Some Notes on the Design of Airscrews.

Paper read by Captain F S Barnwell, B Sc , O B E , A F C , F R Ae S (Hons Member), before the Institution in the Lecture Room of the Junior Institution of Engineers, 39, Victoria Street, London, S W 1, on 25th January, 1927

Dr H C Watts, D Sc , F R Ae S , etc , in the Chair

DR WATTS, in introducing Captain Barnwell, said I am sure we are all very much indebted to Captain Barnwell for giving us the benefit of his knowledge and experience The subject cannot fail to be interesting to all who are associated with aricraft design, although the attitude of aircraft designers generally varies between two extremes On the one hand there are some who consider airscrew design as something mysterious, to be left to an outside expert, and on the other hand there are some who consider it so simple that it can safely be left to an internal subordinate It is quite common knowledge that Captain Barnwell adopts the happy medium, and deals with the subject himself

I remember that 14 or 15 years ago, at the old British and Colonial Aeroplane Company, Captain Barnwell was designing a special " hush-hush " machine I was a mere nobody in the drawing office, entrusted with airscrew design, but I remember that Captain Barnwell designed his own airscrew for this " hush-hush " machine, much to my secret chagrin So behind this paper there is 14 or 15 years of personal knowledge of airscrew design

I now have much pleasure in calling upon Captain Barnwell to give us his paper

Captain F S BARNWELL The basis for the consideration of the aerodynamic forces on an Airscrew is the so-called " Simple-Blade-element Theory," and I propose therefore to expound this briefly as a jumping-off point

Fig (A) in Plate 1 illustrates a two-bladed Airscrew rotating at n revs per second, and also advancing along its axis at a speed of v ft per sec The value of advance in feet per rev , $(v - n)$, is denoted by a Now consider an anular element of a blade at a radial distance of r feet from the axis of rotation See Fig (B) Plate I

AB represents to some scale $2\pi r$, BC represents to same scale advance per rev , a, hence AC represents to same scale the travel of the element per revolution

BD represents to same scale, the geometrical face Pitch, P, of the element, hence, $C\hat{A}D$ is the angle of attack of the element

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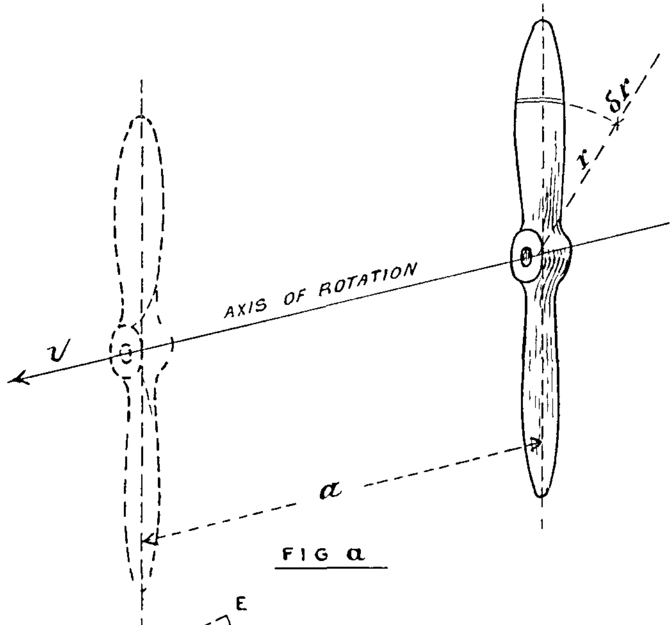

FIG a

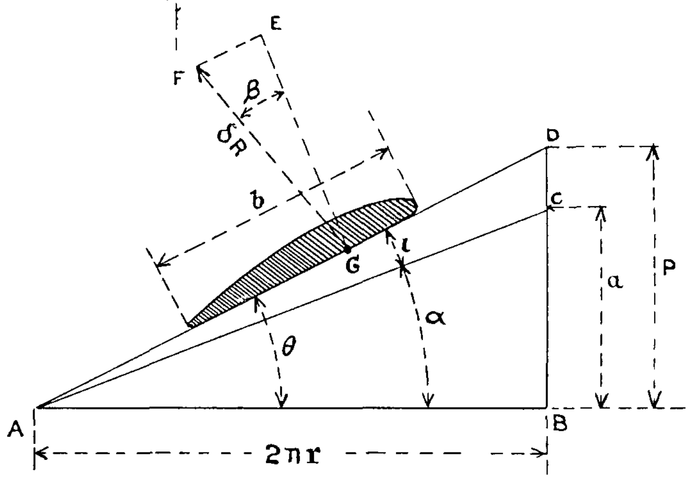

FIG b

PLATE I

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The speed of the element is of course (AC × n), or

$$n\sqrt{(2\pi r)^2 + a^2}$$

Suppose GF represents the total air reaction, δR, in lbs on the Element due to this speed at this angle of attack GE is perpendicular to AC, hence EGF, or β, is the inclination of the total air-reaction to the normal to the flight path, tan β is, of course, the value of $\frac{\text{Drag}}{\text{Lift}}$ and total reaction is $\sqrt{\text{Lift}^2 + \text{Drag}^2}$, using the words "Lift" and "Drag" in their standard aerofoil sense

Now the Thrust, δT, of the Element is, of course, the component of δR parallel to BD, and the resistance to rotation of the element is the component of δR parallel to BA

Hence, Thrust of Element, $\delta T = \delta R \cos(\alpha + \beta)$
and Torque of Element, $\delta Q = \delta R \sin(\alpha + \beta) \times r$
whilst the Efficiency of the Element, by which is meant the value

$$\frac{\text{Work given out by Element in Thrust Power}}{\text{Work absorbed in rotating Element}}$$

is

$$\frac{\delta R \cos(\alpha + \beta) \times a}{\delta R \sin(\alpha + \beta) \times 2\pi r}$$

or

$$\frac{\operatorname{Tan} \alpha}{\operatorname{Tan}(\alpha + \beta)} \tag{1}$$

Assuming, for the time being, that the aerodynamic characteristics of any element of the blade of an airscrew are the same as those of an aerofoil of the same form of section, we obtain from wind tunnel figures on suitable model aerofoils the values for K_R and for β for some chosen number of elements of the blade at some chosen radial distances from the axis The results of wind-tunnel experiments are usually tabulated in the form of values for absolute Lift Coefficient, K_L, and absolute Drag Coefficient, K_D K_R, the absolute total Reaction Coefficient which I have employed, is of course $\sqrt{K_L^2 + K_D^2}$, and β as before stated is the angle whose tangent is $\frac{K_D}{K_L}$

We now calculate for each of these chosen sections the values of t_F, Thrust per foot run of blade, and of p_F, Power absorbed per foot run of blade, from the equations —

$$t_F = K_R \cos(\alpha + \beta)\,[(2\pi r)^2 + a^2]\, n^2\, b\, p \text{ in lbs} \tag{2}$$

$$p_F = K_R \sin(\alpha + \beta)\,[(2\pi r)^2 + a^2]\, n^2\, b\, p\, 2\pi r\, n \text{ in foot lbs per second} \tag{3}$$

b being chord length of section in feet We may then integrate these values throughout the blade length, either graphically or by Simpson's Multipliers Personally, I generally divide the distance from Axis to tip into six equal divisions, sub-divide the tip division, and integrate by Simpson's Multipliers as shown in Plate II

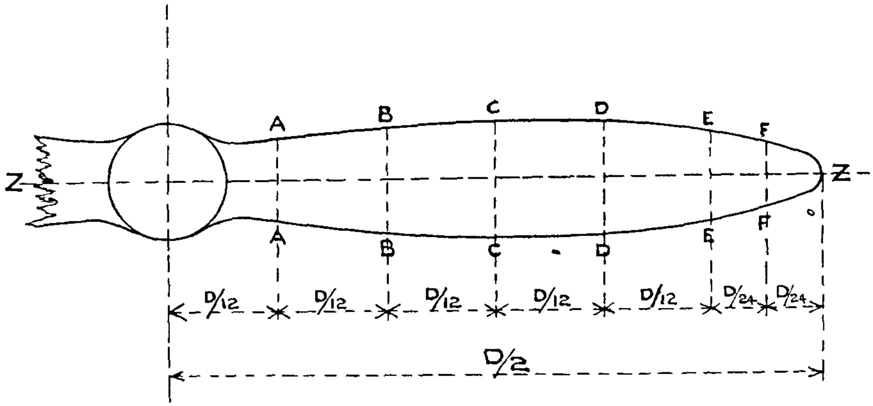

PLATE II —Fig 1

Typical Positions for Sections

Section	T′	S M	(T′ × S M)
A		½	
B		2	
C		1	
D		2	
E		¾	
F		1	
Tip		¼	
		7½	Σ(T′ × S M)

Total Thrust for Airscrew —

$$T = \frac{\Sigma(T' \times S\,M)}{7\ 5} \times \frac{5}{12} D \times N$$

where N = No of Blades

Fig 2

Example of Table for Integrating for Value of Thrust by Simpson's Multipliers

We thus obtain values for thrust in lbs T, and for Power absorbed, in foot lbs per second, P, for the complete Airscrew, and from these obtain the overall efficiency, E , from equation

$$E = \frac{Tv}{P}$$

Let me state at this point that I consider the Airscrew as consisting of the Blades only, and consider the Airscrew Boss as part of the body of the Aeroplane

The values estimated by the " Simple Blade Element Theory," just described, are more or less inaccurate for several reasons —

Firstly, the Coefficient of air-reaction on an element of an airscrew blade is not the same as the mean value over a complete aerofoil (of rectangular plan form and 6/1 Aspect Ratio as is usually tested in a Wind Channel) of the same section

Secondly, the simple Element Theory assumes each element as working in undisturbed air, *i e*, as a monoplane aerofoil , whereas it should properly be considered as working in the middle of an infinite " cascade " of aerofoils

Thirdly, " scale " effect has a modifying influence

The first and second reasons for inaccuracy may be avoided by making modifications to the theory (for which I refer you to H Glauert's work " Elements

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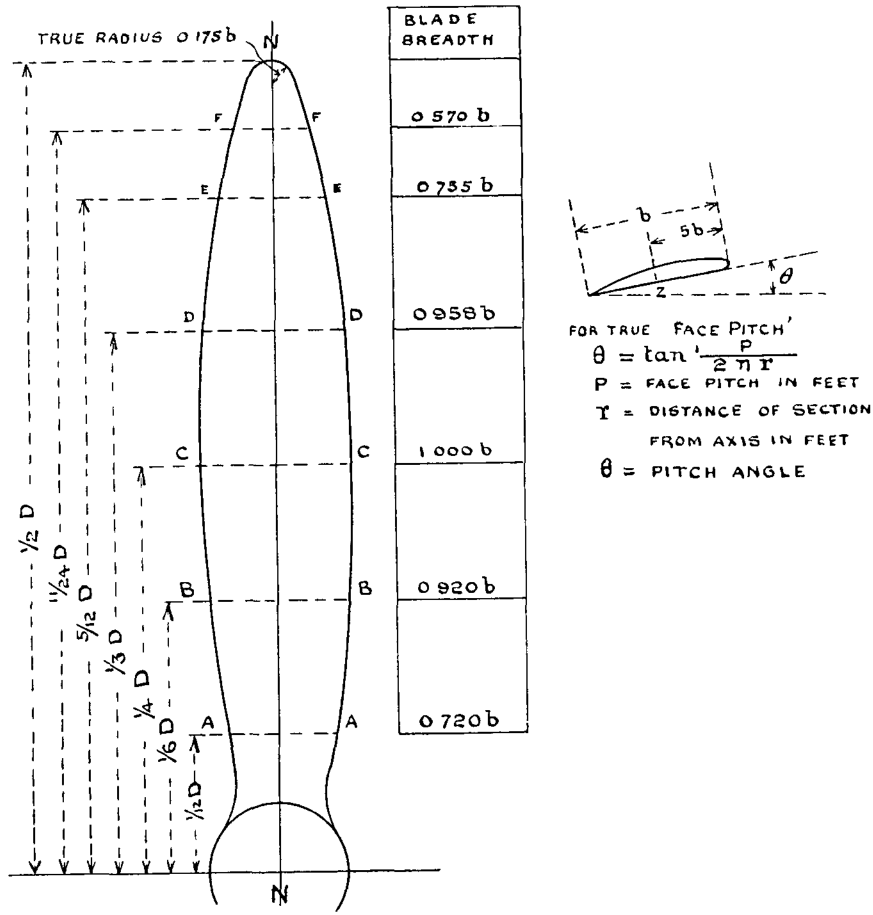
of Aerofoil Theory and of Airscrew Design "), or by evolving empirical corrections to results obtained by the ' simple " theory from the data afforded by experiments on model airscrews, as I attempt in this paper

The third reason for inaccuracy can be allowed for, more or less, by making use of the experimental work done in the variable Density Wind Tunnel in the Massachussetts Institute of Technology, and of the results of experiments at very high speeds on aerofoil models carried out by the Bureau of Standards, U S Army, at the Lynn Works of the General Electric Co I refer you to U S A , N A C A Reports, Nos 233 and 207

To revert for the time to the " Simple " Theory I propose to assume a " standard " form of blade, of constant Face Pitch, of Plan form as given on Plate III having sections as given on Plate IV



PLATF III —STANDARD PLAN FORM OF BLADE OF CONSTANT FACE PITCH

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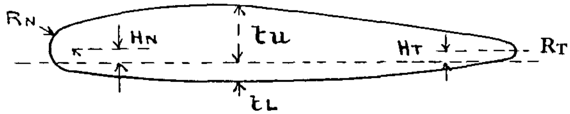
PLATE IV



Dimension		Section A	B	C	D	E	F
RN		1273	0628	0378	0257	0160	0106
HN		00748	0346	0338	0257	0160	0106
0 05 Chord	tU	0997	1121	1000	0776	0490	0328
	tL	0825	0278	00607	0	0	0
0 10 ,,	tU	1334	1439	1287	0992	0620	0413
	tL	1146	0450	00984	0	0	0
0 20 ,,	tU	1738	1769	1553	1182	0739	0491
	tL	1490	0606	01371	0	0	0
0 30 ,,	tU	1922	1874	1620	1230	0768	0510
	tL	1631	0651	0148	0	0	0
0 40 ,,	tU	1970	1851	1583	1200	0750	0498
	tL	1670	0643	01477	0	0	0
0 50 ,,	tU	1915	1733	1466	1112	0695	0462
	tL	1623	0602	0134	0	0	0
0 60 ,,	tU	1763	1540	1291	0981	0612	0407
	tL	1494	0535	0118	0	0	0
0 70 ,,	tU	1532	1283	1066	0810	0505	0337
	tL	1300	0445	00974	0	0	0
0 80 ,,	tU	1230	0982	0897	0606	0384	0260
	tL	1041	0341	00729	0	0	0
0 90 ,,	tU	0840	0628	0492	0375	0246	0170
	tL	0712	0217	0045	0	0	0
RT		0528	0812	0106	0076	0054	0041
HT		00335	0079	0090	0076	0054	0041

Offsets for Standard Sections, expressed as Fractions of Maximum Blade Breadth, b_1

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My reasons for proposing this " Standard " Blade Form for wooden airscrews, are that the proportions are about correct for strength (as we shall see later), the form of section is about as efficient as can be attained within the limitations imposed to ensure a sufficiently robust trailing edge, the whole blade " fairs up " when made to these proportions, and the calculations for aerodynamic forces and for strength are greatly simplified

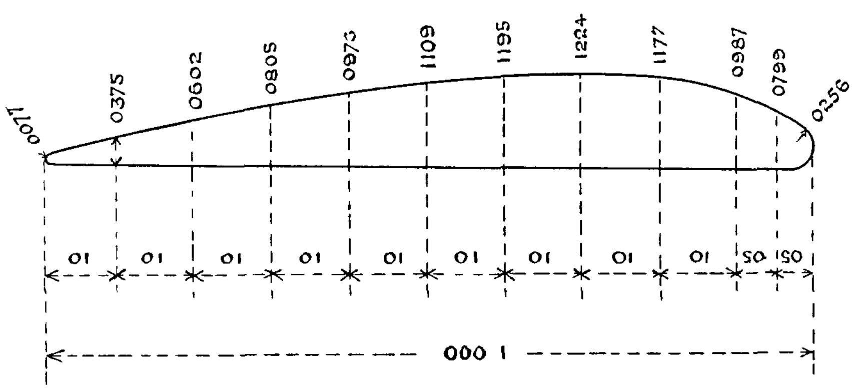
If, by the " Simple Blade Element Theory," as before described, calculations are made for the efficiency at each section and for the overall efficiency, it will be found, for this " Standard " Form of Blade, that the efficiency of the section at radius 35 D from the Axis of Rotation, is very approximately the same as the overall efficiency

Again, if the calculations for Power absorbed be made, it will be found that the power absorbed per blade is very approximately equal to 55 of the power that would be absorbed if the value per foot run at this particular section were constant throughout the Blade-length

I shall therefore from now on call this section the " Test Section," and shall assume that the aerodynamic properties of the whole blade may be arrived at by consideration of this " Test Section " only

For this " standard " form of blade the chord-length of the " Test Section " is 933 of the maximum blade breadth, b_1, and its proportions are as given in Plate V

PLATE V



DIMENSIONS FOR " TEST SECTION " OF " STANDARD " BLADE
TEST SECTION IS SECTION OF BLADE AT 0 35 DIA FROM AXIS

This section is derived from the " Clark Y " and I assume that its aerodynamic properties, at high values of vl, are as follows —

Coefficient of total reaction, K_P^1, linear from —2° to + 14°, and of value

= (20° + 0006 i_M) where i_M is the numerical value for the angle of attack, i^1, expressed in minutes

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β^1 angle between line of total reaction and the normal to the flight-path, has values as given in the Table of Plate VI , I give a Table for the values of β^1 as being more convenient for office use than is a curve , the readings are spaced sufficiently closely to make linear interpolation for intermediate values of sufficient accuracy

PLATE VI

i Deg	β Deg	β Min	i Deg	β Deg	β Min	i Deg	β Deg	β Min
—3	4	16	0	2	45	6	3	22
—2¾	3	59	+½	2	43	7	3	35
—2½	3	45	1	2	42	8	3	49
—2¼	3	33	1½	2	43	9	4	4
—2	3	23	2	2	45	10	4	19
—1¾	3	14	2½	2	47	11	4	35
—1½	3	6	3	2	50	12	4	51
—1¼	3	0	3½	2	54	13	5	8
—1	2	55	4	2	58	14	5	25
— ½	2	49	5	3	9			

VALUES, AT A SERIES OF VALUES FOR ANGLE OF ATTACK i FOR β , FOR " TEST SECTION " OF " STANDARD " BLADE

$$\beta = \tan^{-1} \frac{K_D}{K_L}$$

FOR ANY OF i FROM —2° TO +14°, FOR " TEST SECTION,"

$$K_R = (200 + 0006\, i_M)$$

i_M = Numerical Value of i in Minutes

$$K_R = \sqrt{K_L^2 + K_D^2}$$

These properties, for the " Test Section," are estimated from Tests on a Model Aerofoil of " Clark Y " section at a high Reynolds No , so should rule out " scale effect " , but, when the speed of an aerofoil, relative to the surrounding air, rises *above* say 600 ft per sec , there is a tendency to increase of Drag Coefficient and decrease of Lift Coefficient, the opposite to what we usually expect from " Scale Effect ", this entails that beyond certain tip speeds the efficiency of an airscrew begins to decrease, which point I attempt to deal with later on

We have now arrived at the following conclusions for this " standard " form of blade —

A close approximation to the Efficiency given by the " Simple Blade Element Theory," is achieved by calculating the value $\frac{\tan \alpha}{\tan (\alpha + \beta)}$ for the " Test " Section, which value we shall call the " Test Efficiency " and shall denote by E_1

A close approximation to the power absorbed per blade given by the " Simple Blade Element Theory," is achieved by the value

$$55\ K_r^1 \sin (\alpha^1 + \beta^1) [(2\pi r^1)^2 + a^2]\ l^1\ \rho\ 2\pi r^1 n^3 \frac{D}{2}$$

where K_R^1 is value of K_R for " Test " Section

α^1 is value of α for " Test Section "

β^1 is value of β for " Test " Section

l^1 is chord length of " Test " Section, in ft (= 933 b_1)

r^1 is 35 D

D = diameter of airscrew, in ft

ρ = density of air in lbs mass per cubic foot

Assuming, for further simplification, that the airscrew be a two-blader of Aspect Ratio 12, and ρ be of standard " ground level " value (00237 lbs mass per cubic foot), the value becomes

$$000203\ K_R^1 \sin (\alpha^1 + \beta^1) (4\ 84D^2 + a^2) n^3 D^3 \text{ in foot lbs per sec} \quad (4)$$

for the whole airscrew

Using the letter J to indicate the value $\frac{v}{n\ D}$ ($i\ e$, $\frac{a}{D}$), and working in terms of horse-power, the value may be written

$$405\ K_R^1 \sin (\alpha^1 + \beta^1) (4\ 84 + J^2) \frac{n^3 D^5}{10^6} \ \textit{Horse-power} \quad (5)$$

Now, for all geometrically similar Airscrews, if J be contant, then will α^1, β^1, and K_R^1 also be constants, hence, the value 405 $K_R^1 \sin (\alpha^1 + \beta^1)$ (4 84 + J^2) will be a constant, and the Power absorbed will vary as $n^3 D^5$ This value 405 $K_R^1 \sin (\alpha^1 + \beta^1)$ (4 84 + J^2) we shall term the " Test Power Coefficient " and shall denote by P_C^1

Now to consider the corrections necessary to obtain from the " Test Efficiency " value, E_1, and from the " Test Power Coefficient " value, Pc^1, the actual Efficiency E, an the actual Power Coefficient, Pc, respectively, for this " standard " Blade-form Airscrew These two values give all the data required in a consideration of the Airscrew as a converter of engine power into Thrust power, for

$$\text{H P absorbed by Airscrew} = Pc \times \frac{n^3 D^5}{10^6} \quad (6)$$

and

$$\text{Efficiency of Airscrew, } E = \frac{\text{Thrust} \times v}{\text{H P absorbed} \times 550}$$

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Whence Thrust in lbs

$$T = \frac{Pc \times \frac{n^3 D^5}{10^6} \times 550}{v} \times E \qquad (7)$$

where v = speed along axis of airscrew in ft per sec
n = revs per second of airscrew
D = dia of airscrew in ft

Firstly, to consider corrections for Efficiency —

We have seen that the " Test " efficiency, $E_1 = \frac{\text{Tan } \alpha}{\text{Tan } (\alpha + \beta)}$

for the " Test " Section, so it follows that, if β be constant, the greater the value of α the higher the value of E_1, the maximum being reached at a value of about 45° for α

Assuming the optimum value for β of 2° — 42′ which entails a value of 1° for $\imath$, we obtain —

α	E_1	P/D	$\frac{a}{P}$
10°	782	428	907
20°	870	845	948
30°	900	1 322	962
40°	909	1 912	965
45°	911	2 278	966

If $\imath$, and therefore β, be constant, however, it is obvious that the smaller the value of $\frac{P}{D}$, the greater will be the " interference " effects upon the blade Again, for the *same* airscrew, the smaller the value of advance per rev , the greater will be the " interference " effects If true Efficiency of Airscrew, E = " Test " Efficiency, E_1, multiplied by an empirically determined correction factor, e, it follows that if $\frac{P}{D}$ be constant, the smaller the value of $\frac{a}{P}$ the smaller will be the value of e, whilst if $\frac{a}{P}$ be constant, the smaller the value of $\frac{P}{D}$ the smaller will be the value of e

In Plate VII is given a series of curves for values of " Efficiency Correction Factor " e , these apply strictly to a two-bladed Airscrew of Aspect Ratio 12 They have been arrived at by using the data given in the 1922-3 Report of the Aeronautical Research Committee upon Wind Tunnel Tests on a Family of Air-screws , I calculated, from the data on Aerofoil Tests, the value of K_R and of β for the " Test Section," and thence calculated the " Test Efficiency " values, at a series of values of J, for each of the series of two-bladed airscrews of blade-breadth = 082 D From the data on tests of the airscrews themselves I then obtained (employing a calculated allowance for Boss Drag) the actual *Blade* Efficiencies for the series at the same values of J , e was then arrived at by dividing actual Blade Efficiency by corresponding " Test " Efficiency

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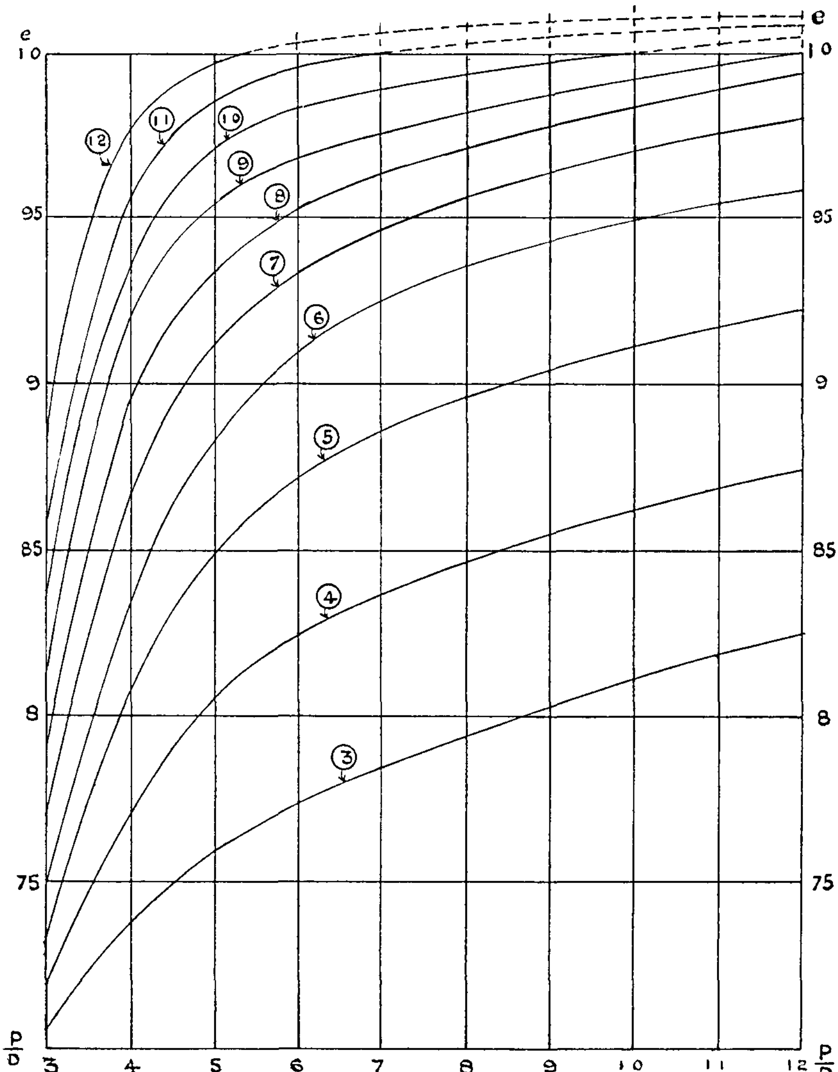

CURVES OF 'EFFICIENCY CORRECTION FACTOR' e
ON A BASE OF VALUE OF P/D   NOS ATTACHED TO
CURVES ARE VALUES OF a/p

$$E = (E' \times e)$$

E = TRUE EFFICIENCY $E' = \frac{\tan \alpha}{\tan(\alpha + \beta)}$ FOR TEST SECTION

PLATE VII

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I attempted to evolve an Equation which would give the value of e in terms of $\frac{P}{D}$ and of $\frac{a}{P}$, but could not achieve anything which would give reasonably accurate values whilst remaining comparatively simple in form

Number of blades, of course, affects the value of e, the greater the number of blades the lower the value of e, but I propose to consider two-bladed airscrews only in this paper

Aspect Ratio (value of diameter of Airscrew divided by maximum blade-breadth), also affects the value of e, the higher the Aspect Ratio the higher the value of e But, since the Aspect Ratio will lie between say 10 and 14 for practically all requirements, and the change in Efficiency for this range is quite small, I propose to consider this factor as negligible

Alteration of blade-section of Airscrew would probably affect the value of e, the values given in these curves are supposed, as before stated, to be strictly applicable to the " standard " blade form previously defined If a thinner blade form were employed, there would probably be slightly less " interference " effect on the blade, whence e would be rather higher, apart, of course, from the alteration in " Test " Efficiency due to alteration of form of " Test " Section But the effect is hardly worth considering within the limits of accuracy aimed at in these Notes

Secondly, for the " Horse-power Coefficient," Pc Here we are in the fortunate position of not requiring corrections at all, that is to say —

$$405\ K_R^1 \sin(\alpha^1 + \beta^1)(4\ 84 + J^2)$$

gives, to a reasonably high degree of accuracy, the " Horse-power Coefficient " for a two-bladed airscrew of 12/1 aspect ratio and of " standard " form of blade, for any value of $\frac{P}{D}$ or of $\frac{a}{P}$, when $\rho = 00237$, Pc, of course varies directly as does air density, ρ The reason for this fortunate state of affairs is, of course, that the inaccuracies of the " Simple Element Theory " formula tend to wash one another out For instance, increase of " interference " on the blade tends to decrease K_R, but to increase β

As regards the effect of blade-breadth, Power-absorbed varies approximately as does blade-breadth at high values of $\frac{a}{P}$, but for low values of $\frac{a}{P}$, increase of blade-breadth does not give a proportionate increase of Power-absorbed

For the " static " condition for example (when $\frac{a}{P} = 0$), the power absorbed by a blade of maximum breadth = 07 D is about 79 of the power absorbed by a blade of maximum breadth = 10 D

In the Table of Plate VIII is given, against a series of values of $\frac{a}{P}$, the values of power-absorbed by various blade-breadths assuming unit values for a blade breadth of 10 D These values have been arrived at after consideration of data on tests of Model Airscrews, and may be taken as reasonably accurate

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PLATE VIII

$\frac{a}{P}$	b_1/D									
	10	0967	0933	09	0867	0833	08	0767	0733	07
0	1 000	987	970	950	927	902	875	847	819	790
3	1 000	978	955	930	903	875	846	816	786	756
4	1 000	976	951	924	896	867	837	807	776	744
5	1 000	974	947	919	890	860	829	798	767	734
6	1 000	972	943	914	883	852	821	790	758	725
7	1 000	970	940	909	788	846	814	782	750	717
8	1 000	968	937	905	873	840	807	775	743	710
9	1 000	967	934	902	869	836	803	770	737	704
1 0 and over	1 000	967	933	900	867	833	800	767	733	700

RELATIVE VALUES OF POWER ABSORBED DUE TO VARIATION OF b_1/D FROM 10

In this consideration of wooden airscrews I regret that I have had to omit the effect of metal sheathing, because I have no reliable data on this point One would expect the presence of the added metal sheath to decrease the efficiency, and increase the Power-absorbed, because the presence of the sheath, however thin and carefully fastened on, must to a certain extent spoil the shape of blade-section at and near the blade tip No model tests are available on this point, to my knowledge, and full-scale tests with the same airscrew, before and after sheathing on the same aeroplane, are inconclusive because of the practical impossibility of reproducing conditions with sufficient accuracy One would like to see the matter investigated on the Spinning Tower at Milton

It remains to consider the effect of very high tip speeds Report No 207 of the U S A National Advisory Committee on Aeronautics gives a series of tests at very high air-speeds on a series of aerofoil models of characteristic airscrew-blade sections From these tests it would appear that, at speeds above about 550 ft per sec , increase of air-speed tends to produce a slight decrease of K_l and a considerable increase of K_D , the thicker the section and the greater the angle of attack, the more pronounced is this evil effect

Using the data given in this Report, I have evolved the distinctly approximate method of dealing with high Tip Speeds given on Plate IX In this Plate is a Table of values of $\delta\beta^1$, the necessary percentage increase of β for the "Test Section," corresponding to a series of values of Tip Speed of Airscrew, v_T The Tip Speed v_T is, of course, equal to $n\sqrt{(\pi D)^2 + a^2}$

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The reasoning employed in achieving this suggested method might be called drastically elementary , to save time I do not give it here, but am prepared to do so should it be desired I suggest therefore, that the values of K_R and of β for the " Test Section " be found (as before described) for any particular case, that if the Tip Speed exceed 700 ft per minute, say, the value for β be increased as per Plate IX, and the Efficiency and Horse-power-absorbed then calculated by the methods previously described

PLATE IX

v_T	$\delta\beta_{14}$
610	0
620	1
630	4
640	95
650	1 8
660	2 8
670	4 0
680	5 3
690	6 8
700	8 5
710	10 3
720	12 3
730	14 5

i^1	$f\delta\beta_{14}$
—2°	15
0	20
+2°	26
4°	33
6°	41
8°	50
10°	61
11°	68
12°	76
13°	86
14°	1 000

v_T = Tip Speed, in Ft per Sec , $= n\sqrt{(\pi D) + a^2}$
$\delta\beta_{14}$ = Percentage increase, of β for " Test Section when $i^1 = 14°$
$f\delta\beta_{14}$ = Fraction of $\delta\beta_{14}$ for Corresponding Value of i^1
i^1 = Angle of Attack for " Test Section "

$$\delta\beta = (\delta\beta_{14} \times f\,\delta\beta_{14}) \text{ per cent}$$

N B —Above 730 for v_T, $\delta\beta_{14}$ increases linearly as and is v_T equal to [14 5 + 24 (v_T —730)]

TABLES FOR DETERMINING INCREASE OF β FOR " TEST SECTION AT HIGH TIP SPEEDS
THESE APPLY TO " STANDARD " BLADE

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So far I have considered only the airscrew by itself, and at that as consisting of blades only, but the airscrew of an aeroplane is working in close proximity to a body having a cross sectional area from 10 to 20 per cent, say, of the disc-area of the airscrew The presence of the body tends to decrease the mean speed of the air flowing through the airscrew and hence to increase both the Thrust, and the Horse-power Absorbed, to some values higher than would obtain for the airscrew working alone One would expect the mean slowing down of the air-speed through the airscrew disc to be roughly proportional to the square-root of the drag of the body, a few experiments carried out in the Wind Tunnel of the Bristol Aeroplane Co appear to bear out this assumption The subject is unfortunately a very complicated one, a small cross section body of bad form may have as large a drag as a body of much greater cross section but of good form, the latter, however, would probably have the greater effect on the airscrew characteristics

However, as I am trying to give simple methods, with of course, the accompanying risks of inaccuracy, I suggest the following means for determining the effect of the body on a tractor airscrew —

Suppose a_B be the cross sectional area of the body in a plane parallel to that of the airscrew disc, and at a distance behind it of $\frac{1}{4}$ D, and A be the disc area of the airscrew, A, of course, is equal to $\frac{\pi D^2}{4}$

PLATE X

$\frac{a}{P}$	δp
0 to 60	0
82	2 65
84	2 92
86	3 22
88	3 55
90	3 90
92	4 28
94	4 70
96	5 15
98	5 65
1 00	6 21
1 01	6 52
1 02	6 85
1 03	7 22
1 04	7 61
1 05	8 03
1 06	8 48
1 07	8 97
1 08	9 50
1 09	10 06
1 10	10 65

From $\frac{a}{P} = 60$ to $\frac{a}{P} = 80$

$$\delta p = 12 \left[\frac{a}{P} - 60\right]$$

a = Advance of Aeroplane per Rev of Airscrew in feet

P = Face Pitch of Airscrew in feet

δp = Percentage Increase of Power absorbed by Airscrew due to Body, when

$$\frac{a_B}{A} = 10$$

δp varies Linearly as $\frac{a_B}{A}$

a_B = Cross Sectional Area of Body in sq ft in a Plane Parallel to the Airscrew Disc, and at a distance $\frac{D}{4}$ feet aft of Airscrew Disc

A = Disc Area of Airscrew, $= \frac{\pi D^2}{4}$ sq ft

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In Plate X is given a Table of values for δp, increment of Horse-power Absorbed, at a series of values of $\frac{a}{P}$ These values of δp are the percentage increase of Horse-power absorbed by an airscrew, running at the corresponding values $\frac{a}{P}$ (advance per rev divided by Pitch), when the previously-defined body cross-section, a_B, is one-tenth of the disc area of the airscrew Further, it is assumed that the value of δp varies linearly as does the value $\frac{a_B}{A}$

This method of computing increase of Power absorbed due to Body, is the most helpful one of any simplicity that I could evolve from the data given by the Advisory Committee for Aeronautics on Wind Tunnel tests of Model Airscrews running in front of Bodies

I suggest considering the cross section of the Body at $\frac{1}{4}$ D aft of the airscrew disc, because one must fix on *a* position, and it seems reasonable to assume that the size of the Body up to that point will materially affect the airflow through the airscrew, whilst further aft than that point the size of the Body will have progressively less and less effect Of course, if there be any local projections, (as say the cylinder heads of a radial engine), ahead of or close behind, this proposed section, the frontal area of such projections should be added in

I suggest therefore that the increase of Power absorbed, due to Body, be found in this manner and that the Efficiency be considered as not affected, in other words, both Power-absorbed and Thrust will undergo the same percentage increase

Regarding now the effect of the Airscrew on the Body As stated several times before, I assume throughout these Notes that the Airscrew consists of Blades only (as regards its characteristics) and that the airscrew hub (complete with spinner if fitted) is part of the Body If now K_S be the drag coefficient fo rall parts of the aeroplane, including airscrew hub, which lie in the slip stream, v (ft per sec) be the speed of the aeroplane, and v_S (ft per sec) be the mean slipstream speed, then the increment of aeroplane Drag due to slipstream will be

$$(v_S^2 - v^2) K_S \rho \text{ in lbs} \quad (8)$$

But if T be the airscrew thrust in lbs , and A be the area of the Airscrew Disc in sq ft , then

$$T = \tfrac{1}{2} \rho A (v_S^2 - v^2) \quad (9)$$

$$\text{or} \quad (v_S^2 - v^2) = \frac{2T}{\rho A} \quad (10)$$

Hence, from Equations (8) and (10), increment of Drag due to slipstream, or "decrement of Thrust" (as it may perhaps more conveniently be regarded)

$$\delta T = \frac{2 T K_S}{A} \quad (11)$$

Finally, to consider a quick and reasonably accurate method of estimating the strength of this "standard" wooden airscrew blade

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Any section of a blade of an airscrew in action is subjected to a centrifugal pull, due to mass of the blade outside the particular section, to a Bending Moment due to the air-load on the blade outside the particular section, and generally, to a Bending Moment due to " offset " of the centrifugal pull These three divisions of the main forces I shall term —

" Centrifugal Pull,"
" Air-load Bending,"
" Centrifugal Bending "

There are, of course, in addition, shear and torsion on any section, but their stress values are comparatively unimportant, at any rate in a blade of this " standard " form

I propose to disregard " Centrifugal Bending " altogether, because the flexure of the blade under the air load almost certainly causes the " Centrifugal Bending " to relieve to some extent the "Air Load Bending " , for the same reason it would be extremely hard to estimate the " Centrifugal Bending " at all accurately

Now Sections "A," " B," " C," " D," and " E," divide the blade-length from airscrew axis to blade tip, into six equal divisions These sections are all of constant proportions with respect to the maximum blade-breadth b_1 , so for each of these five sections we can express the area as a constant times b_1^2 and the moduli as constant times b_1^3

PLATE XI

Section	"A"	"B"	"C"	"D"	"E"
A_C	749	718	714	717	722
x_C	466	443	434	437	441
y_C	493	458	424	407	408
I_C	540	530	558	568	570
A/b_1^2	1962	1674	1261	0845	04184
I/b_1^4	001562	000660	000257	0000842	0000162
Z/b_1^3	00846	00481	00252	001154	000358
Z_T/b_1^3	00872	00569	00343	00168	000518

PROPERTIES OF " STANDARD " SECTIONS b_1 =Maximum Blade-Breadth in inches

Plate XI gives the values, for these five sections, of Coefficient of Area A_C, of Coefficients of co-ordinates of Centroid, x_C and y_C, of Coefficient of minimum Moment of Inertia, I_C, of Area expressed in terms of b_1^2, of minimum Moment of Inertia expressed in terms of b_1^4, of " compression " Modulus, Z_C, expressed in terms of b_1^3, and of " tension " Modulus Z_T, expressed in terms of b_1^3 The " coefficients " of Area and of minimum Moment of Inertia are the fractional values which the area of the section and the minimum Moment of Inertia of the section are of the corresponding values for the circumscribing rectangle

x_C, the coefficient of horizontal co-ordinate of centroid, is the fractional value of horizontal distance from centroid to nose of section divided by chord-length of section, whilst y_C, the coefficient of vertical co-ordinate of centroid is the fractional value of vertical distance from centroid to bottom of section divided by total thickness of section

I give these coefficient values as they are of use for direct comparison of different sections and in rapid approximations for other sections

What I have termed the "compression" Modulus is, of course, the value of minimum Moment of Inertia divided by vertical distance from centroid to top of section, whilst the "tension" Modulus is value of minimum Moment of Inertia divided by vertical distance from centroid to bottom of section

As regards firstly the stresses across these five sections due to Centrifugal Pull —

For each of these sections we can express the volume of the blade, from section considered to blade-tip, as a constant times $b_1^2 \times$ D, and we can express the distance of the centroid of this volume from the axis of rotation in terms of D , hence, if we know the density of the material, we can express the Pull across each of these five sections as a constant times $b_1^2 \times D^2 \times n^2$, and hence the unital tensile stress, t_1, as a constant times $D^2 \times n^2$, n being the revs per second

As regards the stresses due to Air-load Bending I begin by making some assumptions which enormously simplify the calculations whilst providing, I consider, sufficient accuracy for practical purposes

Firstly, it is assumed that the total Air-load on each blade is equal to the total airscrew thrust divided by the number of blades , this, of course, is a slight under-estimation

Secondly, it is assumed that the grading of this air-load along the blade is of constant proportions , this, of course, is slightly inaccurate for all but one particular case, but the inaccuracy is not of a high percentage value, and I have taken care to assume a constant grading that is unlikely to give appreciably smaller bending moments than would actually occur under the worst conditions

Thirdly, it is assumed that, at each section, the bending-moment (due, of course, to that part of the total air-load which lies outside the section), acts along the minor axis of the section , this, of course, is a slight over-estimation

Having, then, for any particular case with any particular airscrew, estimated the Efficiency and the Horse-power absorbed, we can thence obtain the Thrust in lbs , and thence the air-load per blade in lbs , L

As we have assumed constant grading along blade for L we can express, for each of the five sections, the value of Bending Moment due to air-load as a constant times L $\times$ D, and hence (knowing the moduli of these sections in terms of b_1^3) can express the unital compressive and tensile stresses as constant times

$$\frac{L \times D}{b_1^3}$$

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PLATE XII

Section	"A"	"B"	"C"	"D"	"E"	
t_1	01650	01553	01395	01084	00643	$(\times D^2 n^2)$
M	3 120	2 130	1 224	521	106	$(\times L D)$
t_2	359	374	358	310	204	$\left(\times \frac{LD}{b_1^3}\right)$
C_1	368	444	486	451	296	$\left(\times \frac{LD}{b_1^3}\right)$

VALUES, FOR "STANDARD" SECTIONS OF —

t_1, Tensile Stress due to Centrifugal Pull, in lbs per sq inch *
M, Bending Moment (assuming Constant Grading of Air-load), in inch lbs
t_2, Tensile Stress, due to M, in lbs per sq inch
C_1, Compressive Stress, due to M, in lbs per sq inch

D = Dia of Airscrew, in feet
n = Revs per Second
L = Air-load per Blade, in lbs
b_1 = Maximum Blade-Breadth, in inches

In Plate XII are given, for each of the five sections, values of t_1, tensile stress (in lbs per sq inch) due to centrifugal Pull assuming that the airscrew be made of walnut, of M, bending moment (in inch lbs) due to air-load, of t_2, tensile stress (in lbs per sq inch) due to M, and of c_1 compressive stress (in lbs per sq inch) due to M

t_1 is expressed in terms of $D^2 \times n^2$, whilst t_2 and c_1 are expressed in terms of

$$\frac{L \times D}{b_1^3}$$

The maximum unital compressive stress at any section is obtained, of course, by subtracting t_1 from c_1, whilst the maximum unital tensile stress is obtained by adding t_1 to t_2

$(c_1 - t_1)$ should not exceed 2,500 lbs per sq inch and $(t_1 + t_2)$ should not exceed 4,000 lbs per sq inch

Now you will have noted that t_1 depends simply on $(D^2 \times n^2)$ and is constant for all values of b_1, but c_1 and t_2 are reduced by an increase of b_1, hence b_1 is the value, for any airscrew, which must be adjusted so as to attain the desired maxima for the unital stresses

Further, we saw that if $\frac{v}{n D}$ be constant, Thrust, and therefore air-load, is a constant times

$$(Pc \times n^2 \times D^4 \times E)$$

*Assuming Materiel of a Density of 0226 lbs per cubic inch

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This result is obtained by multiplying the equation No 7 for Thrust, given on Page 00, by $\frac{v}{n\,D}$ But since Pc varies approximately as does blade-breadth, and since we may disregard the small change of E due to small changes of blade-breadth, we see that air-load is a constant times $(b_1 \times n^2 \times D^4)$, and therefore unital stress due to air-load is a constant times $\frac{(n^2 \times D^4)}{b_1^2}$

Hence it will be seen that for any particular airscrew, for any constant value of $\frac{v}{n\,D}$, all the fibre stresses vary as $(n^2 \times D^2)$

I have carried the simplification of strength determination a step further by assuming that a walnut airscrew is stressed under " climbing conditions," that the value of $\frac{v}{n\,D}$ is, under " climbing conditions," equal 6 of the value of $\frac{P}{D}$ that the maximum compressive stress is to be 2,500 lbs per sq inch, and the maximum tensile 4,000 lbs per sq inch under these " climbing conditions "

In Plate XIII is given, for a series of values of $(n \times D)$, and a series of values of $\frac{P}{D}$, the necessary values for ratio of maximum blade-breadth to diameter which will entail these maximum stresses under these assumed " climbing " conditions , the figures refer of course to two-bladed airscrew made of walnut with blades of " standard " form

PLATE XIII

$(n \times D)$

$\frac{P}{D}$	100	150	200	250	300
5	0475	0609	0718	0807	0910
6	0494	0633	0746	0838	0946
7	0511	0655	0772	0867	0979
8	0527	0675	0795	0894	1008
9	0541	0693	0817	0918	1036
1 0	0554	0710	0837	0940	1061
1 1	0565	0725	0853	0960	1083
1 2	0574	0737	0868	0977	1101

Walnut Airscrews

Table of Values for $\frac{b^1}{D}$ $\frac{\text{Maximum Blade-Breadth}}{\text{Diameter of Airscrew}}$ Requisite to give a Maximum Stress of either 2,500 lbs per sq inch Compressive, or 400 lbs per sq inch Tensile, when

$$\frac{v}{nD} = 6\,\frac{P}{D} \quad (\text{or } a = 6P)$$

This being assumed to represent Average Normal Climbing Condition

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To arrive at these figures I calculated values for air-load and for stresses by the methods previously described, adjusting the value of b_1 so that the maximum stresses (of 2,500 lbs per sq inch compression of 4,000 lbs per sq inch tension) were just realised at some one of the five sections

It is worth noting that when n D is below about 250, the limitation is that of compressive stress at Section " C " but that when n D is above about 250 the limitation is that of tensile stress at Section " B ", but there is little in it, and the stresses in Sections "A" and " D " are very much of the same value, so my previous statement as to the proportions of this " standard " blade being about correct for strength, under average conditions, seems justified

The values of requisite blade-breadth as given in Plate XIII contain further approximations (and therefore further possibilities of error in unsuitable cases), so I suggest that having tentatively fixed upon b_1 by using Plate XIII, the strength be then checked (by the methods previously outlined) under the correct conditions for the particular case

Finally for a very brief consideration of metal airscrews

In addition to the fact that this paper is already long enough, I must be very brief on the subject of metal airscrews, because I have not yet had time (nor yet been forced by necessity) to attempt any serious investigation of their characteristics Being convinced, however, that wooden airscrews will be entirely superseded by metal ones in a few years, I shall have to get down to the job in the immediate future Here are a few general statements with little or no argument in their support

Firstly, metal airscrews will supersede wooden ones because they are more reliable, more durable, and can be made more accurately They are also (speaking generally) more efficient Though not always to the extent that would appear to be imagined

Secondly, I believe that the most promising form of metal airscrew is one with the solid blades made of aluminium or magnesium alloy, but I am not certain that the claims for solid alloy steel blades should be disregarded

As regards Efficiency, an airscrew with solid metal blades is generally more efficient than a wooden one, because the section can be somewhat thinner (especially towards the root of the blade), because the aspect ratio can be somewhat higher, and because the tips and the trailing edge can be " fined off " very much better, this is probably as important as any of the other reasons But there is no reason to expect great increase in efficiency except at very high tip-speeds, for one must remember that the sections of a wooden airscrew for the outer half of the blade (which does over 80 per cent of the work) are of pretty efficient aerofoil forms Further, owing to its sections being thinner, to absorb the same power at the same value of advance per rev, a metal airscrew must be of somewhat greater diameter, or greater pitch, or greater blade-breadth than a wooden one, and such increases tend in themselves somewhat to reduce efficiency Given two airscrews, one metal and one wooden, both of the same diameter, both designed to turn at the same revs on the same aeroplane at maximum level speed (this being a normal limiting condition), it is almost certain that the metal propeller will be from say 2 per cent

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to 8 per cent more efficient than the wooden one at top speed, but, at *climbing* speed, it is quite possible for the wooden airscrew to be more efficient than the metal one

It is for airscrews of low pitch-diameter ratio, and of high tip speeds that the metal type scores most decidedly in efficiency

DISCUSSION

The CHAIRMAN Captain Barnwell has dealt with a complex subject, complex because unless one is careful there are so many variables in airscrew design, and so many corrections to be taken into account His paper shows how, with systematic design and a careful elimination of many of these variables, also a close comparison between simple theory and actual model tests, airscrew design can be reduced mainly to a question of tables and charts

Of course, if one had one week to design a wooden airscrew and the next week a hollow steel airscrew, and the next week a solid metal one, the method he has described would be somewhat inadequate, but if, as is usually the case, one is designing the same type, and just making variations of pitch and linear dimensions, then the method he has outlined is good and time saving He sticks to the simple old Blade Element theory, and I am bound to agree with him, and have often wondered that the simple Blade Element theory does give very accurate results It is my experience that theory does give very close results of the power absorbed, but of course not quite such correct results in efficiency The proof of the pudding, however, is in the eating, and, evidently, Captain Barnwell, having mixed it and cooked it, has tasted it and decided that, at any rate, if it is not delicious it is extremely wholesome and sustaining fare

I wish he had said something about the more modern vortex theory of airscrew design, which I have tried to a considerable extent recently I can say that it does give extremely close results without any corrections whatever, except those due to body drag and tip speed

I must thank Captain Barnwell for drawing attention to U S A Report 207 I was rather surprised to hear that the lift coefficient decreases above tip speeds of about 500 or 600 feet per second My gospel of tip speed is R and M 884 That Report seems to show the lift coefficients rising from even low speeds The increase is very gradual at first, reaches a maximum at 0 85 the speed of sound, and then starts to decrease

Mr GRIFFITHS There is one point I should like to refer to regarding the twist of the propellers Captain Barnwell says that he disregards centrifugal bending entirely on the ground that the flexure of the blade under the air load causes centrifugal bending to relieve the air load bending to some extent, and that it is difficult to estimate centrifugal bending at all accurately It seems to me it would probably be a safer procedure to calculate final stresses on upward deflection Deflection relieves stresses, but one should assume that, whereas centrifugal bending does so, it cannot be neglected I believe this system has been adopted at Farnborough On solid metal propellers deflection becomes much more important, and you cannot neglect it

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The method adopted to estimate deflection is very laborious You guess the amount which has deflected, and from this you get the corresponding centrifugal bending If this does not work you try it again In practice this can be carried out comparatively quickly The method of final stressing is quite considerably varied for each design

In conclusion I would thank the lecturer for an exceedingly interesting paper

CAPTAIN SAYERS It is difficult for anyone who has not had experience of aircraft design, to discuss this paper I have been trying to compile the facts of the problem into a simplified form suitable for everyday use I am struck by the immense amount of work Captain Barnwell has done, and I am also struck by the extremely simple process to which he has succeeded in reducing the Drawing office design of airscrews It is possible to get out a design if you have access to the N P L reports on the theory of airscrews, and also the American reports, but you may have to make a slight calculation because you find your airscrew falls between the two systems

The most valuable point of this paper is the manner in which Captain Barnwell has reduced the stress calculations to a very practical problem If you tackled the job of stressing an airscrew from first principles, it would take you about as many days as his system takes minutes It will therefore be of immense value to all aeronautical designers You never know when you may want the kind of data which this valuable paper contains

Mr BRAMSON I am a child in these matters, and I feel it is almost sacrilege to try to say anything at all on the subject of airscrew design in the presence of the Lecturer and the Chairman, so I will confine myself merely to asking questions

Captain Barnwell mentioned the fact that at very high tip speeds the lift decreases and the drag increases Has that anything to do with the speed of sound ? If so, does the fact of reaching the speed of sound affect the air flow around the tip, and in what manner ? One can imagine that such an intense vacuum is created behind the blade tip, and that the normal flow is thereby spoilt

Captain Barnwell also referred to body interference, which I suppose is the only type of interference that can be considered in connection with airscrew problems There is, however, another kind of interference which affects the problem, namely that which is due to the fact that a large and important part of the wing which is designed to receive virgin air flow, receives a spiral one instead I think the effect of that is so complex that it defies computation I should like to hear if there are any facts available in this connection

I have been very interested in variable pitch airscrew problems, and I have come up against certain very difficult questions If you vary the pitch of an airscrew by simply rotating the whole blade, you do not really vary the true pitch, because one should at the same time vary the twist of the blade, and I should like to know whether the lecturer or the chairman has any figures as to the loss of efficiency caused by the pitch variation not being really accurate In that connection I am going to be inquisitive and ask one or two more questions

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There are two ways of operating variable pitch propellers—automatic variation and hand operation Is any experience available as to which is the more successful of the two methods ?

Re the stresses in airscrews is there any serious aerodynamic objection to inclining the blades a few degrees forward in such a way that the stresses due to centrifugal forces are just about equalised by bending moments due to the air forces ?

I must agree with Captain Sayers as to the admiration one feels for the immense amount of work represented by this paper, and although I confess that during the course of a lecture it is very difficult to follow so much condensed mathematics, yet I shall regard this paper as a compendium of airscrew design, and value it ccordingly

WRITTEN DISCUSSIONS

Mr DOWTY I have been fortunate in having read through a copy of Mr Barnwell's paper, which I found of considerable interest, particularly that dealing with high tip speeds

In ultra high speed racing machines, tip speeds of 1,120 feet per second have been reached and working out the increased value of β for Mr Barnwell's " Test Section " and taking an angle of attack of 1 5°, I find that the percentage increase is approximately 33 per cent , and this figure is in very good agreement with actual results

There is one point I would like to raise regarding the stressing of metal airscrews In the case of wooden airscrews the air loading and centrifugal bending are taken into account, but deflections of the blades are not considered, because the sections are generally of such a thickness that the deflections are small and can be ignored In the case of the metal airscrew where the blades are necessarily thin, these deflections can no longer be ignored, because the section modulus is exceedingly small in comparison to that of a wooden airscrew I believe this is a matter that is likely to make the stressing of a metal airscrew a somewhat complex matter, and if Mr Barnwell can make any suggestions regarding a straightforward procedure for ascertaining the maximum stresses occurring in the blades, when taking these deflections into account, I should be very pleased

Mr TINSON Referring to Plate 1, I should like to ask what is the value of the angle of attack ι, when the propeller has been designed as a general purpose one, by which I mean one which is pitched not for maximum speed level nor for maximum rate of climb, but the best all round results

I presume that in the case of a racing machine, one would commence with the forward velocity " a " equal to the estimated maximum level speed of the aeroplane, and that the angle ι would be that corresponding to the maximum L/D for the section used, whilst to obtain the greatest possible rate of climb, the forward speed " a " selected would be that corresponding to the estimated " best climbing speed "

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If my assumption be correct, a compromise would have to be made for machines other than record breakers, and some speed value for "a" between climbing speed and maximum speed would be selected to which would be added ι for maximum L/D, in order to determine the geometrical face pitch P

CAPTAIN BARNWELL'S REPLY TO THE DISCUSSION

In reply to Mr Griffiths, I consider it safe to disregard " centrifugal bending " in a Blade of the " standard form " which I have suggested, as it is practically certain that the moments due to centrifugal force and deflection of Blade will relieve those due to "Air-load Bending " In this respect I fear that the particulars I have given for the " Standard Blade form " have not been sufficiently complete Axis Z—Z in Fig 1, Plate II, I term the " Blade Axis ", it is of course at right agles to the axis of rotation , the centre points of the " datum lines " of Sections "A," " B," and " C," lie *on* the " Blade Axis," whilst the centre points of the " datum lines " of Sections " D," " E," and " F," and the tip of the Blade, have a progressive forward " tilt " , that is to say, these points remain in the fore and aft plane containing the " Blade Axis " but lie *ahead* of the " Blade Axis " by the following fractions of the maximum Blade-breadth —

Centre point of " datum line " of Section " D "	013
Centre point of " datum line " of Section " E "	023
Centre point of " datum line " of Section " F "	028
Blade Tip	033

The " datum line " for any section is, of course, the line (shown dotted in the Fig of Plate IV), from which the " offsets " (Table of Plate IV) are given

I agree that it would be more satisfying to calculate as well the alteration in the stresses caused by deflection, but do not think that it would be " safer "

I also agree that although the calculation for these alterations is of a laborious " hit-or-miss " type, yet practice and experience would tend to shorten and simplify the procedure

I agree that with solid metal blades of thin section the deflection might be of greater amount, but think that in this case also neglecting the deflection in stress calculations should be an error on the " safe " side , possibly neglecting deflection might lead one to design an unnecessarily heavy blade

I imagine that with thin solid metal blades our greatest troubles will come from blade tip " flutter "

In reply to Mr Bramson, I believe that the progressive decrease in Lift Coefficient and increase of Drag Coefficient which occur above a certain speed are due to *compression* of the adjacent air more and more upsetting the air flow round the blade I do not think that the speed of sound has any special significance other than that at this speed the effect has become of very great magnitude

I do not consider that the rotation of the slipstream has any appreciable effect on the efficiency of the wings

Regarding Air-screws of Variable Pitch Firstly, I consider that, speaking loosely, variation of pitch is not required for normal non-supercharged engines It must be borne in mind when considering variable-pitch Airscrews, that a certain

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loss of efficiency at the blade root must necessarily be incurred, that the Airscrew must necessarily be considerably heavier, and that it is very difficult to attain the same degree of reliability as is attained in a " fixed " blade

With regard to varying the pitch by rotating the whole Blade about its axis this is, within limits, quite a satisfactory procedure Experiments carried out on a " Family " of Airscrews, the results of which are given in the 1922-3 Report of the Aeronautical Research Committee, sufficiently prove this

It must be remembered that an Airscrew of " true pitch " has a constant " angle of attack " for one value of v/nD only, for any other value the " angle of attack " varies all along the Blade

With regard to operating a variable pitch Airscrew, speaking personally, I should much prefer to do this by hand, and not to have to trust to " automatic " mechanism , but this, of course, is really a question of perfection of detail design, I am not aware that an entirely satisfactory variable pitch Airscrew of any form has yet been developed

As regards forward tilt of Blades to attain by centrifugal moments a reduction of air-loads moments I do not think any appreciable alterations of aerodynamic characteristics are involved by so doing , but it must be noted that it is impossible to achieve " balance " of these moments in any one Airscrew save under one particular set of conditions, for instance, greater tilt is required under " climbing conditions " (when revs are low and thrust high) than under "full-speed" conditions (when revs are higher and thrust lower) Further, there is a danger in giving a forward tilt to the Blade of introducing serious torsional moments

For this reason the Air Ministry recommend that little if any forward tilt be given to the Blade of a wooden Airscrew, and for this reason I have suggested a "Standard Blade Form" with a very small amount of tilt on the outer half of the blade only

In reply to Mr Dowty, I am very glad to hear that he has applied my suggested methods for tip-speed correction in a particular case, and has found it reasonably accurate , this particularly because I am not satisfied with the figures I have given I hope to be able to go over the question aagin when I am able to obtain more reliable data, and possibly to supply then a " corrigendum " sheet for my paper

I am not certain that the deflection of the Blade of a Metal Airscrew with no tilt need be greater than that of a wooden one , it is true that the moduli will be smaller because the sections are thinner, but E is greater and density greater In any case, I believe it safer to tilt forward the blade of a metal airscrew because the material is relatively much stronger to resist torsion than is wood Further, I rather fear that, with metal airscrews, limiting values of thinness of section will be imposed by considerations of blade vibration, and that we may find " in practice " a thicker section required to prevent vibration than is shown to be requisite by stressing calculations

I have been doing some work recently on solid aluminium-alloy blades, but so far have had far too little experience of these in service to feel justified in suggesting any " standard forms "

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In reply to Mr Tinson, it is rather dangerous to attempt to reply categorically to Mr Tinson's first question, as probably no one particular case would be exactly suited by a generality The procedure I should adopt myself for a " general purpose " Airscrew would be to consider what are normally the two " limiting conditions," namely —

(1) At ground level, at optimum climbing speed, revs to be the maximum *normal*

(2) At full-speed level, at some specified height (generally about 15,000 ft), revs to be the maximum *normal*

Under both these conditions I should determine the " optimum diameter " using the " ground level " equation

$$* D^4 = 4\,1 \frac{P}{n^2\, v} 10^6 \qquad \begin{cases} D = \text{dia ft} \\ P = \text{H P absorbed} \\ n = \text{revs per sec} \\ v = \text{speed, ft per sec} \end{cases}$$

(This equation is arrived at by assuming an angle of attack of 1° for the " Test Section," and using sundry approximations I do not give the calculations by which it was arrived at, as they are rather lengthy, and of no particular interest)

Of course, in case (2) the B H P must be corrected for the height, and the power absorbed by the Airscrew will be reduced in the ratio of density at the height to ground-level density

The pitch is determined for the two cases since i (see Fig B, Plate I) is 1° for the " Test Section " and will, of course, be greater for (2) than for (1)

I should then proceed to take a diameter probably mid-way between the two thus found and find the pitches requisite to achieve the two " limiting conditions " , if as is probable these were *different*, the longer pitch would have to be employed

In the case of a Racing machine the problem becomes simple,—knowing the revs , the approximate speed and the height (presumably ground level) the pitch must be such that $i = 1°$ for the " Test Section," hence the approximate diameter is given by the equation for " optimum diameter " already quoted

Unfortunately, the problem is generally complicated by questions of Body drag, of Tip Speed and, sometimes, of ground clearance , if the Body drag be abnormally high a rather larger diameter probably gives the best combination, but if the tip speed be high there is little to be gained by increase of diameter

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**N B*—This equation refers to a two-bladed airscrew, of " Standard Form " with $v_1 = D/12$ and at standard " ground level " density Dr Watts in his book " Screw Propellers for Aircraft " gives a similar equation

$$P = \frac{1\,11\ D^4\ N^2\ V}{10^{10}}$$

where P = horse-power absorbed,
D = diameter in feet,
N = Revs per minute,
V = Speed in M P H

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The CHAIRMAN I should like to refer to Mr Bramson's suggestion as to inclining the blade forward I do not think there is any aerodynamic objection to doing that, the Air Ministry objection is that it does introduce unknown and incalculable torsional stresses

Mr Bramson mentioned a point with regard to the speed of sound I do not think that speed of sound has any peculiar significance I think that what does matter is that right on the nose of your aerofoil you have a very high suction, and that this suction can never, whatever your speed, exceed atmospheric pressure

The point Mr Griffiths raised about centrifugal bending arises from the question as to how you are off-setting the blade If you are dealing with the subject from the Air Ministry point of view the matter requires no explanation, but if you are dealing with it generally there are cases where you can afford to ignore centrifugal bending

It now only remains for me to ask you to accord Captain Barnwell your very hearty thanks for having given us this very valuable paper

Mr BRAMSON We all know Captain Barnwell as an expert on airscrew design, and we know Dr Watts as the designer of the Leitner-Watts propeller It is most kind of him to have come here to-night, and I am sure you will join with me in thanking both the lecturer and the chairman for having given us such an interesting evening

The votes of thanks were passed with acclamation, and the meeting closed