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Propellers in High-Speed Dives

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and Miss E. M. Love,
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Summary.—The performance of a variable-pitch, 3-bladed propeller has been calculated for conditions of fixed power absorption, fixed rotational speed and varying advance speed. Curves of efficiency and power-loss ratios are given to a base of V/a (advance speed/velocity of sound, Fig. 1), together with thrust, torque grading and compressibility loss curves to a base of $(\text{radius})^2$ (Fig. 2). Increasing values of V/a (up to 0·85 or 600 m.p.h. at 21,000 ft.) representing the conditions of a high-speed dive, are accompanied by marked decreases in efficiency and under these conditions the thrust becomes negative over the tips of the blades.

1. A request was made by the Royal Aircraft Establishment that the order of magnitude of the thrust forces on a propeller blade should be investigated for the conditions encountered during high-speed dives. The performance of a variable-pitch 3-bladed propeller has, therefore, been computed under these conditions. The fundamental data are: diameter, 14·0 ft.; b.h.p., 2,000; propeller revs./min., 1028; speed, 428 m.p.h. in level flight, at 21,000 ft. altitude. These give $k_Q = 0{\cdot}053$, $V/a = 0{\cdot}608$, $\Omega R/a = 0{\cdot}730$. The performance characteristics were computed for values of V/a equal to 0·608, 0·70, 0·75, 0·80 and 0·85. Particulars of the propeller are given in Table 1; it was the same as propeller B of R. & M. 2021[5] and may be regarded as a typical high-efficiency design.

2. The calculations were made by standard methods described elsewhere[1]. The data used were the best available at the time and are those given in Part II of R. & M. 2020[2], but the calculations involved a slight extrapolation in the direction of higher M and a considerable extrapolation in the direction of negative C_{L0} for the curves of negative local thrust near the tip (Fig. 2a). The blade settings required to give the required conditions of fixed power absorption with fixed rotational speed were determined and the full performance calculations carried out. The results are summarized in Tables 1 and 2 and illustrated in Figs. 1 and 2.

Blade root losses have also been computed using: (*a*) data derived from 4736[4] as used in R.A.E., B.A. Dept. Note Performance No. 18[3]*; (*b*) data of Part II of R. & M. 2020[2] slightly extrapolated to larger values of t/c (Table 3). The former give a considerably higher figure for the losses than the latter at high V/a but data are not available beyond a Mach number of 0·8. The effect on the efficiency of including the root losses is shown in Fig. 1; it is considered that curve (*a*) is the more nearly correct.

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* This is the same principle as the method described in §8 of R. & M. 2035[1].

It must be emphasized that the figures given here for root loss apply to the unusually thin roots of the propeller chosen for this example and that the root losses would be much greater for a more normal type of blade root.

3. Examination of the results shows that as V/a increases, with fixed power absorption and fixed rotational speed, there is a marked and progressive decrease of efficiency (Fig. 1), due mainly to a marked increase in k_{PS}, the power loss due to compressibility. Simultaneously the local thrust on the outer part of the blades diminishes in magnitude (Fig. 2), changes sign and finally, at $V/a = 0{\cdot}85$, becomes negative over the outer fifth of the blade.* The torque grading shows similar characteristics, although to a lesser degree.

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4	C. N. H. Lock, W. F. Hilton and G. A. M. Hyde	Measurement of Airscrew Blade Root Losses in the High Speed Wind Tunnel. 4736—A.P. 238. (October, 1940.) (To be published.)
5	R. C. Pankhurst and R. G. Fowler	Calculation of the Performance of Two Airscrews for a High Speed Aeroplane. R. & M. 2021. (April, 1941.)

* A strict application of the data of Part II of R. & M. 2020[2] would require the use of " range 3 " for C_L at $V/a = 0{\cdot}85$ for the outer blade sections. This has been ignored since the use of " range 3," for negative C_L, is not strictly logical; the effect on the results would be small in any case.

List of Symbols

a	Speed of sound at height h.
c	Chord of blade element at radius r.
C_D	Drag coefficient of blade element.
C_L	Lift coefficient of blade element.
C_{L0}	Low-speed lift coefficient.
D	Propeller diameter.
h	Operating altitude of aircraft.
J	Advance ratio (V/nD).
k_P	Total power loss coefficient $(\text{Power}/2\pi\rho\, n^3 D^5)$
k_{P0}	Low-speed component of the profile drag power loss coefficient.
k_{P1}	Induced power loss coefficient.
k_{PS}	Compressibility component of the profile drag power loss coefficient.
k_Q	Torque coefficient $(\text{Torque}/\rho\, n^2 D^5)$.
k_T	Thrust coefficient $(\text{Thrust}/\rho\, n^2 D^4)$.
M	Mach number of blade element.
M_t	Mach number of propeller blade tip.
n	Rotational speed (r.p.s.).
N	Number of blades.
p_{CS}	Grading coefficient of the compressibility component of the profile drag power loss : $dk_{PS}/d(r_c^2)$.
q_c	Torque grading coefficient : $dk_Q/d(r_c^2)$.
r	Radius at blade element.
r_c	Fractional radius at blade element (r/R).
R	Tip radius.
s	Solidity $(Nc/2\pi r)$.
t	Thickness of blade section.
t_c	Thrust grading coefficient : $dk_T/d(r_c^2)$.
V	Forward speed.
α	Incidence of blade element.
ε_0	Zero-lift angle at low speed.
η	Propeller efficiency.
θ	Blade angle.
ρ	Air density.
Ω	Rotational speed (radians per second).

TABLE 1

	r_C	0·3	0·45	0·6	0·7	0·8	0·9	0·95	0·975
	c (ins.)	11·51	12·51	12·10	11·07	9·59	7·60	6·38	5·66
	s	0·218	0·158	0·115	0·090	0·068	0·048	0·038	0·033
	t/c %	16·6	11·0	8·5	7·5	6·7	6·0	5·5	5·2
	$\varepsilon_0{}^\circ$	5·17	4·34	3·29	2·87	2·59	2·39	2·33	2·30
	Basic θ°	71·9	64·7	57·6	53·1	48·8	44·7	42·7	41·7
	α°	−0·47	0·59	0·99	0·94	0·64	0·16	−0·22	−0·54
$J = 2·62$	C_L	0·622	0·682	0·645	0·606	0·541	0·433	0·358	0·300
$V/a = 0·608$	C_D	0·0109	0·0095	0·0087	0·0104	0·0169	0·0229	0·0253	0·0261
*B.S. = −0°·3	M	0·646	0·692	0·750	0·794	0·844	0·896	0·922	0·936
	p_{CS}	0	0	0	0·0005	0·0018	0·0026	0·0027	0·0025
	α°	−0·20	0·191	0·31	0·17	−0·09	−0·44	−0·71	−0·89
$J = 3·012$	C_L	0·653	0·658	0·553	0·473	0·371	0·225	0·145	0·103
$V/a = 0·70$	C_D	0·0183	0·0169	0·0187	0·0203	0·0309	0·0396	0·0434	0·0458
B.S. = 2°·4	M	0·734	0·773	0·826	0·867	0·912	0·960	0·986	0·999
	p_{CS}	0·0031	0·0027	0·0033	0·0036	0·0059	0·0067	0·0065	0·0062
	α°	0·41	0·42	0·34	0·18	−0·07	−0·41	−0·66	−0·81
$J = 3·232$	C_L	0·649	0·656	0·520	0·411	0·279	0·121	0·050	0·021
$V/a = 0·75$	C_D	0·0378	0·0344	0·0336	0·0371	0·0437	0·0527	0·0560	0·0576
B.S. = 4°·1	M	0·783	0·820	0·869	0·908	0·951	0·998	1·022	1·034
	p_{CS}	0·0137	0·0108	0·0094	0·0098	0·0104	0·0107	0·0098	0·0091
	α°	1·30	0·99	0·76	0·52	0·21	−0·16	−0·40	−0·51
$J = 3·443$	C_L	0·643	0·639	0·468	0·348	0·204	0·048	−0·021	−0·048
$V/a = 0·80$	C_D	0·0589	0·0580	0·0524	0·547	0·0594	0·0667	0·0697	0·0715
B.S. = 5°·9	M	0·829	0·864	0·912	0·950	0·991	1·035	1·059	1·071
	p_{CS}	0·0291	0·0246	0·0191	0·0178	0·0170	0·0156	0·0140	0·0129
	α°	2·38	1·78	1·33	1·00	0·63	0·26	−0·03	−0·11
$J = 3·663$	C_L	0·627	0·608	0·430	0·291	0·144	−0·015	−0·082	−0·103
$V/a = 0·85$	C_D	0·0840	0·0820	0·0748	0·0744	0·0772	0·0835	0·0855	0·0876
B.S. = 7°·8	M	0·879	0·913	0·957	0·993	1·032	1·075	1·098	1·110
	p_{CS}	0·0524	0·0430	0·0332	0·0290	0·0258	0·0225	0·0195	0·0180

* Blade setting.

TABLE 2

V/a	0·608	0·700	0·750	0·800	0·850
$\Omega R/a$	0·730	0·730	0·730	0·730	0·730
M_t	0·950	1·011	1·047	1·083	1·120
k_Q	0·053	0·053	0·053	0·053	0·053
k_T	0·112	0·0908	0·0751	0·0557	0·0337
J	2·62	3·012	3·232	3·443	3·663
k_{P1}/k_Q	0·0681	0·0630	0·0632	0·0634	0·0630
k_{P0}/k_Q	0·0311	0·0402	0·0465	0·0544	0·0645
$(k_{P1} + k_{P0})/k_Q$	0·0992	0·1032	0·1096	0·1178	0·1275
k_{PS}/k_Q	0·0200	0·0789	0·1723	0·3121	0·5048
k_P/k_Q	0·1192	0·1821	0·2819	0·4299	0·6323
η	0·881	0·818	0·718	0·570	0·368

TABLE 3

Blade root power losses (k_P)

V/a	0·608	0·7	0·75	0·8	0·85
(a) Data of PN.18[3]	0·0003	0·0006	0·0024	0·0056	—
(b) Data of Part II of R. & M. 2020[2]	0·0002	0·0006	0·0013	0·0022	0·0036

Blade root efficiency losses (k_P/k_Q)

(a) Data of PN.18[3]	0·005	0·012	0·045	0·104	—
(b) Data of Part II of R. & M. 2020[2]	0·004	0·011	0·024	0·042	0·066

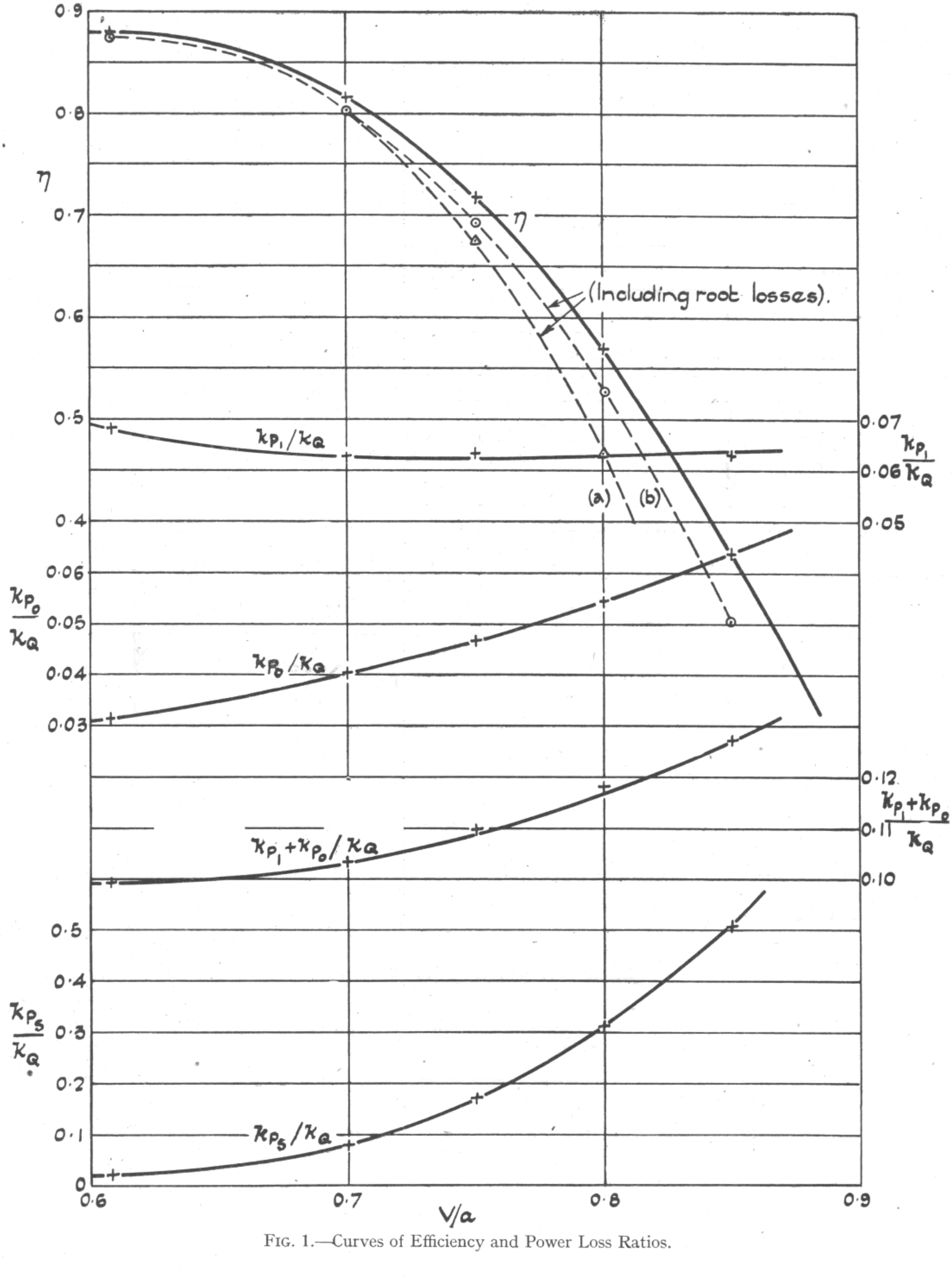

FIG. 1.—Curves of Efficiency and Power Loss Ratios.

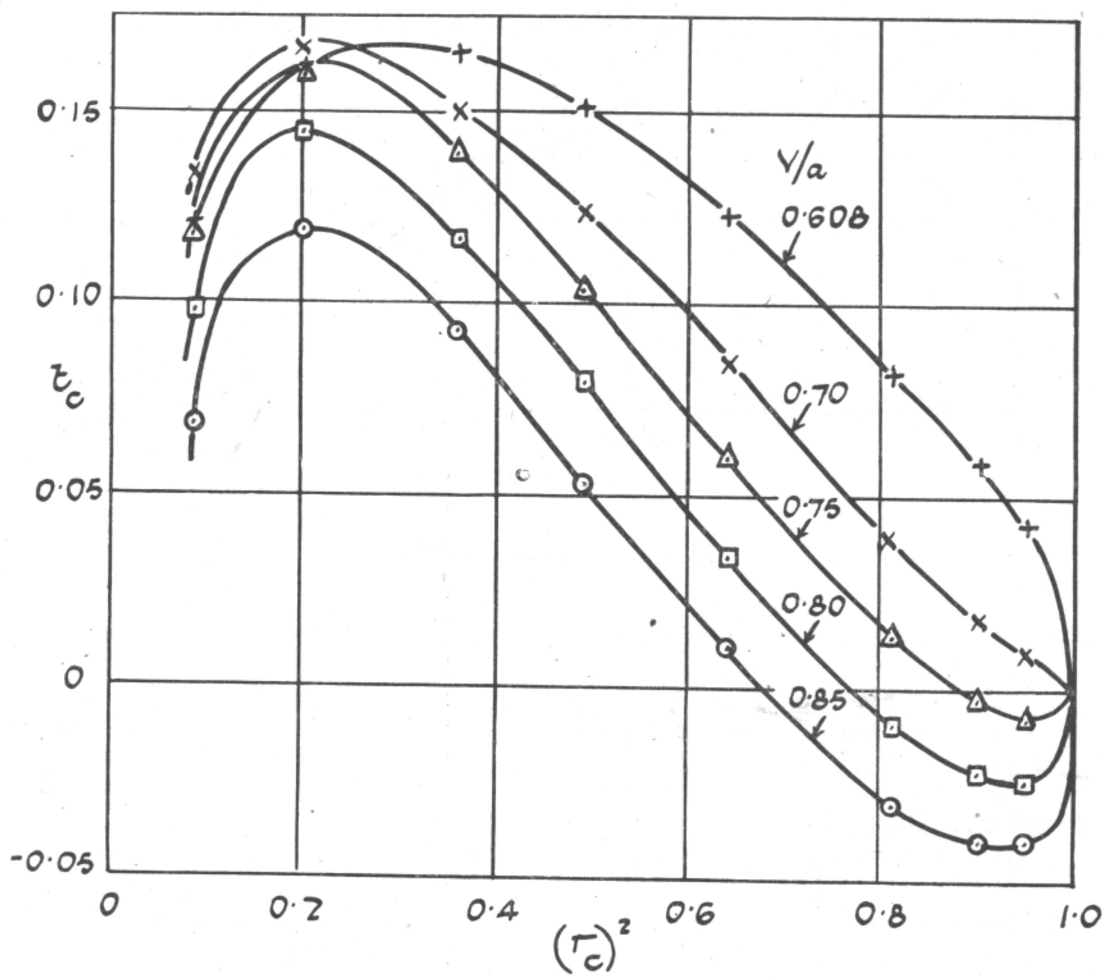

FIG. 2 (a).—Thrust Grading.

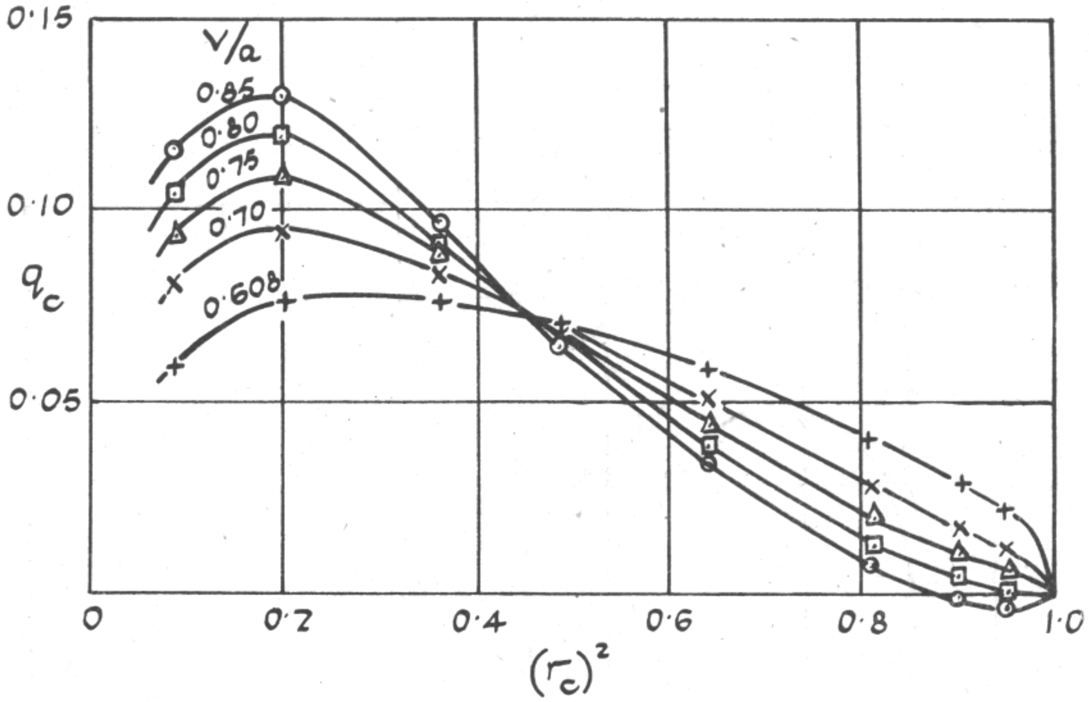

FIG. 2 (b).—Torque Grading.

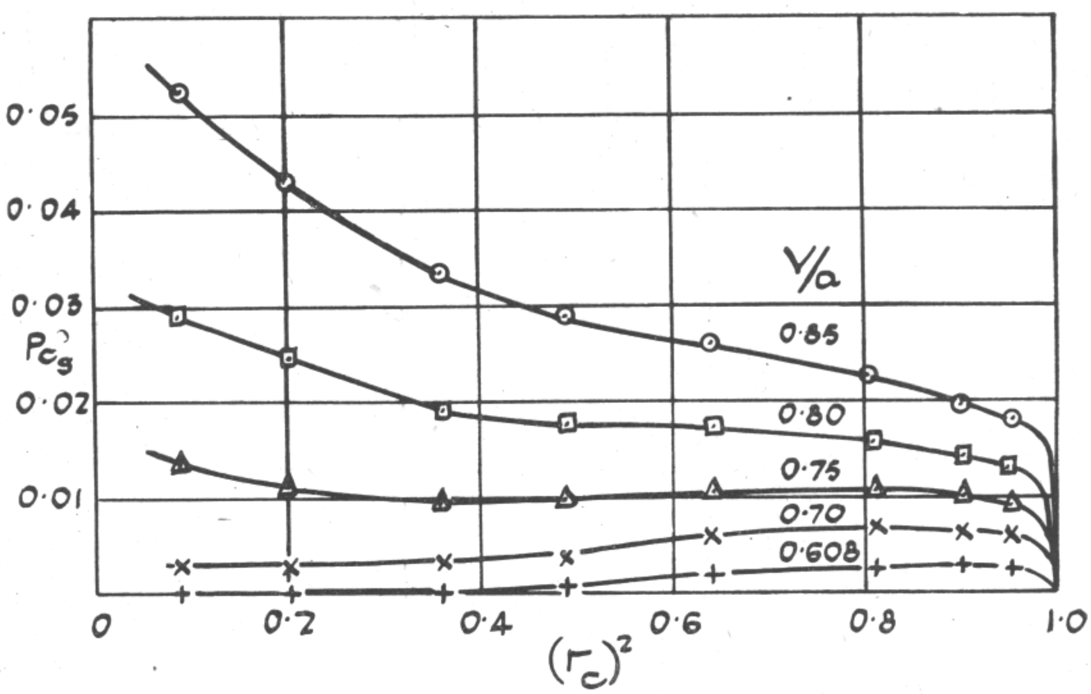

FIG. 2 (c). Compressibility Loss Grading.

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