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The Effect of Differing Thickness Distributions on a Propeller's Efficiency

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SUMMARY.—Calculations of the efficiency of propellers having five different thickness distributions (effects of other variants having been eliminated) have been made for forward speeds from 300 to 600 m.p.h. at 20,000 ft. It is shown that the efficiency becomes very sensitive to the thickness (particularly of the root end of the blade) as the speed is increased beyond 500 m.p.h., but that at this speed the effects of tip thickness are relatively minor provided the blade is at least as thin as, say, a modern compressed wood propeller.

1. *Introduction.*—With increase of forward speed of modern fighters, the problem of maintaining propeller proficiency, despite the high tip Mach numbers, becomes more and more severe. This problem is being met in two ways : by the use of thinner sections and also by the use of sections more suitable for operation at high Mach numbers.

Excessive thinning of the blade has, however, led in one or two cases to flutter of the propeller ; sometimes over a wide range of blade angles ; sometimes only in the take-off condition. With any further thinning flutter may well become critical, and to avoid it a great deal of experimental and theoretical work would be required.

The present note describes the results of an investigation made to determine the effect of the thickness/chord ratio on the propeller efficiency. It covers a range of forward speeds up to the highest envisaged for conventional propeller driven aircraft. Five propellers of differing thickness/chord ratio are considered, and an attempt is made to obtain the optimum conditions for each propeller. It must be emphasised that the report is, strictly speaking, confined to a comparison of propellers of varying thickness/chord ratio, other conditions being as far as possible the same.

It is clear for instance that at the highest forward speed a considerably greater power than that considered would be required to overcome the aircraft drag, and that either an increased number of blades, or an increase of solidity or diameter would be needed. This, however, should affect only the absolute values of the efficiencies given and not the relative magnitudes.

2. *Range and Method of Calculations.*—2.1. *Design Conditions.*—It was assumed that the propellers were 3-bladers of 0·092 solidity at 0·7 radius and were working at peak efficiency for the given conditions of speed. The calculations were made for a range of forward speed (V) from 300 to 600 m.p.h. (V/a from 0·426 to 0·852 where $a =$ speed of sound at 20,000 ft.). For a given power input at a given height, it is to be expected that with increasing forward speed, the optimum propeller tip speed will increase. A compromise must be adopted

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allowing on the one hand for the serious compressibility losses that would result from keeping the rotational speed constant as the design forward speed is increased, and on the other hand for the poor climb performance that would result from reducing the rotational speed sufficiently to maintain a constant tip speed. It is also to be expected that thick propellers known to have a poor performance at high tip speed would be designed to run more slowly than thinner blades. In virtue of these arguments, the calculations were made for two variations of tip speed with forward speed.

V m.p.h. ..	..	..	..	..	300	400	500	600
Low tip speed M_T	..	..	..		0.9	0·925	0·95	0·975
High tip speed M_T	..	..	..		0·95	0·975	1·00	1·025

where $M_T = \dfrac{\text{propeller tip speed}}{\text{speed of sound at 20,000 ft.}}$

It will be seen that for a propeller of given diameter, this implies that the values chosen for the rotational speed will vary with the design forward speed.

2.2. *Details of Propellers* (*other than thickness distributions*).—Since the object of this investigation was to determine the effect on the propeller efficiency of varying thickness distributions, the propellers had to be so designed that effects due to other variants were not present.

All propellers were taken to be of the same plan form and diameter. The plan form adopted was that of the de Havilland propeller P.55409B (for Spitfire II aircraft). Hence all designs were taken to be 3-bladers of normal size (the solidity at the 0·7 radius = 0·092).

The pitch distribution was determined for each propeller at each combination of forward and rotational speeds to be such that C_{LO}—the low speed lift coefficient—was constant along the blade in that condition. It has been shown 1 that this represented a close approach to the optimum distribution. The pitch distribution, therefore, not only varies from design to design but also with the design condition. This is equivalent to the assumption that given the design conditions and the thickness distribution, an attempt would be made to determine the optimum twist along the blade. This is a better assumption than taking the designs all to have the same pitch distribution which may be optimum for one t/c distribution and far from the optimum for another. (The same idea was not extended to the plan form as the effects of such change as would be practically possible in a given example are not serious enough to warrant the additional labour).

It is considered that the above assumptions are the best possible to eliminate the effects of variables other than the thickness.

2.3. *Propeller Thickness Distributions.*—The five thickness distributions considered are given in Table 1 and Figure 1. It will be seen that they are representative of an old wooden blade (I), a metal blade of moderate thickness (II), an extremely good metal blade (III), a typical compressed wood design (IV), finally what is considered to be a very conservative estimate of the thinnest practicable blade—12 per cent thick at the 0·3 radius tapering to about 5 per cent thick at the tips. This does not represent any undue thinning on modern standards (of III) at the tips but considerable root thinning rather envisages spinners of increased size over present designs. The similarity of distributions II and IV near the tips is useful in showing the relative importance of different parts of the blade (*see* para. 3. 2).

2.4. *Method of Calculation : Data Used.*—The calculation of the efficiencies of the various designs under differing conditions was made by the method of Ref. 2. The data used for the section drag characteristics were based as follows :—

(i) For thick sections (*i.e.*, for $t/c > 10$ per cent), on results of the analysis 3 of the R.A.E. tests of the Clark Y 15 per cent and Clark YM 25 per cent "constant thickness" propellers.

(ii) For thin sections, on those given in Part II of Ref. 3. These values have been shown in Part III of Ref. 3 to be optimistic for Clark Y sections, but it is considered that they represent what could be achieved with more favourable sections. (The effect of using Clark Y section data is discussed at the end of para. 3.2).

The calculations were made for each design in each speed condition over a range of values of C_{LO} (constant along the blade) in order to determine the peak efficiency and the corresponding value of $P/\sigma D^2$. To absorb other powers with similar efficiency, the basic solidity would have to be varied.

It should be noted that the efficiency values as calculated relate to performance of the blades from the 0·3 radius outward. Unless the need for increased spinner size is conceded the effect of thick sections near the roots will be greater than shown by these calculations.

3. *Discussion of Results of Calculations.*—The values of the free-air peak efficiencies calculated for the various conditions of forward and rotational speeds and for the five thickness distributions are given in Table 2 and the results are plotted for the lower tip speed range in Fig. 2 and for the high tip speed range in Fig. 3. These efficiency values are not only free-air but also are integrated from 0·3 of the tip radius outwards. Also given in Figs. 2 and 3 are corresponding optimum values of $P/\sigma D^2$.

3.1. *Interpretation of Results.*—Before drawing any conclusions from the results, it is advisable to realise their limitations. It has already been pointed out (2.1, 2.2) that the curves of efficiency against forward speed for a given thickness distribution do not represent the performance of one propeller design running at different rotational speeds. The values read off the curves at any forward speed give the efficiency that could be achieved by designing the pitch distribution to be optimum for that speed, and by absorbing the optimum $P/\sigma D^2$ for each design under those conditions. The rotational speed is also varied with the forward speed.

As would be expected from considering compressibility effects on C_L, the power loading *i.e.* $P/\sigma D^2$, for maximum efficiency increases considerably as the design speed is raised from 300 to 500 m.p.h., but beyond this speed, there is little variation (except for design IV which apart from design I, is the poorest at high speeds—in this case, the power that can be absorbed with maximum efficiency begins to fall with increasing speed). It should be added that the efficiency *vs* power input curves have very flat peaks and until the critical conditions of, say 600 m.p.h. are reached, values of $P/\sigma D^2$ over the range $0·9 (P/\sigma D^2)$ opt. to $1·1 (P/\sigma D^2)$ opt. are absorbed with negligible difference in efficiency.

It is important to note that the calculations give the relative effect of altering the thickness at any given forward speed. They must not be taken to give the relative effect of forward speed for a given thickness distribution.

As the forward speed increases, a more solid propeller will in practice be required to absorb the higher engine powers. Also the operating value of C_{LO} might have to be increased. For both of these reasons the efficiency values given here may be optimistic at high forward speeds. The above, however, does not affect the primary purpose of the calculations—to show the relative effect of differing thickness distributions.

It should also be noted that the efficiency values relate to the performance of the blade from 0·3 radius outwards. This has been done in the expectation that the need for increased spinner sizes for high speed aircraft is realised. With conventional spinner sizes, however, the effect of thick root sections will be worse than shown by these calculations.

3.2. *Effect of Thickness Distribution.*—From Figs. 2(a), 3(a), it will be apparent that the efficiency becomes much more sensitive to variations of section thickness as the speed is increased, *e.g.*, the difference in efficiency between the two metal blades II and III (see Fig. 1) is less than 1 per cent at 400 m.p.h. but is about 12 per cent at 600 m.p.h.* forward speed. It is also clear that the favourable effect of changing from distribution I (31 per cent at the roots to 7·7 per cent at the tips) to, say, distribution IV (21·9 per cent at the roots to 6 per cent at the tips) is very considerable: amounting to about 3 per cent at 300 m.p.h., 8 per cent at 400 m.p.h.* and about 30 per cent at 500 m.p.h.*   To assess the effect of further thinning, say to distribution III, it is fairest to compare distribution III at the higher tip speed and distribution IV at the lower.   The advantage of III on this basis does not appear until the speed exceeds 500 m.p.h.*— —it amounts to 7·5 per cent at 600 m.p.h.*   Therefore provided it is possible (after consideration of the climbing condition, etc.) to run at the lower rotational speeds, it is seen that there is no absolute necessity to continue thinning beyond IV or II if the top speed is of the order of say 450 m.p.h.   On the other hand, for speeds of 500 m.p.h. or more, thickness distributions approaching the "practical optimum" V are essential (particularly if spinner sizes are not increased).

A comparison of the performance of II and IV (these distributions are very similar near the tips) is also instructive.   At speeds up to 500 m.p.h. there is little to choose between them, but at 600 m.p.h. II which is the thinner blade from $r_c = 0·38$ to about $r_c = 0·9$ is the better by from 3 to 6 per cent depending on the tip speed.   This illustrates the importance of keeping all the blade and not merely the tips as thin as possible for applications at high forward speeds. Provided the tip speed can be kept down to a reasonable value (as is done in these examples) thinning say the 0·95 radius from 6 per cent to 5·5 per cent thick may have less effect than thinning the middle part of the blade by a proportionate amount.   This is because of the larger power absorption of the middle sections.

Fig. 4 indicates for the most extreme case ($M_T = 1·025$, $V = 600$ m.p.h.) the grading along the blade of the compressibility drag power loss coefficient.   It will be seen that it is appreciable all along the blade and particularly at the root.   This was realised in deriving the "practical optimum" distribution (V) in which attention was mainly directed to the root and centre sections. From the magnitude of the losses at the root end, it is clear that spinner sizes greater than the present value of $0·15D$ to $0·2D$ will be necessary at high forward speeds.

Finally, it should be repeated here that the thin tip sections have the drag characteristics given in Part II of Ref. 3.   If they had been assumed to be of Clark Y shape the effect would have been a loss of about 1 per cent in efficiency at speeds up to 500 m.p.h. for distributions II and IV, but for distributions III and V a value of 3 per cent lower than that given here (Table 2) at 500 m.p.h. and 8 per cent lower at 600 m.p.h.   This shows that if the use of Clark Y sections were contemplated for these applications, no tip thinning beyond 6 per cent would be advisable.

4. *Conclusions.*—1. The efficiency of a propeller becomes much more susceptible to changes in thickness distribution as the forward speed increases.

2. For use at high speeds (in excess of 500 m.p.h. at 20,000 ft.) some distributions such as the "practical optimum" (Table 1, Fig. 1) would be essential.

3. Provided the tip speed can be kept down to a little over the speed of sound, attention must be principally directed to thinning the root and centre sections.   At high forward speeds the gain produced by thinning the extreme tips beyond, say $t/c = 6$ per cent would not be appreciable.

4. A propeller efficiency of about 60 per cent at 600 m.p.h. at 20,000 ft. might be achieved provided the propeller was operating at its optimum disc loading and provided that its roots were carefully designed.

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* At 20,000 ft. where $a = 704$ m.p.h.

REFERENCES

No.	Author	Title, etc.
1	Lock, Pankhurst and Fowler	Determination of the Optimum Twist of an Airscrew Blade by the Calculus of Variations. A.R.C. Report 5550, January, 1942. (To be published.)
2	Conn, Lock and Pankhurst	Strip Theory Method of Calculation for Airscrews on High Speed Aeroplanes. R. and M. 2035 (October, 1945).
3	Pankhurst and Haines	Account of the Derivation of High Speed Lift and Drag Data for Propeller Blade Sections. R. and M. 2020 (August, 1945).

LIST OF SYMBOLS

a .. .. .. Speed of sound.

C_{LO} .. .. .. Low speed value of lift coefficient at a given incidence.

M_T .. .. .. $\dfrac{\text{Propeller tip speed.}}{\text{Speed of sound.}}$

p_{cs} .. .. $= \dfrac{dK_{ps}}{d(r_c{}^2)}$: Compressibility drag power loss grading coefficient.

r_c .. .. $= r/R$: fractional radius.

R .. .. .. Tip radius.

t/c .. .. .. Section thickness/chord ratio.

V .. .. .. Forward speed.

η .. .. .. Free-air efficiency. (Uncorrected for losses inboard of 0·3 radius.)

P .. .. .. Input power. (Horse power.)

σ .. .. .. Relative air density.

D .. .. .. Propeller diameter (feet).

TABLE 1

Thickness Distribution

I. Rotol propeller for Spitfire I (Jablo 3001800).
II. de Havilland propeller (metal) for Spitfire II (P.55409B).
III. de Havilland propeller (metal) for Typhoon (P.4551157).
IV. Rotol hydulignum propeller for Spitfire IX (R.A. 10046).
V. " Practical optimum " distribution.

Values of t/c per cent.

r_c	0·3	0·45	0·6	0·7	0·8	0·9	0·95	0·975
I	31·0	22·4	16·9	13·5	10·7	8·7	7·9	7·7
II	37·0	13·1	8·7	7·6	6·85	6·35	6·2	6·0
III	16·3	10·95	8·6	7·4	6·75	6·2	5·7	5·5
IV	21·9	14·7	11·0	9·3	7·85	6·5	6·1	6·0
V	12·0	8·6	7·1	6·4	5·95	5·5	5·2	5·0

TABLE 2

Propeller Efficiencies*

Altitude = 20,000 ft.   Power for Optimum Efficiency

V m.p.h.	300		400		500		600	
M_r Propeller	0·9	0·95	0·925	0·975	0·95	1·0	0·975	1·025
I	0·874	0·848	0·832	0·781	0·571	0·438	—	—
II	0·889	0·875	0·891	0·873	0·808	0·776	0·530	0·450
III	0·903	0·884	0·900	0·879	0·867	0·834	0·623	0·580
IV	0·890	0·875	0·893	0·872	0·830	0·775	0·505	0·390
V	—	—	—	—	0·883	0·854	0·703	0·665

* All efficiencies are free-air values and are uncorrected for losses inboard of $r_c = 0·3$.
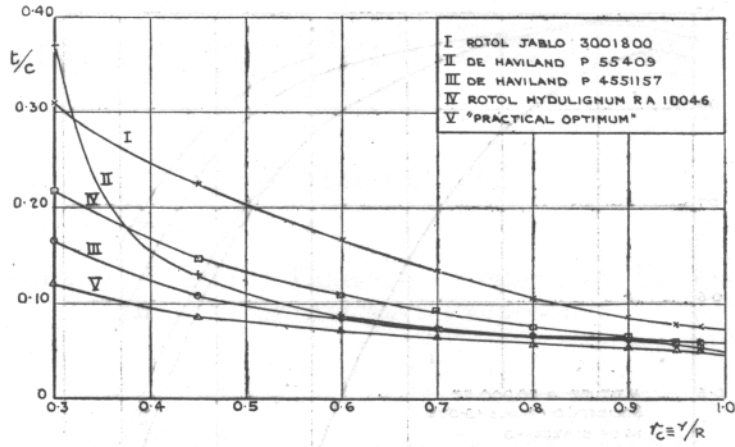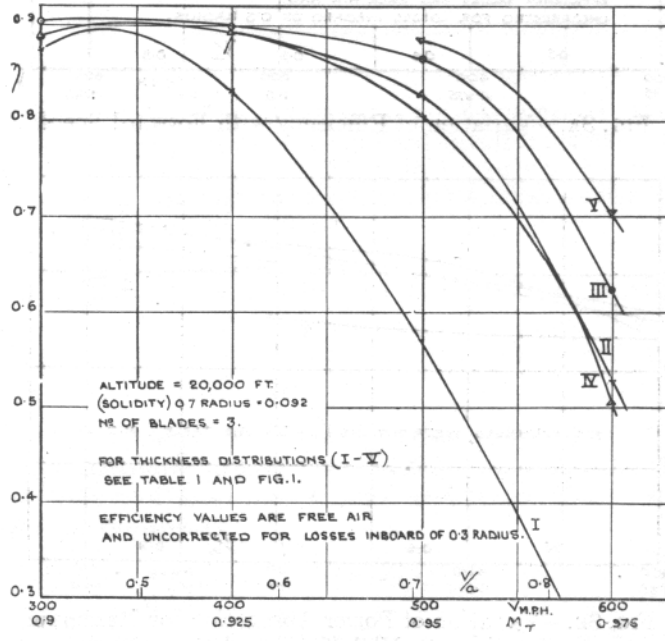
FIG. 1.—Propeller Thickness Distributions.

I ROTOL JABLO 3001800
II DE HAVILAND P 55409
III DE HAVILAND P 4551157
IV ROTOL HYDULIGNUM R A 10046
V "PRACTICAL OPTIMUM"

ALTITUDE = 20,000 FT.
(SOLIDITY) O·7 RADIUS = 0·092
N⁰. OF BLADES = 3.

FOR THICKNESS DISTRIBUTIONS (I - V)
SEE TABLE 1 AND FIG.1.

EFFICIENCY VALUES ARE FREE AIR
AND UNCORRECTED FOR LOSSES INBOARD OF 0·3 RADIUS.

FIG. 2A.—Variation of Efficiency with Forward Speed.

FOR THICKNESS DISTRIBUTIONS (I - V) SEE TABLE 1 AND FIG.1.
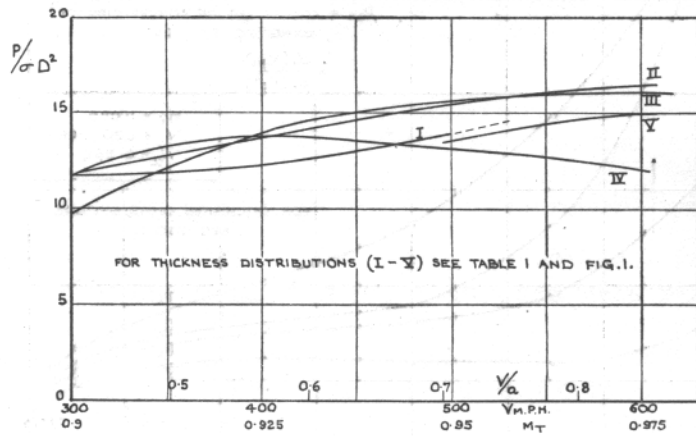
FIG. 2B.—Variation of Power Absorption for Maximum
Efficiency.   Low Tip Speed Range.
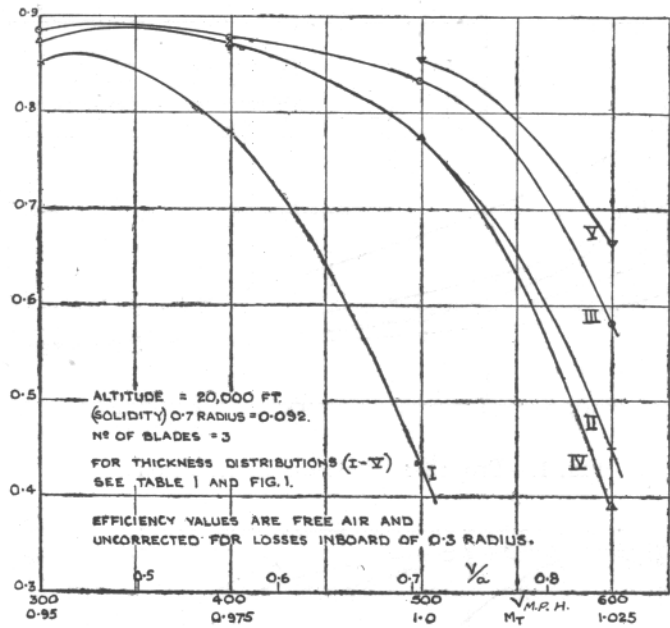
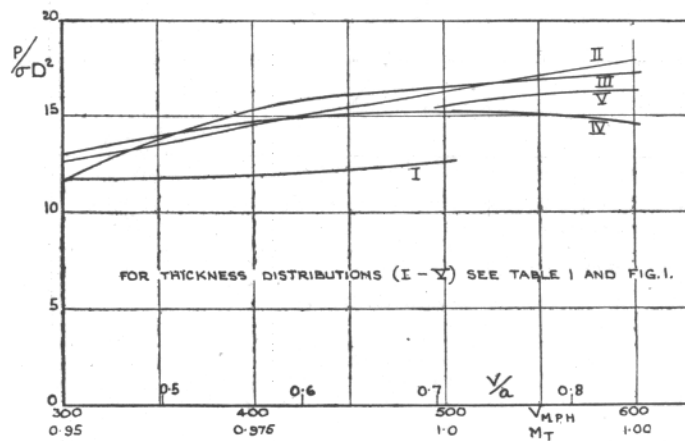FIG. 3A.—Variation of Efficiency with Forward Speed.

FIG. 3B.—Variation of Power Absorption for Maximum
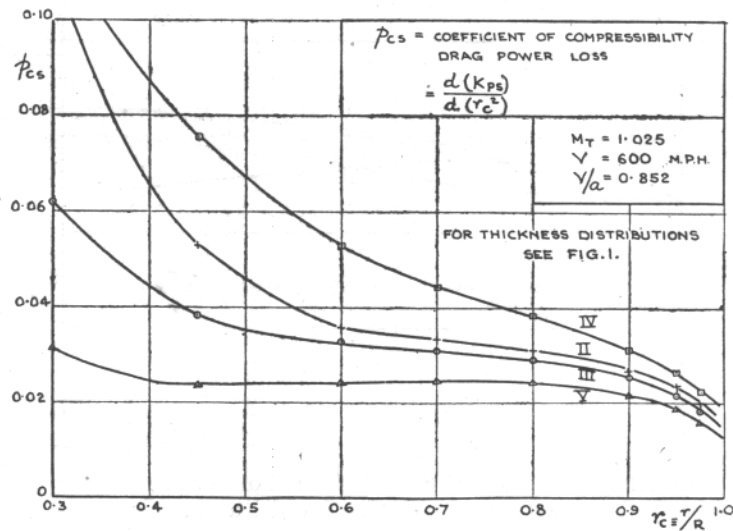Efficiency.   High Tip Speed Range.

FIG. 4.—Compressibility Drag Power Loss Grading.

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