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COMMUNICATED BY THE PRINCIPAL DIRECTOR OF SCIENTIFIC RESEARCH (AIR), MINISTRY OF SUPPLY

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Summary.—Some measurements of downwash have been made in a plane behind a 12-ft diameter helicopter rotor over a range of shaft inclination and tip speed ratio. In the various operating conditions, the tunnel tests are in reasonable agreement with the theoretical results for the appropriate type of loading.

1. *Introduction.*—With the advent of multi-rotor helicopters, the problem of rotor interference is becoming important. For a tandem layout, the most important interference effect is likely to arise from the operation of the rear rotor in the downwash of the front rotor. At present, experimental data on the downwash field behind a helicopter rotor are very scanty, although the problem has been dealt with theoretically by Mangler (R. &. M. 2642[1]). Some downwash measurements have therefore been made behind a 12-ft diameter rotor in the 24-ft Wind Tunnel of the Royal Aircraft Establishment, and the results are given in this Note. The relevant data from R. & M. 2642[1] are also given for comparison.

2. *Description of Tests.*—The 12-ft diameter rotor and associated equipment are fully described in R. & M. 2695[2]. The downwash measurements were made with a set of ten yawmeters mounted on a vertical mast which was placed in four spanwise positions at a constant distance of 1·5 rotor radii behind the rotor centre. The yawmeter positions are shown in Fig. 1. It should be noted that the yawmeter locations are given relative to the centre of the rotor at zero shaft inclination. At positive shaft inclinations, the centre of the rotor is moved forward and slightly downward in the tunnel but it was not considered worthwhile to reset the yawmeter mast after changing the shaft inclination.

The yawmeters were connected to a multi-tube manometer and pressure difference was plotted against yawmeter angular setting with and without the rotor. (Four yawmeter settings were used.) The difference in yawmeter setting for zero pressure difference was taken to be the downwash produced by the rotor.

The results obtained showed a number of irregularities and it was thought possible that interference effects were arising from the wake of the rotor passing completely round the tunnel. Accordingly, a few traverses were made ahead of the rotor. The results of these traverses are shown in Fig. 3a, 3b, and 3c, and 4a, and 4b. It was evident that in general a slight rotation of the air in the same direction as the rotor had persisted round the tunnel. A rotation of the air in the opposite direction in the empty tunnel has been measured, however (Ref. 3), and the effect is of the same order of magnitude (Fig. 3d and 3e, and 4c).

Throughout the tests the rotor speed was 600 r.p.m. and the blade angle setting was 8 deg.

* R.A.E. Tech. Note Aero. 2018, received 25th January, 1950.

3. *Results.*—The tests covered a range of shaft inclination from 0 deg to 30 deg and a range of tip speed ratio from approximately 0·1 to 0·3. In order to avoid low and negative thrusts, the higher values of the tip speed ratio were not tested at large shaft inclinations. Values of thrust coefficient and flapping angle have been measured previously (R. & M. 2695[2]) and are given in Table 1*. The results of the downwash measurements behind the rotor are given in terms of downwash angle α_i and also in form α_i/C_T in Tables 2 to 9. Values of α_i/C_T are plotted as shown in Figs. 5 to 10 together with theoretical results obtained from Mangler's calculations for two types of pressure distribution on the disk as indicated in Fig. 2.

4. *Discussion.*—In comparing the measured values of α_i/C_T with the theoretical values, it must be remembered that the calculations are based on a first-order theory and do not allow for the actual displacement of the jet. This jet displacement occurs in all cases and is very clearly shown in Fig. 7b, 10b, and 10c.

The two calculated pressure distributions correspond to extreme types of disk loading distribution and the load distribution over the disk will lie somewhere between these two extremes depending on the conditions of test. For the advancing blade at the higher value of tip speed ratio there will be lift right up to the blade root and the loading will correspond to type I (Fig. 2). On the other hand, on the retreating blade at the higher values of tip speed ratio, there will be no lift over the inner part of the blade and the loading will correspond to type III (Fig. 2). It will be seen that the measured values of the downwash correspond approximately with the above ; for example in Fig. 7 the downwash distribution behind the advancing blade corresponds to the calculated distribution for the type I pressure distribution, and the distribution behind the retreating blade to the calculated distribution for type III pressure distribution.

LIST OF SYMBOLS

ρ	Air density (slugs/cu ft)
R	Radius of rotor disk (ft)
z	Vertical distance from plane through rotor centre (positive measured upwards)
V	Tunnel velocity (ft/sec)
α_i	Downwash angle induced by the rotor
Ω	Angular velocity of rotor (radn/sec)
i_s	Shaft inclination (deg) positive when shaft is tilted forward
a_1	Longitudinal flapping angle (deg)
ε	Downwash angle in front of rotor
T	Thrust (lb)
T_C	Thrust coefficient based on tip speed $= \dfrac{T}{\rho\pi R^2\Omega^2R^2}$
C_T	Thrust coefficient based on wind speed $= \dfrac{2T}{\rho V^2\pi R^2} = \dfrac{2Tc}{\mu^2}\cos^2 i_s$
μ	Tip speed ratio $= \dfrac{V}{\Omega R}\cos i_s$

* The experimental values are used, not corrected for support interference, since it is not clear how the interference changes the conditions at the blades.

REFERENCES

No.	Author	Title, etc.
1	K. W. Mangler and H. B. Squire ..	The induced velocity field of a rotor. (Summary report.) R. & M. 2642. May, 1948.
2	H. B. Squire, R. A. Fail and R. C. W. Eyre	Wind-tunnel tests on a 12-ft diameter helicopter rotor. R. & M. 2695. April, 1945.
3	W. E. Gray	Calibration of the R.A.E. 24-ft Wind Tunnel for yaw and pitch. A.R.C. 8417. (Unpublished.)

TABLE 1

Thrust Coefficient and Flapping Angle

Blade angle = 8 deg

Symbol	$i_s = 0$ deg			$i_s = 15$ deg		$i_s = 30$ deg
	$\mu = 0{\cdot}099$	$\mu = 0{\cdot}199$	$\mu = 0{\cdot}296$	$\mu = 0{\cdot}096$	$\mu = 0{\cdot}192$	$\mu = 0{\cdot}086$
$10^3 T_c$	5·9	7·8	8·6	4·2	3·4	2·7
$57{\cdot}3 C_T$	68·99	22·57	11·25	48·73	9·86	31·37
a_1 deg	2·1	4·8	9·2	1·8	3·3	1·3

TABLE 2

Downwash Angle in Degrees $1{\cdot}5R$ *behind Helicopter Rotor* $0{\cdot}278R$ *from Rotor Centre-Line Behind Advancing Blade*

Blade angle = 8 deg

$\frac{z}{R}$	$i_s = 0$ deg			$i_s = 15$ deg		$i_s = 30$ deg
	$\mu = 0{\cdot}099$	$\mu = 0{\cdot}199$	$\mu = 0{\cdot}296$	$\mu = 0{\cdot}096$	$\mu = 0{\cdot}192$	$\mu = 0{\cdot}086$
+1·0	9·3	2·0	1·9	6·6	0·5	4·6
+0·6	15·0	5·1	3·7	10·5	2·5	6·0
+0·4	17·0	7·5	5·3	12·1	3·5	7·3
+0·2	22·2	9·8	7·5	15·2	5·0	11·6
0	27·5	12·5	9·7	19·8	5·6	11·5
−0·2	31·0	17·9	13·0	22·6	6·6	9·5
−0·4	31·4	12·9	7·5	20·6	5·8	9·8
−0·6	28·6	8·4	4·8	16·6	4·2	10·2
−0·8	23·1	6·5	2·6	14·3	3·0	7·6
−1·2	15·0	5·0	1·4	10·6	2·2	5·3

TABLE 3

Downwash α_i/C_T (radians) $1 \cdot 5R$ behind Helicopter Rotor
$0 \cdot 278R$ from Rotor Centre-Line Behind Advancing Blade

Blade angle = 8 deg

$\frac{z}{R}$	$i_s = 0$ deg			$i_s = 15$ deg		$i_s = 30$ deg
	$\mu = 0 \cdot 099$	$\mu = 0 \cdot 199$	$\mu = 0 \cdot 296$	$\mu = 0 \cdot 096$	$\mu = 0 \cdot 192$	$\mu = 0 \cdot 086$
$+1 \cdot 0$	$0 \cdot 13$	$0 \cdot 09$	$0 \cdot 17$	$0 \cdot 14$	$0 \cdot 05$	$0 \cdot 15$
$+0 \cdot 6$	$0 \cdot 22$	$0 \cdot 23$	$0 \cdot 33$	$0 \cdot 22$	$0 \cdot 25$	$0 \cdot 19$
$+0 \cdot 4$	$0 \cdot 25$	$0 \cdot 33$	$0 \cdot 47$	$0 \cdot 25$	$0 \cdot 35$	$0 \cdot 23$
$+0 \cdot 2$	$0 \cdot 32$	$0 \cdot 43$	$0 \cdot 67$	$0 \cdot 31$	$0 \cdot 51$	$0 \cdot 37$
0	$0 \cdot 40$	$0 \cdot 55$	$0 \cdot 86$	$0 \cdot 41$	$0 \cdot 57$	$0 \cdot 37$
$-0 \cdot 2$	$0 \cdot 45$	$0 \cdot 79$	$1 \cdot 16$	$0 \cdot 46$	$0 \cdot 67$	$0 \cdot 30$
$-0 \cdot 4$	$0 \cdot 46$	$0 \cdot 57$	$0 \cdot 67$	$0 \cdot 42$	$0 \cdot 59$	$0 \cdot 31$
$-0 \cdot 6$	$0 \cdot 41$	$0 \cdot 37$	$0 \cdot 43$	$0 \cdot 34$	$0 \cdot 43$	$0 \cdot 33$
$-0 \cdot 8$	$0 \cdot 33$	$0 \cdot 29$	$0 \cdot 23$	$0 \cdot 29$	$0 \cdot 30$	$0 \cdot 24$
$-1 \cdot 2$	$0 \cdot 22$	$0 \cdot 22$	$0 \cdot 12$	$0 \cdot 22$	$0 \cdot 22$	$0 \cdot 17$

TABLE 4

Downwash Angle in Degrees $1 \cdot 5R$ Behind Helicopter Rotor
$0 \cdot 75R$ from Rotor Centre-Line Behind Advancing Blade

Blade angle = 8 deg

$\frac{z}{R}$	$i_s = 0$ deg			$i_s = 15$ deg		$i_s = 30$ deg
	$\mu = 0 \cdot 099$	$\mu = 0 \cdot 199$	$\mu = 0 \cdot 296$	$\mu = 0 \cdot 096$	$\mu = 0 \cdot 192$	$\mu = 0 \cdot 086$
$+1 \cdot 0$	$7 \cdot 0$	$2 \cdot 8$	$1 \cdot 0$	$5 \cdot 3$	$1 \cdot 5$	$2 \cdot 3$
$+0 \cdot 6$	$12 \cdot 0$	$4 \cdot 4$	$1 \cdot 6$	$8 \cdot 7$	$1 \cdot 4$	$6 \cdot 0$
$+0 \cdot 4$	$11 \cdot 3$	$4 \cdot 6$	$1 \cdot 9$	$8 \cdot 0$	$1 \cdot 6$	$5 \cdot 5$
$+0 \cdot 2$	$11 \cdot 0$	$7 \cdot 3$	$2 \cdot 5$	$9 \cdot 4$	$3 \cdot 0$	$4 \cdot 7$
0	$21 \cdot 0$	$18 \cdot 3$	$3 \cdot 5$	$16 \cdot 0$	$7 \cdot 5$	$7 \cdot 7$
$-0 \cdot 2$	$41 \cdot 0$	$13 \cdot 0$	$0 \cdot 7$	$29 \cdot 0$	$7 \cdot 5$	$21 \cdot 0$
$-0 \cdot 4$	$30 \cdot 6$	$6 \cdot 2$	$1 \cdot 0$	$21 \cdot 7$	$4 \cdot 0$	$16 \cdot 3$
$-0 \cdot 6$	$21 \cdot 3$	$6 \cdot 7$	$3 \cdot 6$	$18 \cdot 7$	$3 \cdot 7$	$15 \cdot 1$
$-0 \cdot 8$	$18 \cdot 0$	$7 \cdot 1$	$3 \cdot 5$	$12 \cdot 5$	$4 \cdot 0$	$6 \cdot 6$
$-1 \cdot 2$	$9 \cdot 5$	$4 \cdot 8$	$2 \cdot 5$	$6 \cdot 5$	$2 \cdot 4$	$2 \cdot 0$

TABLE 5

Downwash α_i/C_T (radians) 1·5R Behind Helicopter Rotor 0·75R from Rotor Centre-Line Behind Advancing Blade

Blade angle = 8 deg

$\frac{z}{R}$	$i_s = 0$ deg			$i_s = 15$ deg		$i_s = 30$ deg
	$\mu = 0{\cdot}099$	$\mu = 0{\cdot}199$	$\mu = 0{\cdot}296$	$\mu = 0{\cdot}096$	$\mu = 0{\cdot}192$	$\mu = 0{\cdot}086$
+1·0	0·10	0·12	0·09	0·11	0·15	0·07
+0·6	0·17	0·19	0·14	0·18	0·14	0·19
+0·4	0·16	0·20	0·17	0·16	0·16	0·18
+0·2	0·16	0·32	0·22	0·19	0·30	0·15
0	0·30	0·81	0·31	0·33	0·76	0·25
−0·2	0·59	0·58	0·06	0·60	0·76	0·67
−0·4	0·44	0·27	0·09	0·45	0·41	0·52
−0·6	0·31	0·30	0·32	0·38	0·38	0·48
−0·8	0·26	0·31	0·31	0·26	0·41	0·21
−1·2	0·14	0·21	0·22	0·13	0·24	0·06

TABLE 6

Downwash Angle in Degrees 1·5R Behind Helicopter Rotor 0·278R from Rotor Centre-Line Behind Retreating Blade

Blade angle = 8 deg

$\frac{z}{R}$	$i_s = 0$ deg			$i_s = 15$ deg		$i_s = 30$ deg
	$\mu = 0{\cdot}099$	$\mu = 0{\cdot}199$	$\mu = 0{\cdot}296$	$\mu = 0{\cdot}096$	$\mu = 0{\cdot}192$	$\mu = 0{\cdot}086$
+1·0	9·0	3·4	1·0	7·0	1·4	3·7
+0·6	11·7	5·0	1·4	8·7	1·4	5·2
+0·4	15·9	5·4	3·9	11·9	1·6	7·8
+0·2	20·0	8·5	6·4	13·5	3·0	9·3
0	26·5	10·0	6·7	18·5	2·0	11·0
−0·2	26·0	11·0	3·5	16·5	1·7	4·2
−0·4	29·3	8·3	4·7	12·7	3·3	3·9
−0·6	23·0	7·2	2·0	13·2	2·9	3·2
−0·8	18·0	5·2	2·0	13·6	2·0	7·3
−1·2	11·5	1·6	0·9	7·0	0·4	4·4

TABLE 7

Downwash α_i/C_T (radians) $1{\cdot}5R$ behind Helicopter Rotor $0{\cdot}278R$ from Rotor Centre-Line Behind Retreating Blade

Blade angle = 8 deg

$\frac{z}{R}$	$i_s = 0$ deg			$i_s = 15$ deg		$i_s = 30$ deg
	$\mu = 0{\cdot}099$	$\mu = 0{\cdot}199$	$\mu = 0{\cdot}296$	$\mu = 0{\cdot}096$	$\mu = 0{\cdot}192$	$\mu = 0{\cdot}086$
+1·0	0·13	0·15	0·09	0·14	0·14	0·12
+0·6	0·17	0·22	0·12	0·18	0·14	0·17
+0·4	0·23	0·24	0·35	0·24	0·16	0·25
+0·2	0·29	0·38	0·57	0·28	0·30	0·30
0	0·38	0·44	0·60	0·38	0·20	0·35
−0·2	0·38	0·49	0·31	0·34	0·17	0·13
−0·4	0·42	0·37	0·42	0·26	0·33	0·12
−0·6	0·33	0·32	0·18	0·27	0·29	0·10
−0·8	0·26	0·23	0·18	0·28	0·20	0·23
−1·20	0·17	0·07	0·08	0·14	0·04	0·14

TABLE 8

Downwash Angle in Degrees $1{\cdot}5R$ Behind Helicopter Rotor $0{\cdot}75R$ from Rotor Centre-Line Behind Retreating Blade

Blade angle = 8 deg

$\frac{z}{R}$	$i_s = 0$ deg			$i_s = 15$ deg		$i_s = 30$ deg
	$\mu = 0{\cdot}099$	$\mu = 0{\cdot}199$	$\mu = 0{\cdot}296$	$\mu = 0{\cdot}096$	$\mu = 0{\cdot}192$	$\mu = 0{\cdot}086$
+1·0	7·3	4·0	1·4	5·7	1·3	3·6
+0·6	9·0	4·2	0·5	6·4	0·8	3·9
+0·4	11·0	5·0	0·6	8·0	1·0	4·0
+0·2	14·0	7·1	1·6	8·5	2·2	4·0
0	25·3	21·0	4·5	13·5	5·5	7·0
−0·2	36·1	6·5	2·0	28·1	5·0	16·1
−0·4	27·2	4·5	1·7	21·7	2·7	15·7
−0·6	16·5	2·7	1·7	15·6	1·3	12·0
−0·8	14·5	2·5	1·4	10·5	1·0	4·5
−1·2	9·5	2·4	0·9	5·7	0·6	3·0

TABLE 9

Downwash α_i/C_T (radians) $1 \cdot 5R$ Behind Helicopter Rotor
$0 \cdot 75R$ from Rotor Centre-Line Behind Retreating Blade

Blade angle = 8 deg

$\frac{z}{R}$	$i_s = 0$ deg			$i_s = 15$ deg		$i_s = 30$ deg
	$\mu = 0 \cdot 099$	$\mu = 0 \cdot 199$	$\mu = 0 \cdot 296$	$\mu = 0 \cdot 096$	$\mu = 0 \cdot 192$	$\mu = 0 \cdot 086$
$+1 \cdot 0$	$0 \cdot 11$	$0 \cdot 18$	$0 \cdot 12$	$0 \cdot 12$	$0 \cdot 13$	$0 \cdot 11$
$+0 \cdot 6$	$0 \cdot 13$	$0 \cdot 19$	$0 \cdot 04$	$0 \cdot 13$	$0 \cdot 08$	$0 \cdot 12$
$+0 \cdot 4$	$0 \cdot 16$	$0 \cdot 22$	$0 \cdot 05$	$0 \cdot 16$	$0 \cdot 10$	$0 \cdot 13$
$+0 \cdot 2$	$0 \cdot 20$	$0 \cdot 31$	$0 \cdot 14$	$0 \cdot 17$	$0 \cdot 22$	$0 \cdot 13$
0	$0 \cdot 37$	$0 \cdot 93$	$0 \cdot 40$	$0 \cdot 28$	$0 \cdot 56$	$0 \cdot 23$
$-0 \cdot 2$	$0 \cdot 52$	$0 \cdot 29$	$0 \cdot 18$	$0 \cdot 58$	$0 \cdot 51$	$0 \cdot 51$
$-0 \cdot 4$	$0 \cdot 39$	$0 \cdot 20$	$0 \cdot 15$	$0 \cdot 45$	$0 \cdot 27$	$0 \cdot 50$
$-0 \cdot 6$	$0 \cdot 24$	$0 \cdot 12$	$0 \cdot 15$	$0 \cdot 32$	$0 \cdot 13$	$0 \cdot 38$
$-0 \cdot 8$	$0 \cdot 21$	$0 \cdot 11$	$0 \cdot 12$	$0 \cdot 22$	$0 \cdot 10$	$0 \cdot 14$
$-1 \cdot 2$	$0 \cdot 14$	$0 \cdot 11$	$0 \cdot 08$	$0 \cdot 12$	$0 \cdot 06$	$0 \cdot 10$

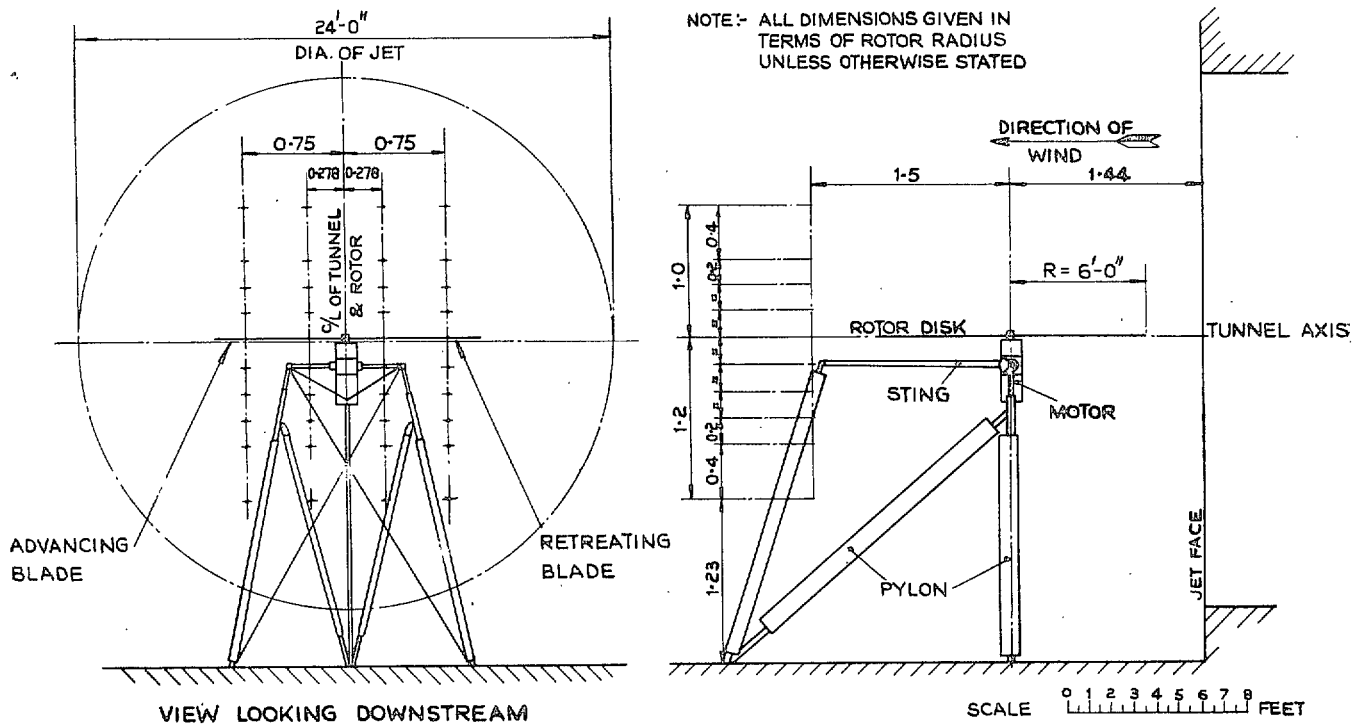

FIG. 1. General arrangement of 12-ft rotor in 24-ft tunnel showing positions of yawmeter traverses.

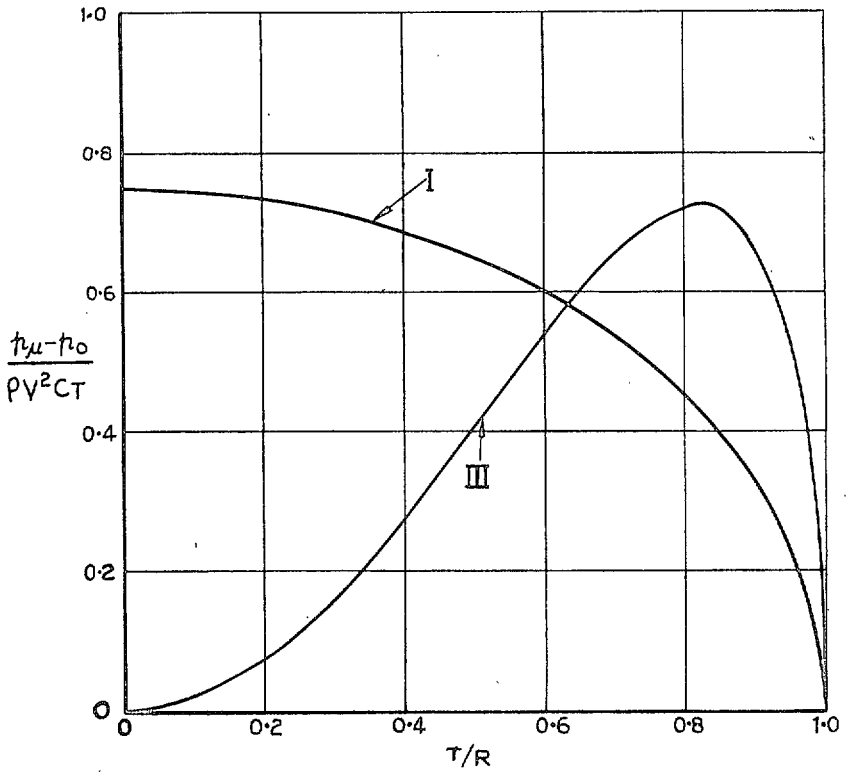

FIG. 2. Assumed pressure distributions on rotor disk (Ref. 1).

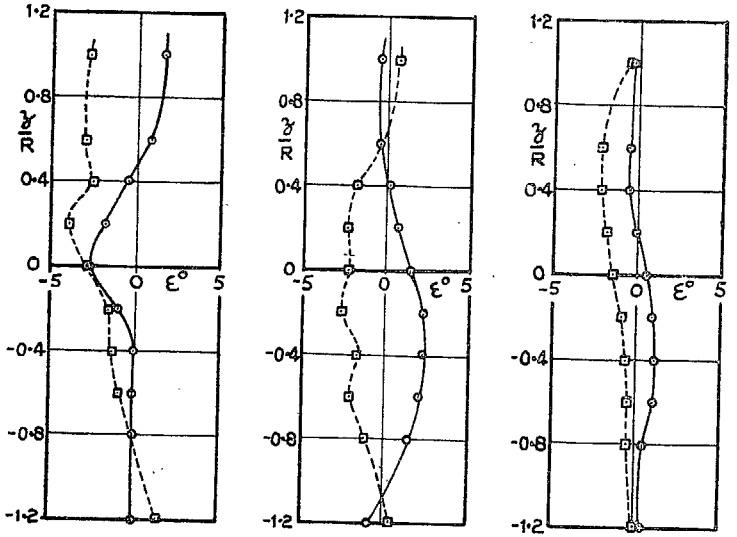

FIG. 3(a) WITH ROTOR
$\mu = 0{\cdot}098$, V = 37·5

FIG. 3(b) WITH ROTOR
$\mu = 0{\cdot}196$, V = 76·0

FIG. 3(c) WITH ROTOR
$\mu = 0{\cdot}292$, V = 113·0

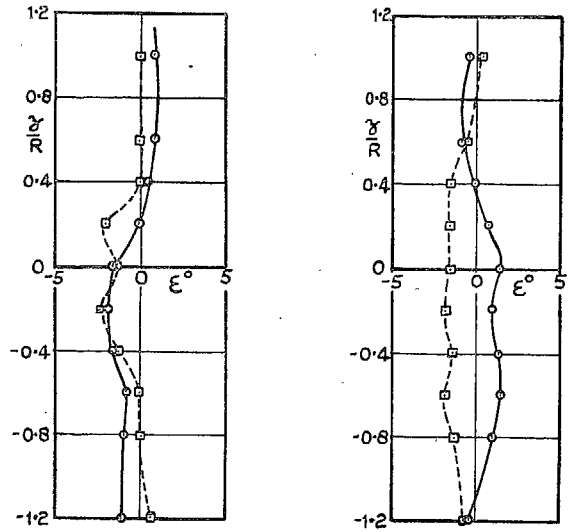

FIG. 4(a) WITH ROTOR
$\mu = 0{\cdot}095$, V = 37·5

FIG. 4(b) WITH ROTOR
$\mu = 0{\cdot}189$, V = 76·0

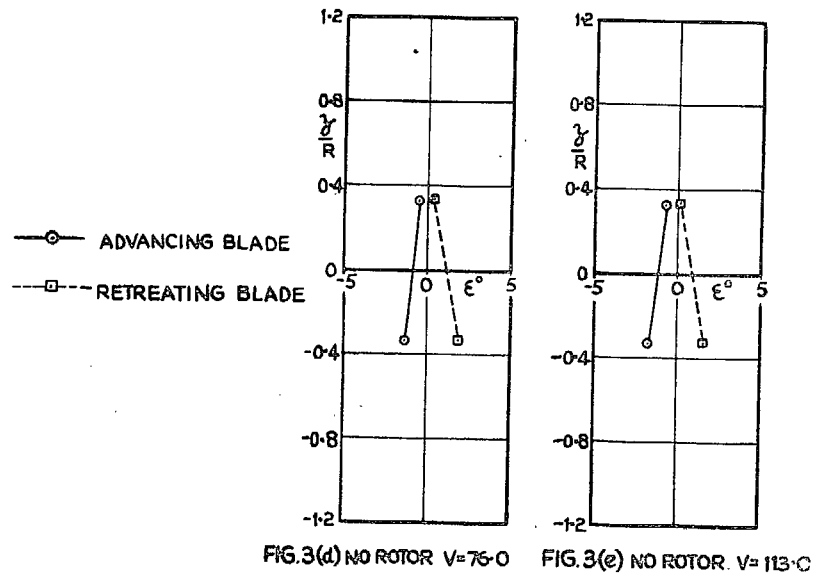

FIG. 3(d) NO ROTOR V=76·0

FIG. 3(e) NO ROTOR V= 113·0

FIG. 3. Downwash ahead of 12-ft diameter rotor. $i_s = 0$ deg, $0{\cdot}75R$ from centre-line of rotor.

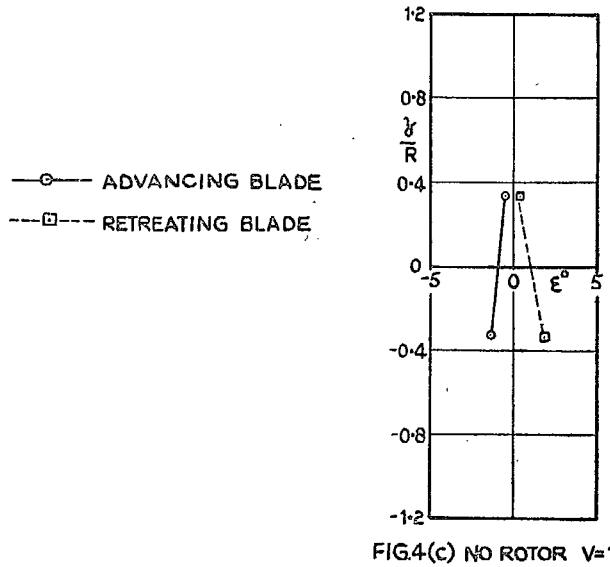

FIG.4(c) NO ROTOR V=76·0

FIG. 4. Downwash ahead of 12-ft diameter rotor. $i_s = 15$ deg, $0{\cdot}75R$ from centre-line of rotor.

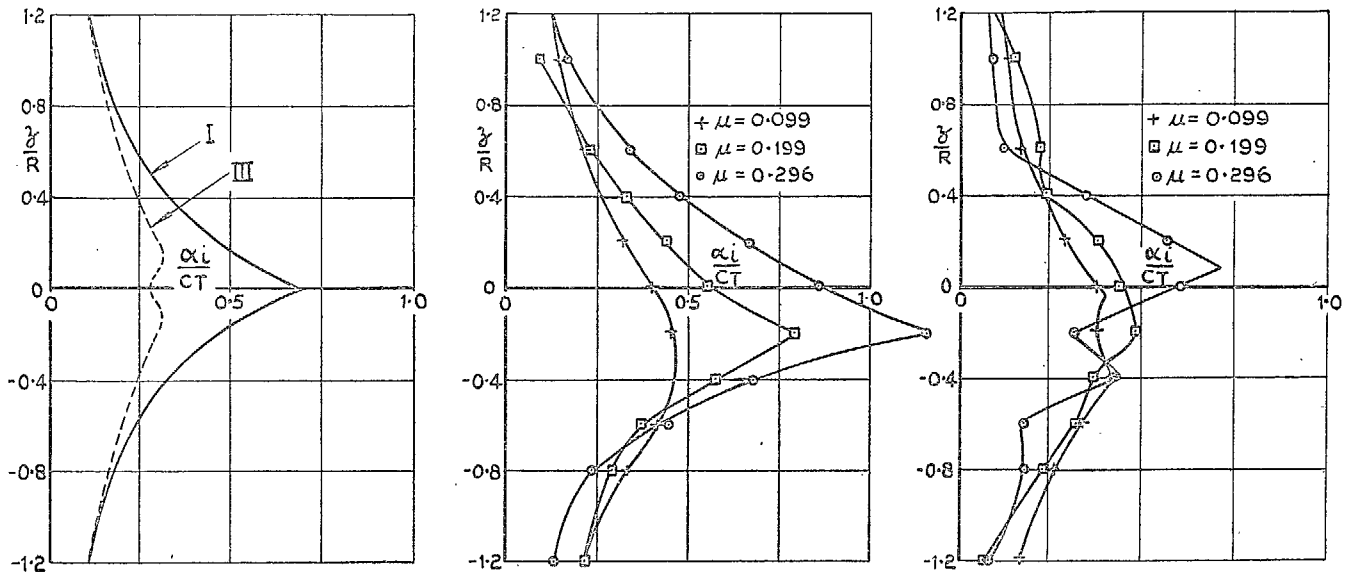

FIG. 5 (a) CALCULATED FIG. 5 (b) ADVANCING BLADE FIG. 5 (c) RETREATING BLADE

FIG. 5. Downwash α_1/C_T (radians) behind 12-ft diameter rotor. $i_s = 0$ deg, $0{\cdot}278R$ from centre-line of rotor.

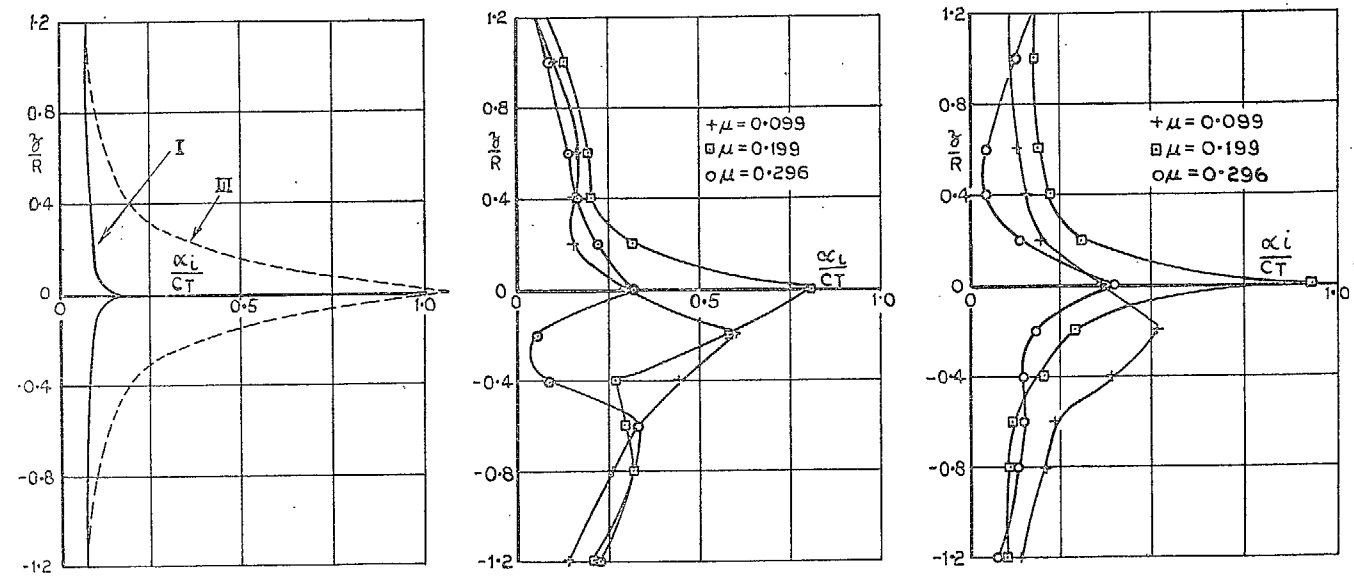

FIG.6(a) CALCULATED FIG.6(b) ADVANCING BLADE FIG.6(c) RETREATING BLADE

FIG. 6. Downwash α_i/C_T (radians) behind 12-ft diameter rotor. $i_s = 0$ deg, $0{\cdot}75R$ from centre-line of rotor.

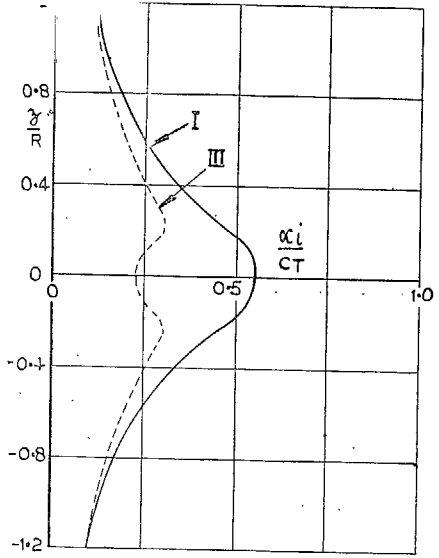

FIG.7(a) CALCULATED

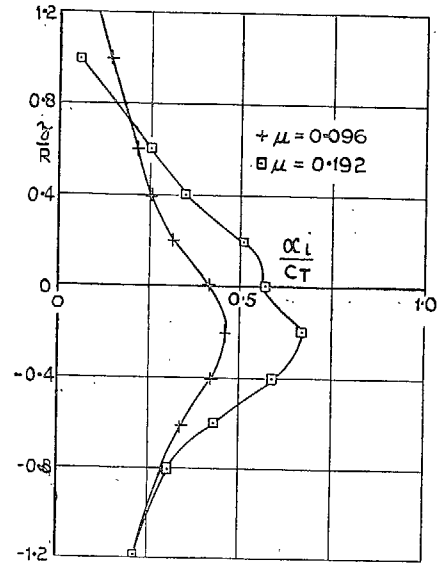

FIG.7(b) ADVANCING BLADE

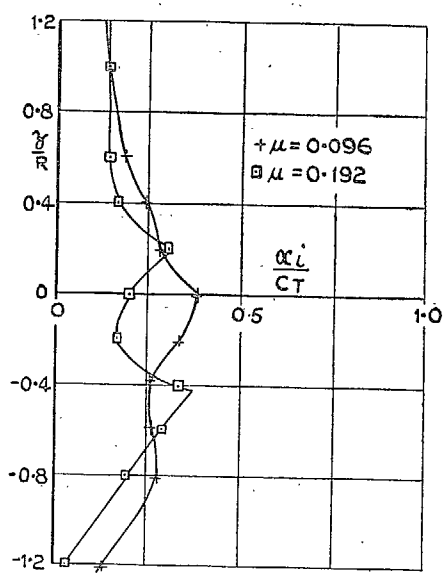

FIG.7(c) RETREATING BLADE

FIG. 7. Downwash α_i/C_T (radians) behind 12-ft diameter rotor. $i_s = 15$ deg, $0{\cdot}278R$ from centre-line of rotor.

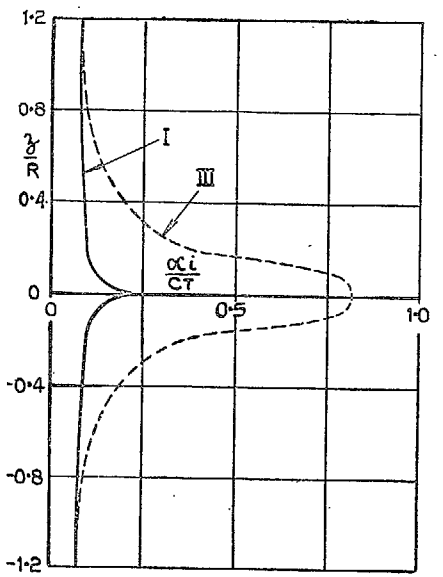

FIG 8 (a) CALCULATED

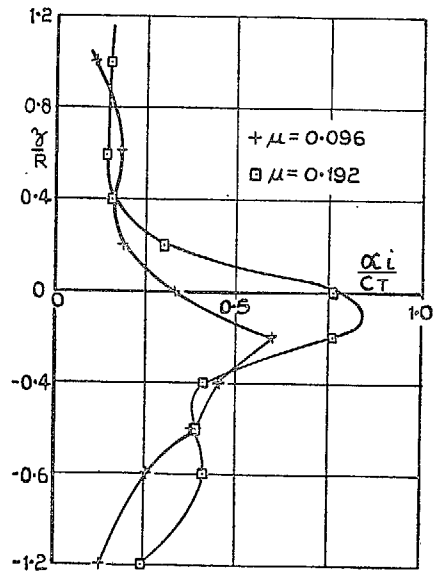

FIG.8(b) ADVANCING BLADE

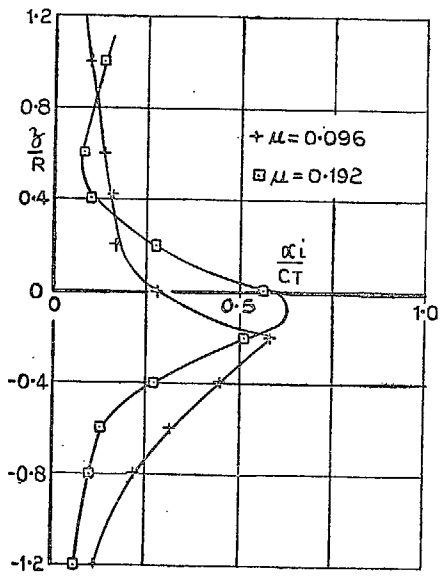

FIG.8(c) RETREATING BLADE

FIG. 8. Downwash α_i/C_T (radians) behind 12-ft diameter rotor. $i_s = 15$ deg, $0{\cdot}75R$ from centre-line of rotor.

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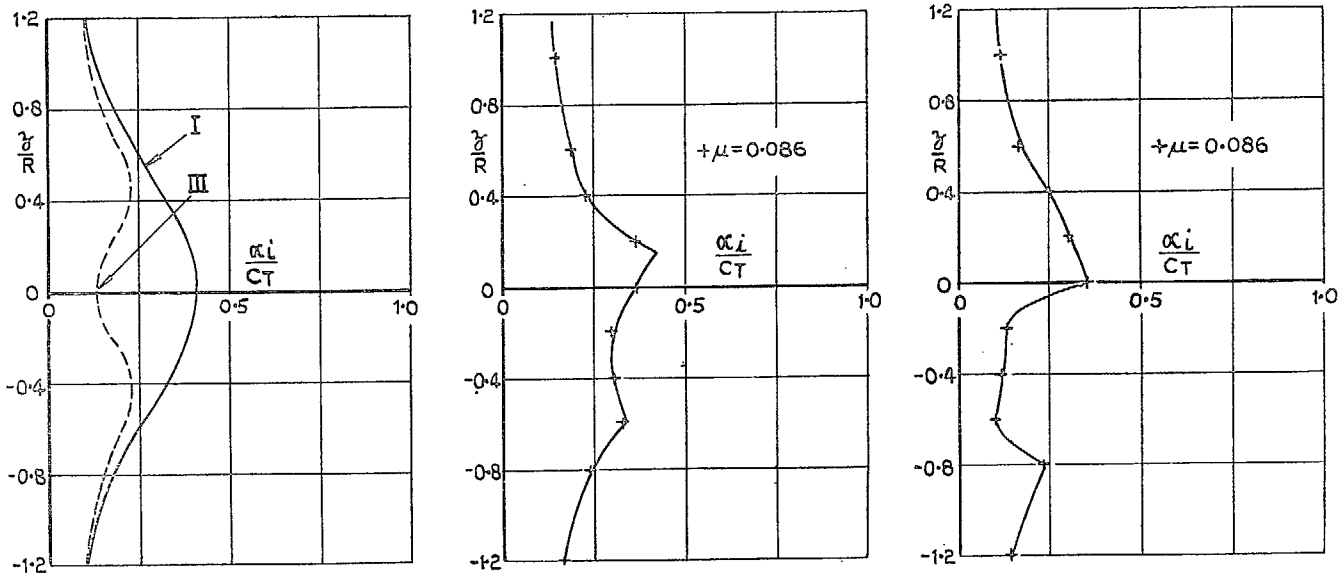

FIG. 9 (a) CALCULATED — FIG. 9 (b) ADVANCING BLADE — FIG. 9 (c) RETREATING BLADE

FIG. 9. Downwash α_i/C_T (radians) behind 12-ft diameter rotor. $i_s = 30$ deg, $0{\cdot}278R$ from centre-line of rotor.

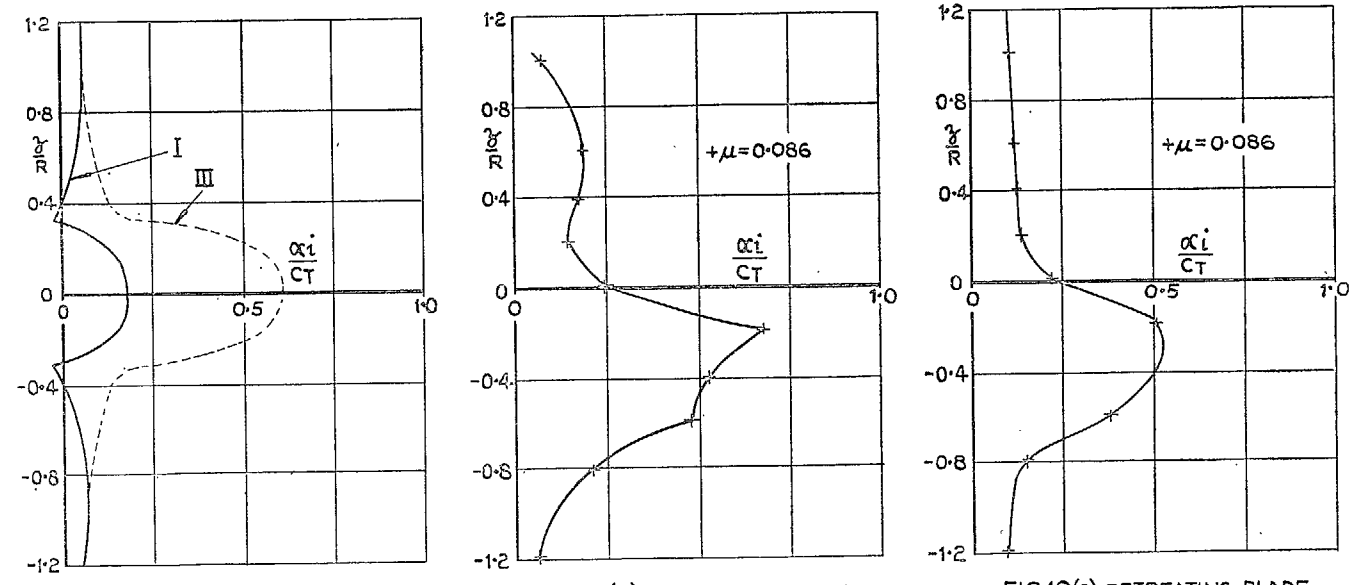

FIG.10(a) CALCULATED — FIG.10(b) ADVANCING BLADE — FIG.10(c) RETREATING BLADE

FIG. 10. Downwash α_i/C_T (radians) behind 12-ft diameter rotor. $i_s = 30$ deg, $0{\cdot}75R$ from centre-line of rotor.

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