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The influence of inlet bellmouth geometry on the performance of a ducted fan

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PREPARED BY H.S.Fowler

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NATIONAL RESEARCH COUNCIL
DIVISION OF MECHANICAL ENGINEERING
OTTAWA, CANADA
LABORATORY MEMORANDUM

SECTION Engine Laboratory

NO. NRC-ENG-16

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SUBJECT THE INFLUENCE OF INLET BELLMOUTH GEOMETRY ON THE PERFORMANCE OF A DUCTED FAN

PREPARED BY H. S. Fowler

ISSUED TO

THE INFLUENCE OF INLET BELLMOUTH GEOMETRY ON THE PERFORMANCE OF A DUCTED FAN

SUMMARY

The N.R.C. fan-in-wing VTOL scheme employs a ducted fan completely immersed in the wing of an aircraft. This means that the fan must have the minimum possible axial length, to allow its installation in the thickness of a thin wing section. An investigation of the relation between fan performance and inlet bellmouth dimensions was therefore carried out to find the minimum bellmouth size consistent with any desired fan performance. These experiments covered a range of fan hub/tip diameter ratios, and a large range of fan disc loadings.

INTRODUCTION

In the fan-in-wing VTOL scheme visualized at N.R.C. it is important to keep the fan to the minimum axial length, to allow it to be completely buried in a thin wing. After an extensive general exploratory programme, the 12-inch ducted fan rig in the Engine Laboratory at the National Research Council was therefore used to test a series of inlet bellmouths, over a large range of disc loadings, through a range of different hub/tip diameter ratios of the fan.

A general picture emerged, from which minimum desirable inlet bellmouth dimensions can be given for any particular combination of hub/tip ratio and disc loading. This picture is complicated by the fan characteristics, notably in the stalling region at maximum disc loading.

DESCRIPTION OF RIG

The 12-inch ducted fan test rig consists of a shaft running in oil mist-lubricated bearings, and driven by an air turbine at one end. The shaft is split near the turbine to take the quill shaft of an optical torquemeter, for power measurement. The experimental fan is mounted on the far end of the shaft. The six turbine nozzles are mounted three on each side of the wheel, so that the residual turbine thrust on the shaft is zero. This has been checked by calibration. The whole shaft mounting frame is held on flexure pivots at one end, and a hydraulic weighing cell at the other, to measure thrust.

Wall static tappings, pitot static arrays, and remote controlled traversing probes are mounted on the fan as required for each experiment. Pressures are recorded photographically from a 27-tube manometer bank.

The rig, which has been run at 20,000 r.p.m. on the 200 h.p. turbine, is set up in a jet engine test cell, and is operated from a control panel outside.

DETAILS OF BELLMOUTHS AND FANS TESTED

The series of bellmouth intakes tested is shown in Fig. 4. This provided a series of bellmouths having radius ratios, (i.e., lip radius/throat diameter,) of 1/2, 1/3, 1/4, 1/6, 1/12, 1/24, and $1/\infty$. Each of these was run with fans of hub/tip diameter ratios of .25, .375, and .5, in order to see whether the ratio of lip radius to annulus width was of importance. Since the smallest hub tested had a parallel shaft housing of full hub diameter built out from it, all hubs were fitted with a plain long cylinder of proportional diameter to obtain geometrical similarity. The variable bellmouth inlet tested was therefore confined to the outer wall of the inlet annulus.

The rotor blades are shown in Fig. 5. This shows that the blade form is the same in all cases, except that for other reasons the .375 H/T blades alone had no taper.* This appears to have given them a much more abrupt stall characteristic, which shows up in the performance curves.

All three blades had approximately free vortex twist, and the profile varied uniformly from 7.4% t/c Clark 'Y' at the tip to 17% t/c Sikorski GS-M at 3" P.C.D. This root section was only actually present on the .25 H/T fan; the blades with larger hubs were eclipsed by the hub before they reached this point.

TEST PROCEDURE

The fan was run over the range 6000 - 17000 r.p.m., and readings of thrust, shaft torque, r.p.m., exit air total pressure

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* Tip was increased to eliminate taper in the .375 H/T blades to obtain more blade area.

on a 27-point pitot rake, inlet barometric pressure and air temperature were taken at each 500 r.p.m. through this range. This run was accomplished in two parts, 6000 - 11000 r.p.m. using a small quill shaft in the torquemeter, and 10000 - 17000 r.p.m. with a heavier shaft. The curves of thrust vs. r.p.m. were found to overlap satisfactorily where the two ranges met.

Since the flow and r.p.m. could not be held perfectly steady, the 27-tube manometer readings were recorded photographically, to get a simultaneous picture. The validity of this method was shown by the repeatability of points, and the smallness of scatter of points.

DISCUSSION OF RESULTS

Figs. 6, 7 and 8 show the results of tests on the range of bellmouths, with hub/tip ratios .25, .375, and .50 respectively. The curves plot thrust (corrected to ICAN conditions) against bellmouth lip radius ratio (lip radius/throat diameter) for a series of constant corrected r.p.m. These curves have been obtained by cross-plotting from the usual curves of thrust vs. r.p.m. curves, at constant lip radius ratio.

These curves show the fall-off of thrust at a given speed with reduction of bellmouth lip radius in a very obvious way. It is interesting to notice that in the optimum region (e.g., 110-150 lbs. thrust, in Fig. 6) the thrust is unaffected by bellmouth lip radius right down to values of 1/12 lip radius ratio, or less, after which it falls off drastically. However, above, and to a lesser extent below, this optimum, a considerable region of gradual thrust fall-off exists. This is shown quantitatively in Fig. 9, which plots lines of 2% and 5% loss from the curves of Figs. 6, 7, and 8. These losses are based on the thrust at $r/D = 1/2$ as the 100% datum.

In the light of these tests, and of observations made during the programme as a whole, it appears that this behaviour is the result of two interacting effects. The slow loss of lift appears to be due to the loss of tip effectiveness of the fan, due to the alteration of tip incidence due to the wall effect close to the bellmouth.

Not directly related to this is the abrupt loss of lift when the blade stalls. The connection, although indirect, is still there, since the blade stalls from the tip inwards when the tip incidence is forced outside the working range by the fall-off in axial velocity at this point. However, this tip stall represents the complete loss of lift from an increasing length of blade. It is quite distinct from the increasing slight loss of lift from the tip region due to operating at a less favourable incidence but still within the working range.

This suggestion is confirmed by the fact that tests on blade twist for optimum performance have led to tip pitch angles coarser than those calculated from pure free vortex considerations.

It is interesting to notice that the stall line, which is basically a property of the blade sections rather than of the bellmouth, is definitely modified by the inlet flow. Of the three sets of blades, the .5 and .25 H/T sets are both tapered and stall in a gentle, progressive manner from the tip inwards. The .375 H/T blades differ only in the fact that they are not tapered, and they have a very abrupt stall, which appears to occur all up the blade at once. It is therefore very suggestive that the .375 H/T set is affected quite heavily over the slow loss increase region, which is not connected with stall. Its stall line,however,which is a full-span phenomenon, is hardly affected by bellmouth effects on the tip flow. The .5 and .25 H/T blades, which stall from the tip first, on the other hand, show the effect of bellmouth radius equally in both low-loss and stall regions.

CONCLUSIONS

1. The 12-inch O/D ducted fan has been run with a series of bellmouths, having lip radius ratios of from 1/2 to 0, at fan hub/tip diameter ratios of .5, .375, and .25. Curves are presented showing the loss of thrust due to reduction of bellmouth lip radius.

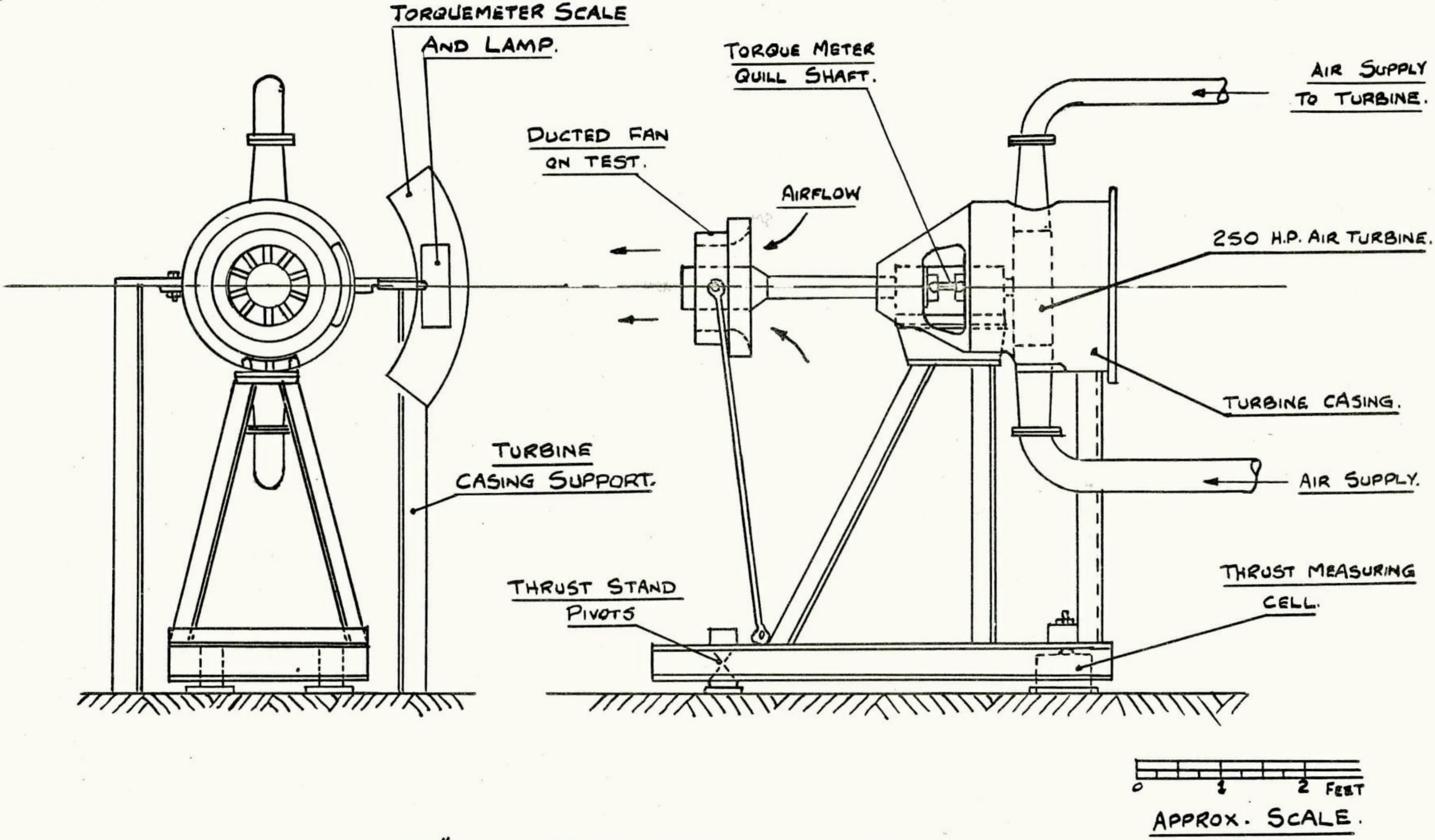
2. The relation between lip radius and thrust loss is complex, and no simple law can be stated to cover it. The two main causes are discussed in the report.

3. In general, it is suggested that, up to gross disc loadings of 200 lbs/ft^2, a bellmouth lip radius ratio (lip radius/throat diameter) of not less than 1/12 is advisable, while for higher disc loadings this figure should be increased to 1/6 or even higher.

4. Apart from the stall characteristics of the blading, a lower value of fan hub/tip ratio requires an increase of bellmouth lip radius ratio to have the same operating range;

but this effect is small, and is critically dependent on the stalling characteristics of the blades.

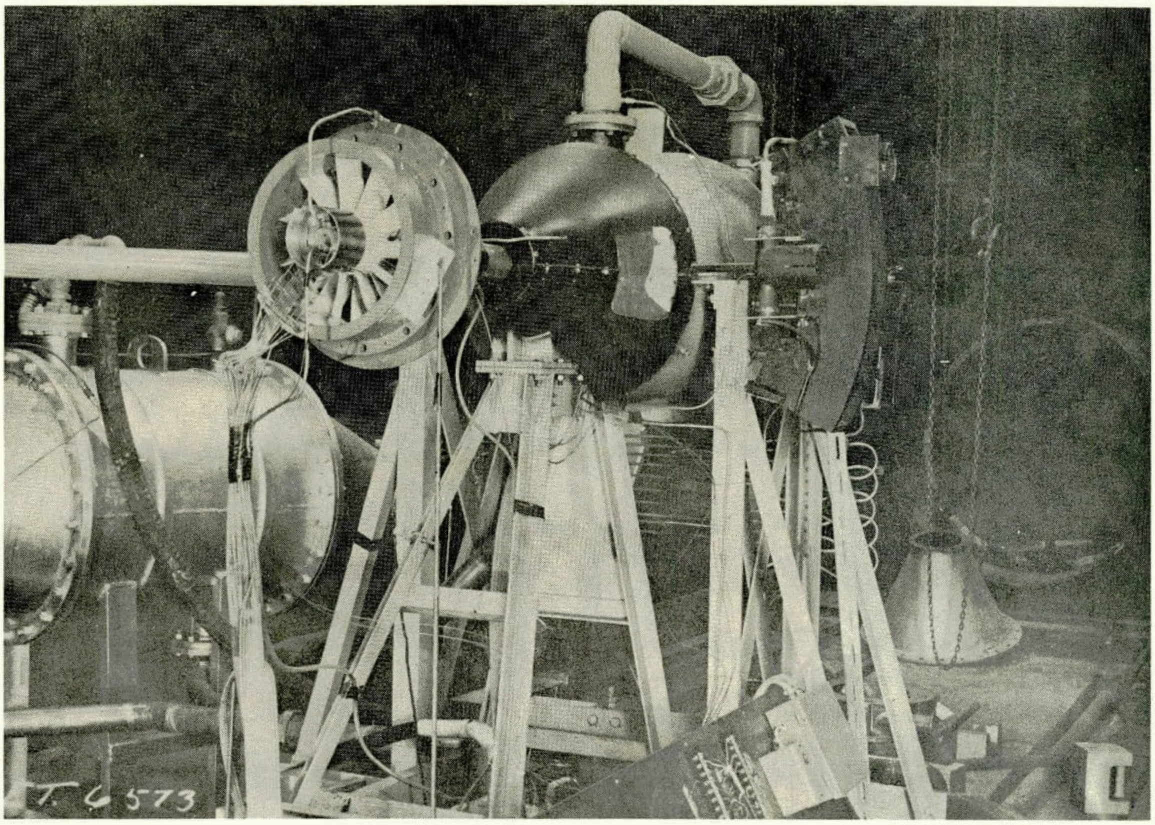
5. It has been shown that in the present set-up there is close interaction between bellmouth and fan flow profiles and characteristics. The investigation described here has considered the bellmouth purely as a fan inlet, and not as a device converting pressure to velocity with an efficiency to be found. It would be of interest to investigate the optimum proportions of a bellmouth in uniform flow, without interference from fan characteristics.



12" V.T.O. DUCTED FAN TEST RIG.

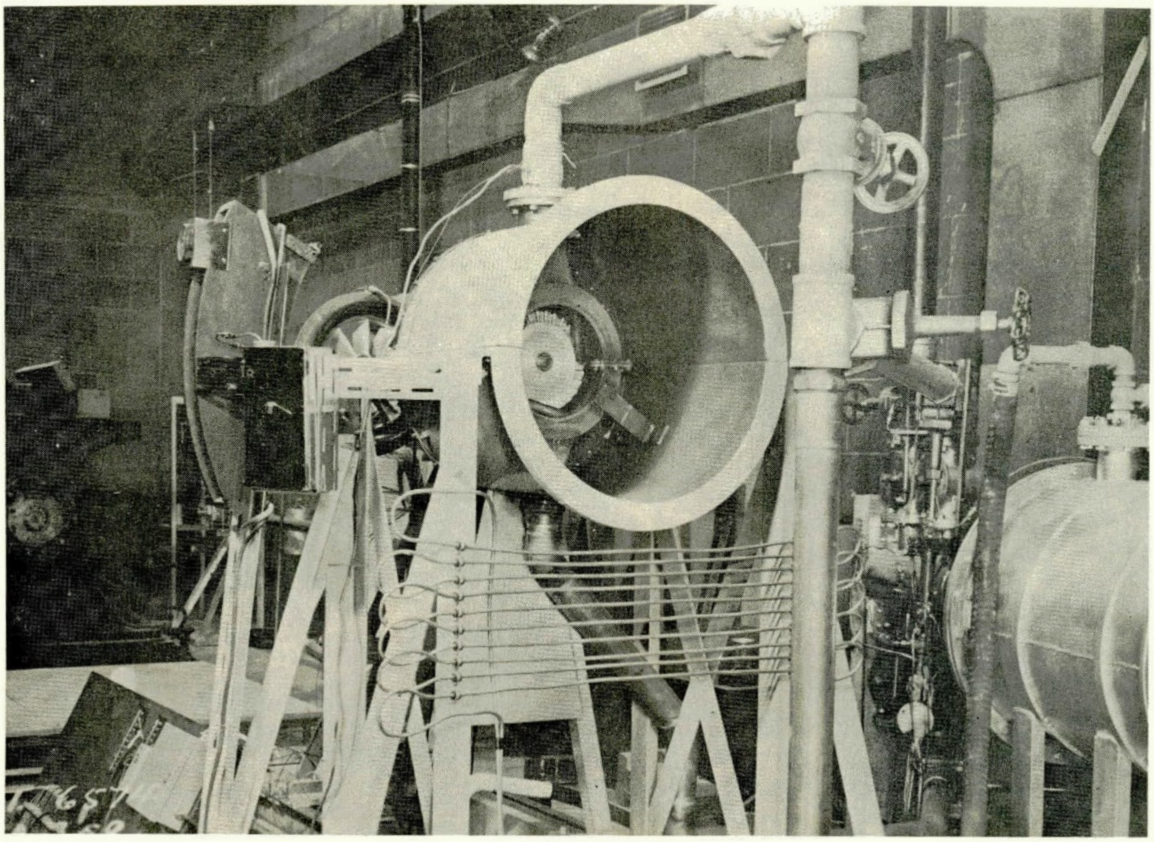
ENGINE LABORATORY.

FIG. 1.



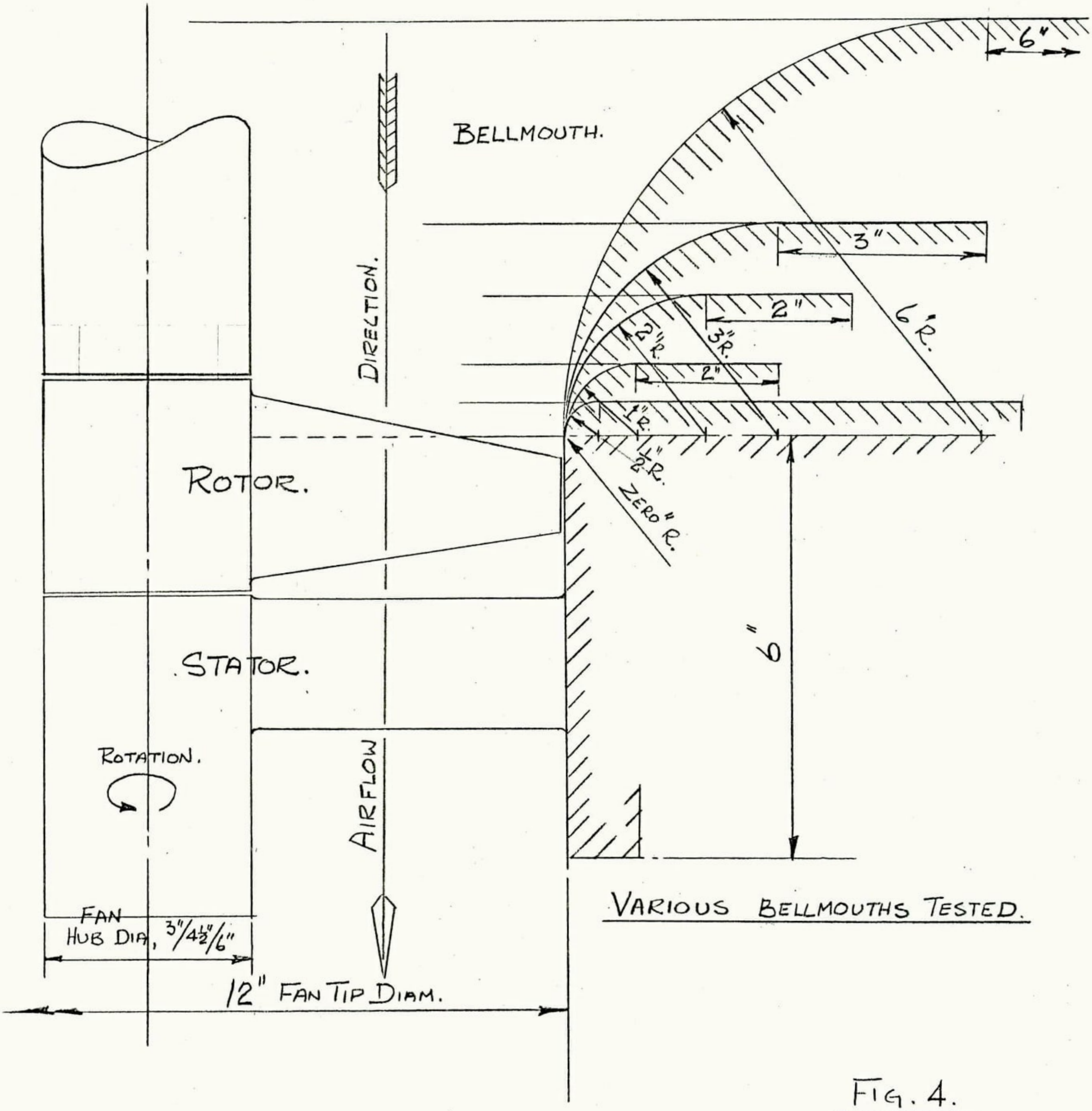
FAN END OF RIG.

FIG. 2.



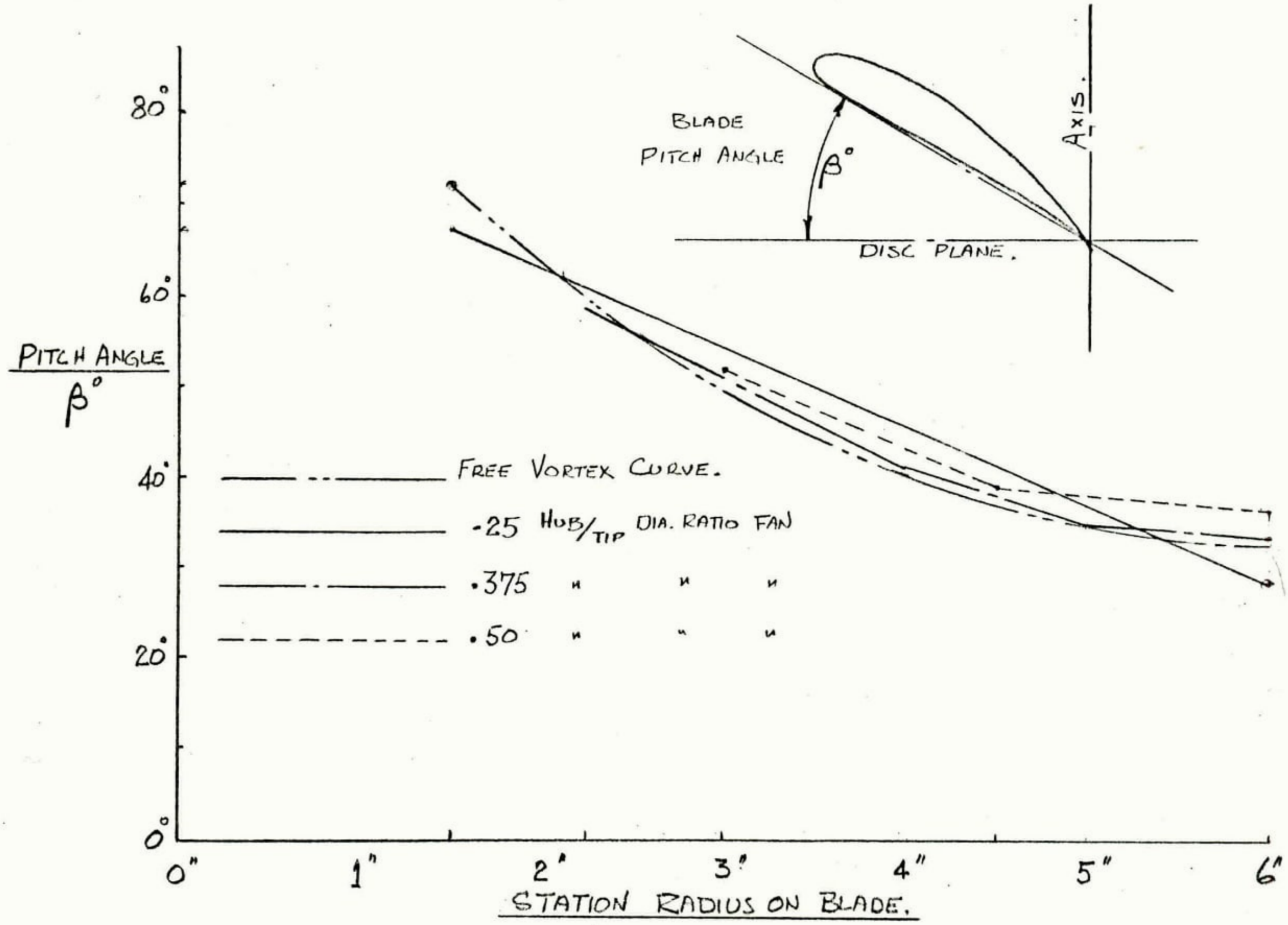
TURBINE END OF RIG.

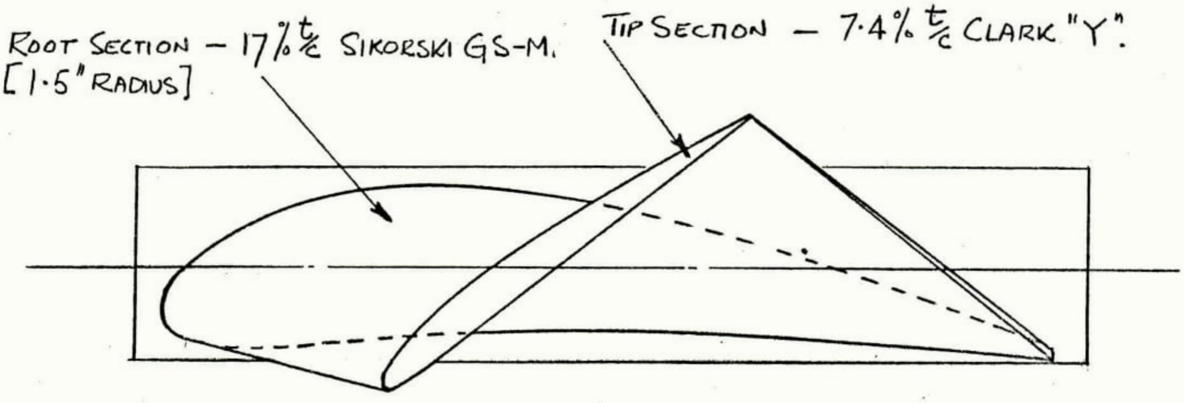
FIG. 3.



VARIOUS BELLMOUTHS TESTED.

FIG. 4.





END VIEW OF ·25 H/T BLADE [2× FULL SIZE]
SHOWING AEROFOIL SECTIONS.

ROTOR BLADES

FIG 5.

0·25 H/T RATIO

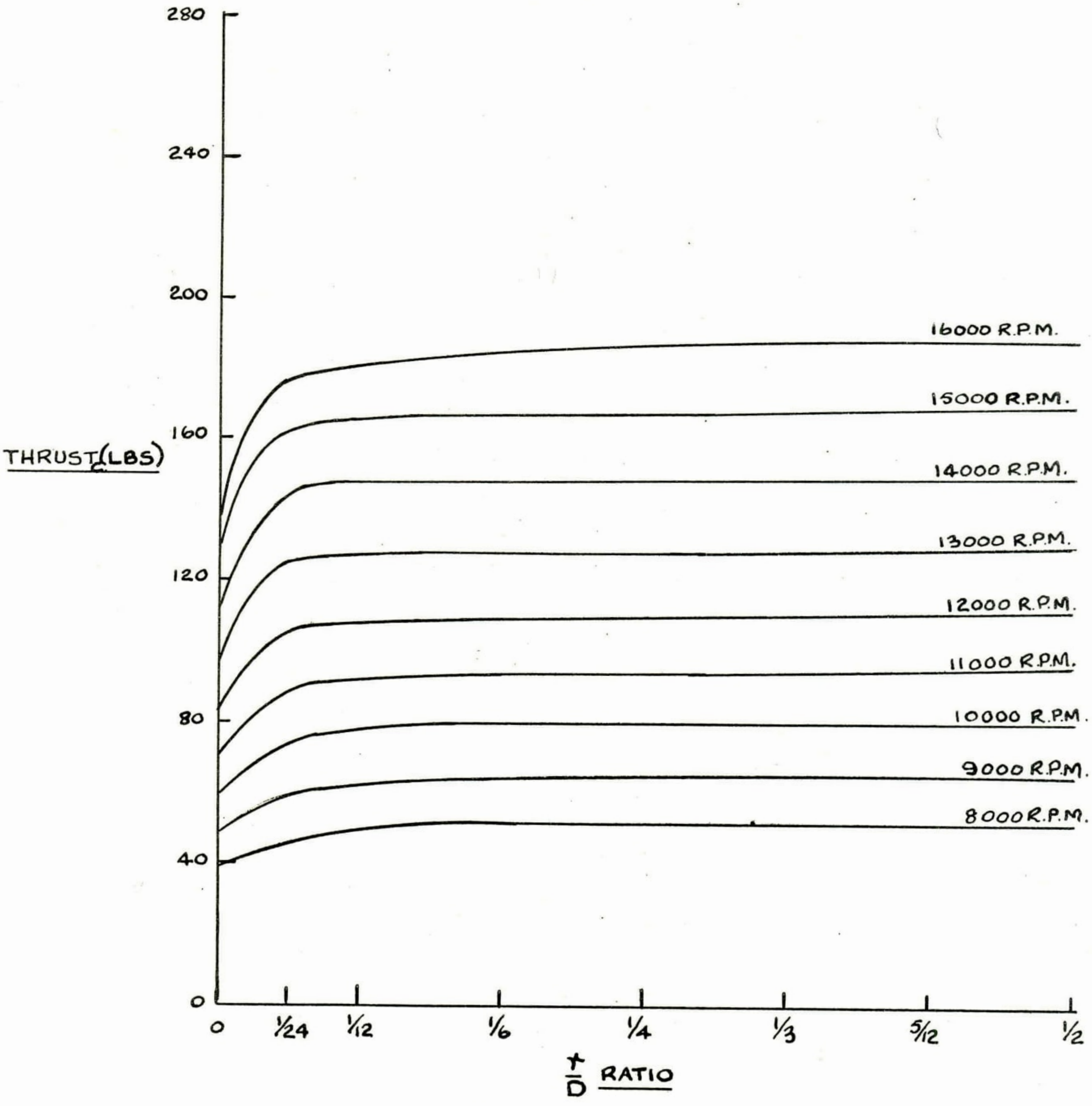


FIG. 6.

0·375 H/T RATIO

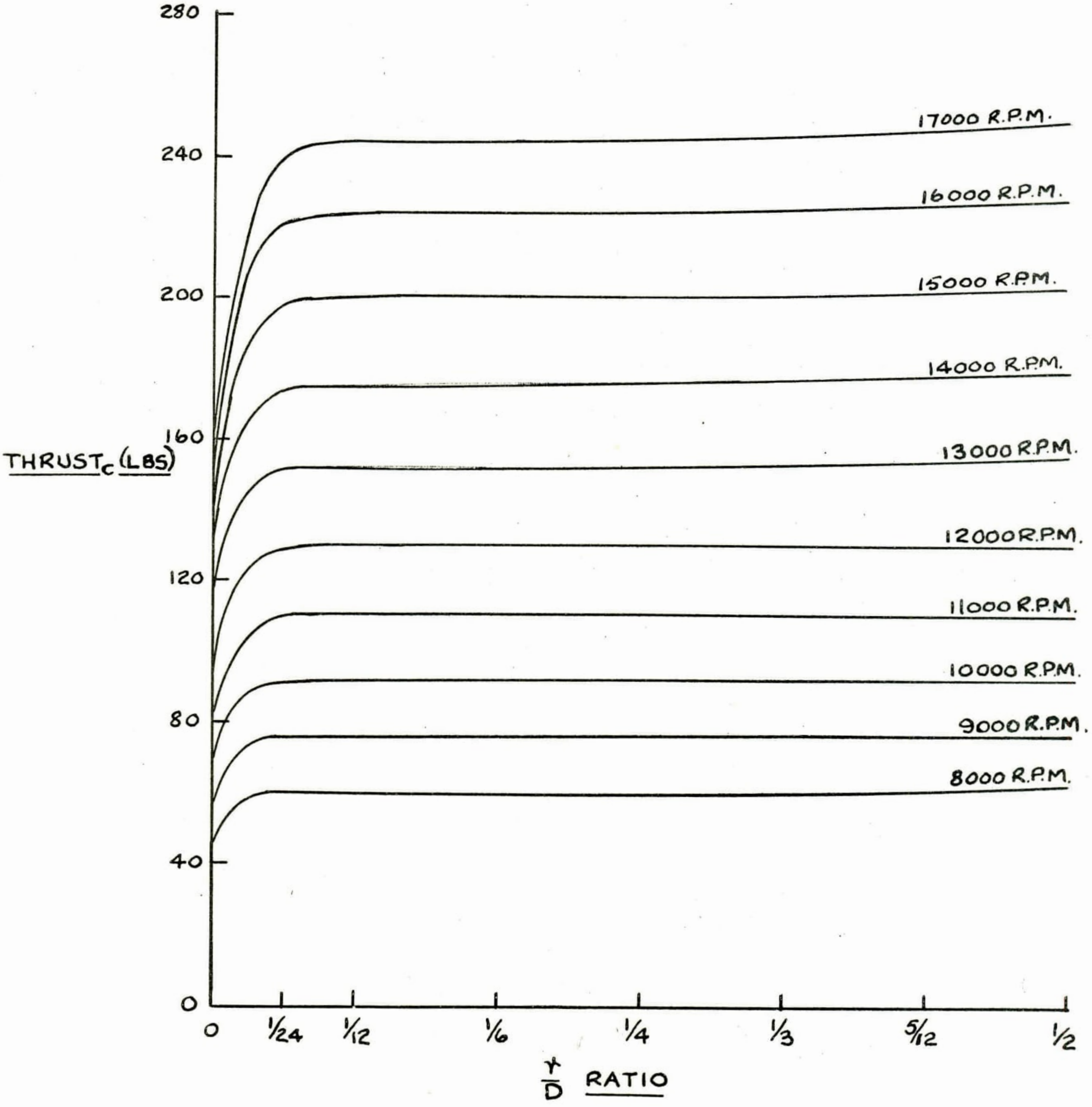


FIG. 7.

0·5 $^H/_T$ RATIO

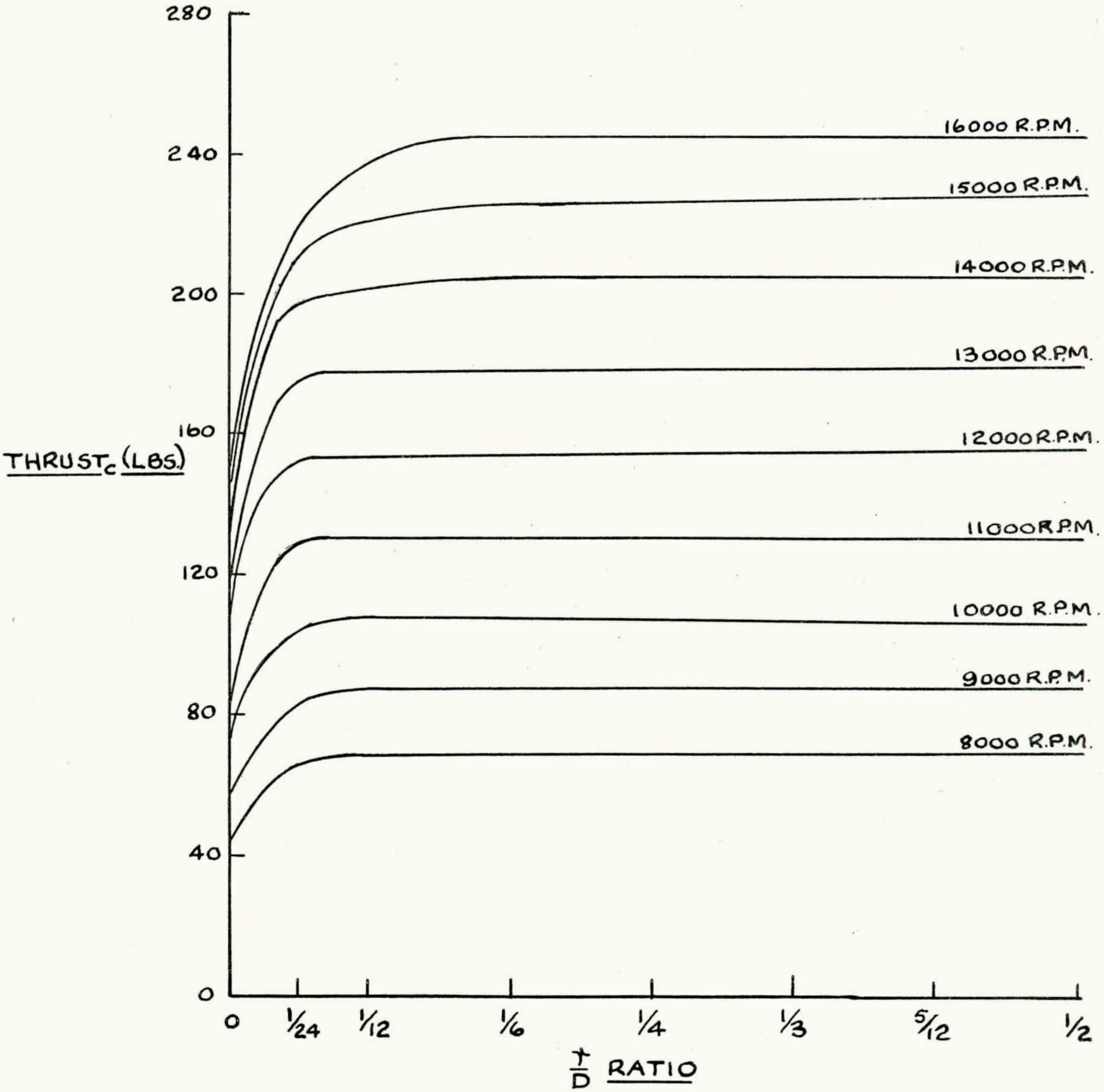


FIG. 8.

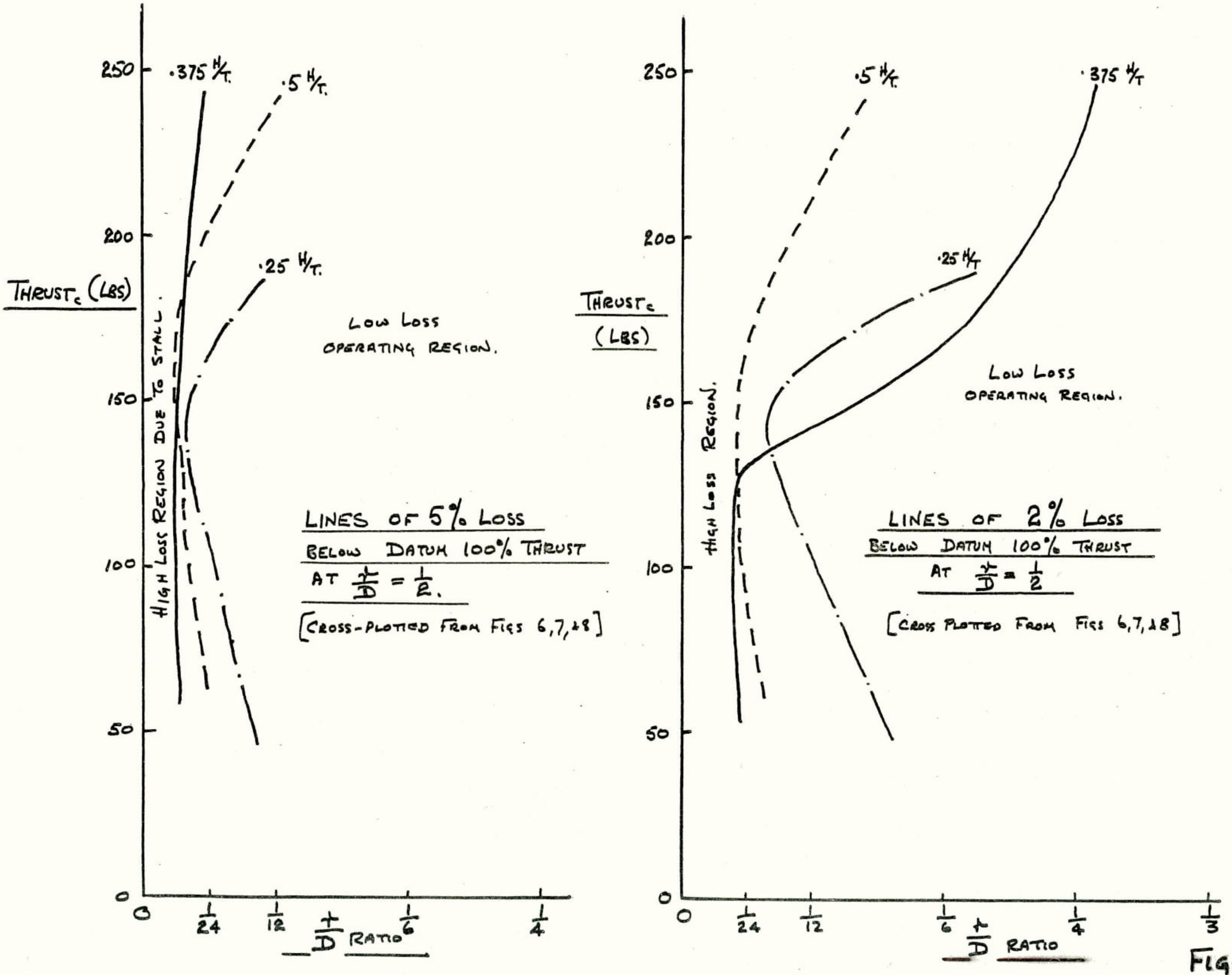

250
200
150
100
50
0
THRUST$_c$ (LBS)
·375 H/T.
·5 H/T.
·25 H/T.
LOW LOSS OPERATING REGION.
HIGH LOSS REGION DUE TO STALL
LINES OF 5% LOSS
BELOW DATUM 100% THRUST
AT $\frac{r}{D} = \frac{1}{2}$.
[CROSS-PLOTTED FROM FIGS 6,7,&8]
0
$\frac{1}{24}$
$\frac{1}{12}$
$\frac{1}{6}$
$\frac{1}{4}$
$\frac{t}{D}$ RATIO
250
200
150
100
50
0
THRUST$_c$ (LBS)
·5 H/T.
·375 H/T
·25 H/T
LOW LOSS OPERATING REGION.
HIGH LOSS REGION.
LINES OF 2% LOSS
BELOW DATUM 100% THRUST
AT $\frac{r}{D} = \frac{1}{2}$
[CROSS PLOTTED FROM FIGS 6,7,&8]
0
$\frac{1}{24}$
$\frac{1}{12}$
$\frac{1}{6}$
$\frac{1}{4}$
$\frac{1}{3}$
$\frac{t}{D}$ RATIO

FIG. 9.