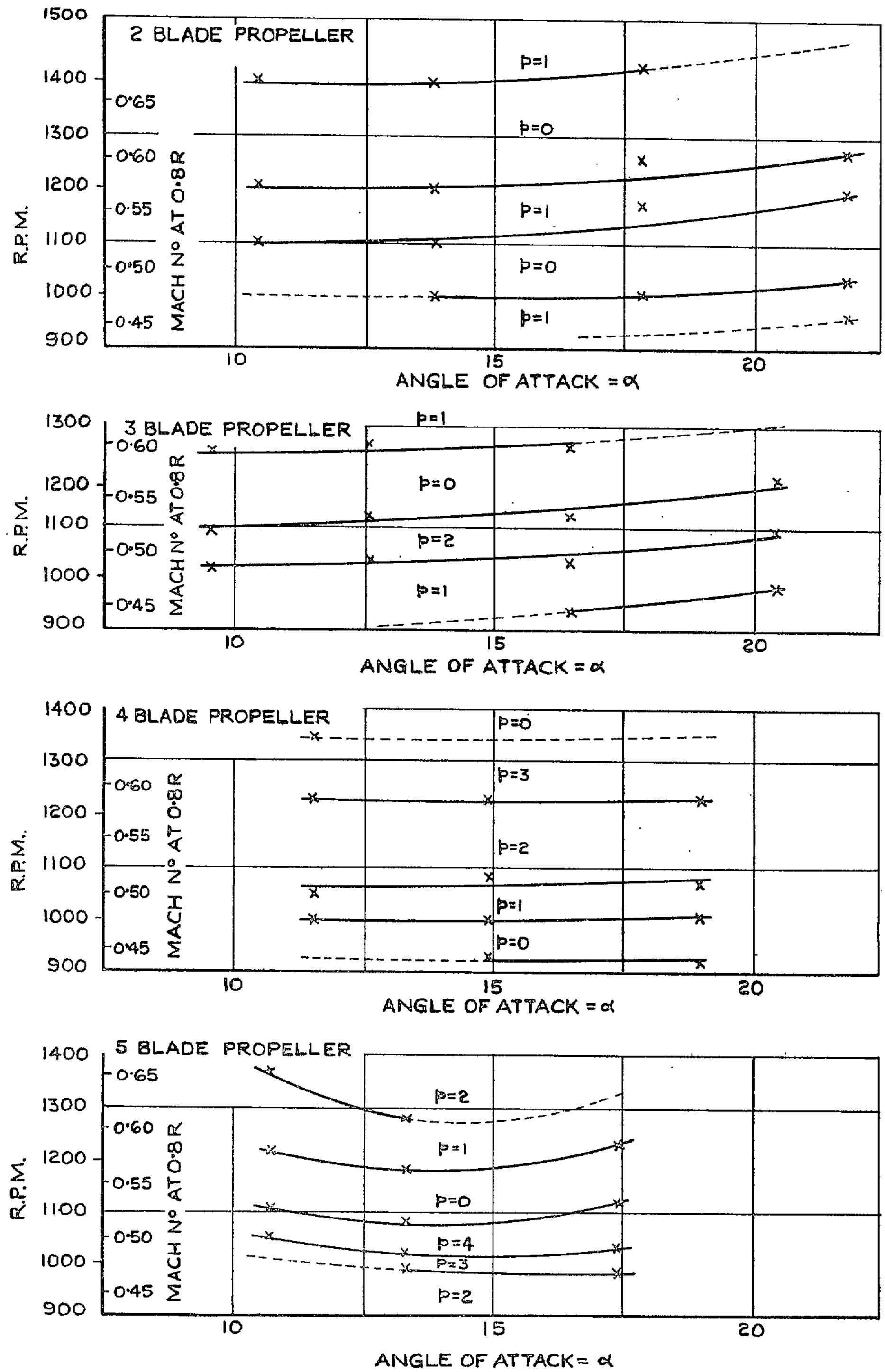

FIG. 7. Phasing diagram, two, three, four and five blades.

(51500) Wt. 15/806 K.5 6/52 Hw.

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