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Observations of Stall Cells in a Single Stage Compressor

by

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Observations of Stall Cells in a Single Stage Compressor

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SUMMARY

A specially developed pressure-measuring instrument has been used to observe instantaneous values of the pressure, velocity and direction of the flow in a single stage, low hub-tip ratio, axial compressor. During stall propagation, the flow appeared to change from a point on the unstalled characteristic towards a point on the fully stalled characteristic and back again. The stall cells occurred only at the tips of the rotor blades. Despite these large fluctuations in the instantaneous flow, the time-average overall pressure rise characteristic was of the "progressive stall" type. The experiment demonstrated, therefore, a realistic model for the theoretical analysis of fully-developed stall cells.

Introduction

Existing theories of stall propagation are, with one exception, based on the small perturbation approach. Small perturbation theories give a stability criterion which establishes the point of stall inception, and the velocity of propagation of "small" cells. Fully developed stall cells are found to be so large, however, that they cannot adequately be represented as a small perturbation of the unstalled flow, so some other mathematical "model" is needed, which must necessarily be non-linear, as a basis for further analysis.

One published theory based on a non-linear model is that of Fabri and Siestrunck[1]. They postulated that the flow divided into two separate régimes,

(a) Unstalled flow at the peak of the pressure rise characteristic.

(b) Stalled flow at zero velocity and the same outlet static pressure.

McKenzie[2] proposed a more general model, in which the two régimes were,

(a) Unstalled flow at some point on the pressure rise characteristic.

(b) Stalled flow at the point on the stalled branch of the pressure rise characteristic at the same outlet static pressure.

Another non-linear theory is given in Ref. 3.

However/

Previously issued as A.R.C.22,915.

However, the outlet static pressure of the stalled flow is not necessarily the same as that of the unstalled flow, especially in multistage compressors. A more satisfactory general model simply postulates that the pressure rise is a two-valued function of the mass flow, and that the flow during stall propagation seeks equilibrium at points on each branch alternately.

That the detailed nature of stall cells should still be a matter of debate 18 years after their discovery shows how difficult it is to observe them. Three methods have been reported:-

(1) Hot wire anemometers are usually used. They give accurate values of stall propagation velocity and stall cell width, and estimates of velocity fluctuation. They cannot indicate the pressure.

(2) A few investigations have been made with pressure transducers, usually at wall static tappings.

(3) With inlet guide vanes set very much at the "wrong" angle, the stall propagation speed can be reduced to zero. The aerodynamic conditions can then be observed with conventional pitot tubes and yawmeters. This excellent method (Ref.3) is open only to the objection that the conditions are very unrealistic.

Ideally, instantaneous measurements of the pressure, velocity, and direction of the flow at any point are required. An attempt to do this is described in this report, using a pressure transducer instrument. Its design, development, and method of operation are fully described in Ref.4. The experimental results are examined to see how they compare with the proposed model. A necessary preliminary was a thorough survey of the flow conditions using a conventional 3-hole tube.

The Compressor

The experiments were carried out on the two-stage 0.4 hub-tip ratio compressor in the Cambridge University Engineering Laboratory, described in Ref.5. Only a single stage was included, inlet guide vanes followed immediately by rotor blades and stator blades. After a long gap (due to the absence of the second stage) came a row of outlet guide vanes. Provision for traversing over an arc of 36°, at all radii, in front of and behind every blade row except the outlet guide vanes, was available, Fig.1 is a diagrammatic layout of the compressor. Details of the blading are given in Fig.2.

The compressor was driven at 4,500 r.p.m. by an electric motor. Wall static pressure tappings were provided in the various traversing planes, there was a calibrated airmeter, and a torquemeter. The outlet static pressure was measured as the mean of 5 outer wall tappings and 5 inner wall tappings. An outlet throttle controlled the flow.

This compressor, and this blading, had been used previously by Horlock[5] for actuator disc experiments, and its stalling characteristics had been thoroughly investigated by Wood, Horlock and Armstrong[6], using a hot wire anemometer.

Experimental Procedure and Results

For the purpose of this experiment, a single circumferential position was chosen, well clear of the wake of the stator blades, and all readings were taken at that position. Three radial positions were then chosen, at radii 3.6 in., 4.9 in. (the mean radius) and 6.5 in., as representative of root, mean, and tip sections respectively (see Fig.1). All readings were taken at one of these three locations, and are labelled root, mean, or tip accordingly. So the total number of sets of readings at any throttle setting was:-

$$\left.\begin{array}{l}\text{before IGV's}\\ \text{after IGV's}\\ \text{after rotors}\\ \text{after stators (plane S)}\\ \text{2.1 in. downstream of plane S}\\ \text{4 in. downstream of plane S}\end{array}\right\}\ \text{at root, mean, tip} = 18$$

(1) The overall characteristics (Fig.3) of the compressor were measured, as a function of the flow-coefficient

$$\frac{\overline{V_a}}{\overline{U}} = \frac{\text{average axial velocity}}{\text{blade velocity at mean flow radius}} = \frac{\text{mass flow}}{\text{flow area}} \times \frac{1}{\text{blade velocity at mean flow radius}}$$

(2) Using a standard 3-hole tube, and manometers (Ref.5), the pressure, velocity, and flow angle were measured at a wide range of throttle settings from fully unstalled to fully stalled. During stall propagation, these values were in effect time average values. In Figs.4 to 6 the local axial velocity at each section is shown in terms of the average axial velocity through the compressor. In Figs.7-30, all the other measurements are plotted in terms of the local velocity. All the parameters are expressed non-dimensionally. (Note: 2.35 in. meths was equivalent to a $p/\rho U^2$ of 0.1.)

(3) It was found that stall cells were only obtainable at two particular throttle settings; one gave a single cell pattern and the other a two-cell pattern. Using the high-frequency response instrument, estimates were made of the instantaneous values of pressure, velocity, and flow angle for the unstalled and stalled parts of the flow. The time average pressure readings at each point were also obtained by connecting a manometer to the probe. All these results are also plotted in Figs.7-30, at the appropriate instantaneous flows.

The technique for making the instantaneous flow readings is explained in Ref.4. Some typical oscillograph photographs in Fig.31 illustrate the highly turbulent nature of the flow within the stall cell. There was no question of plotting pressure against time; all that could be done was to make an estimate of the pressure in the middle of the stall cell, averaging out the turbulence by eye. The measurements were made by using the previously calibrated shift controls on the oscillograph; no film measurements were attempted, but films were useful in eliminating spurious readings. As explained in Ref.4, the stalled and unstalled pressures were measured over a range of yaw angles. Fig.32 shows a typical result: the measure of consistency in the stalled readings justifies the use of the method, and gives some idea of its accuracy.

Analysis of the Results

The operating range of the compressor can be divided up into the following regions:-

(1) Completely unstalled $\overline{V_a}/\overline{U} > 0.53$.

(2) Stator root only stalled $0.53 > \overline{V_a}/\overline{U} > 0.44$.

When the air angle approaching the stators at the root exceeded 40°, they stalled. This happened below a local $V_a/\overline{U}$ of 0.48. The outlet angle changed and the stagnation pressure loss increased sharply. (Figs.10, 12, 19, 22.) The axial velocity through the tip section was constant

throughout/

throughout this region (Fig.6). There was a tendency to form stall cells at the stator root, but they were too irregular for any measurements to be made on them.

(3) Rotor tip stalled: single stall cell: $0.43 < \overline{V_a}/\overline{U} < 0.44$

When the relative inlet angle to the rotors, at the tip, fell below 67°, they stalled. A single stall cell appeared suddenly, rotating at 0.51 × blade speed. It can be seen in Fig.31 that the pressure change at the edge of the stall cell was by no means instantaneous; the change of about 10 in. meths. took place in 0.01 secs. The response of the instrument is much faster than this, and Wood[7] using a hot wire anemometer with a much better response observed a similarly shaped stall cell. The observed rate of change of pressure at the boundary of the stall cell can be expected to depend on boundary layer effects at the blade row, and the distance of the probe downstream of the blade row.

The instantaneous flow measurements in Figs.9, 11, 18 and 21 showed the stall cell to be a violent disturbance of the flow. Air was centrifuged outwards in the stalled blade passages of the rotor, and blown forwards towards the IGV trailing edges; the stagnation pressure of the centrifuged air was very high. Only a small flow emerged from the trailing edges of the rotors.

The stall cell covered only the tips of the rotor blades. At the mean section, there was a tendency for the flow to increase during the passage of a stall cell rather than decrease. Diversion of the flow from the tip sections towards the hub unstalled the stator root section, but (Figs.22, 25, 28) this three-dimensional effect had the result that the pressure rise characteristic did not follow the previously observed unstalled branch.

(4) Rotor tip stalled: two stall cells $0.40 < \overline{V_a}/\overline{U} < 0.43$

A further slight movement of the throttle caused a sudden jump to a two stall cell pattern rotating at the same speed. In this case (Fig.31) the rate of pressure change across the edge of the stall cells was similar to the single stall cell case, and the flow had not time to reach its "equilibrium" value when the next edge was reached. This reflects in the instantaneous readings; fully unstalled conditions were not reached. Otherwise the flow was similar to the single cell pattern. The stall pattern was subject to a slight hysteresis; on unstalling, changes of régime were delayed by a $\overline{V_a}/\overline{U}$ of the order of 0.015.

(5) Rotor tip fully stalled $0.32 < \overline{V_a}/\overline{U} < 0.40$

With further throttling, the stall cells broke up into confused turbulence, of an amplitude generally similar to that of the stall cells. The time average flow at the tip section was about the same as the flow within the stall cells during the stall propagation régimes; that is, small flows centrifuged up the rotor blade passages and emerging from both leading and trailing edges. This was pointed out in Ref.5, but only the use of the new pressure-measuring instrument in the present tests showed the stall cells to be of this nature too.

(6) Mean section stalling: 0.22 (lowest tested) $< \overline{V_a}/\overline{U} < 0.32$.

Below a $\overline{V_a}/\overline{U}$ of about 0.32, the stalling spread to the mean section. After the stator blades, a redistribution of the flow now started to take place. The air tended to flow outwards away from the hub, leaving the root section downstream of the stators with a very low flow, and causing a pressure recovery at the tip section.

Discussion

The shape of the observed stall cells shows that the flow does not, in fact, jump suddenly from unstalled to stalled and back again. It seems reasonable to suggest that the "equilibrium" conditions jump suddenly, but that the actual flow can only change towards the hypothetical "equilibrium" states at a limited rate.

Figs.6, 11 and 21 show that at the rotor tip, the time average flow during stall propagation can be divided into unstalled flow at a point on or near the unstalled branch of the characteristic, and stalled flow apparently seeking an "equilibrium" state, as explained, on the fully stalled branch of the characteristic. This fully stalled branch is obtained by conventional measurements at very low compressor flows. The pressure rise characteristic of the tip section, then, is sharply discontinuous; points appearing in between the two branches are only time average observations during stall cell régimes. The mean section only stalls at very low flows; the characteristic is probably of a similar two-branch nature. Otherwise, the operating points at the root and mean sections are exclusively on unstalled branches of the pressure rise characteristics of the rotor.

So the combination of time-average points on two-branch characteristics and steady flow points on unstalled characteristics contributed to the typical "progressive stall" characteristic, Fig.3. These experiments have demonstrated that a "progressive stall" does not mean that the stall cells themselves are small flow changes.

There is a clear distinction between stall cells, involving a jump from one characteristic branch towards another, and the wakes of stall cells, such as are found at the mean section $(\bar{V}_a/\bar{U} > 0.32)$ and are oscillations up and down the same branch.

The static pressures of the stalled and unstalled flows are equal after the stators, but after the rotors the static pressure of the unstalled flow tends to be slightly higher than that of the stalled flow.

Conclusions

Use of a specially developed pressure measuring instrument with a rapid response, in conjunction with conventional methods, has enabled a detailed examination of the flow through the compressor to be made at all flow conditions. The "progressive stall" characteristic is shown to be built up by time-average observations of a violent partial-span stall cell pattern involving reverse flow. It seems likely that this pattern is obtained from a pressure rise characteristic at the tip section comprising two separate branches, stalled and unstalled, and that the flow jumps from one branch towards the other, and back again. Such a model would afford a realistic basis for theoretical studies of stall propagation.

Acknowledgement

The author gratefully acknowledges the support of a D.S.I.R. Research Fellowship in carrying out this project.

References/

References

No.	Author(s)	Title, etc.
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2	A. B. McKenzie	Rolls-Royce Ltd., unpublished report.
3	A. H. Stenning, B. S. Seidel and Y. Senoo	Effect of cascade parameters on rotating stall. NASA Memo. No.3-16-59W (NASA/TIL 6335). April, 1959.
4	J. Dunham	A rapid response pressure measuring instrument for compressor research (unpublished). March, 1961.
5	J. H. Horlock	Some aerodynamic problems of axial flow turbomachines. Cambridge University Ph.D. Thesis, 1955; see also: Experimental and theoretical investigations of the flow of air through two single stage compressors. A.R.C. R. & M.3031, March, 1955.
6	M. D. Wood, J. H. Horlock and E. K. Armstrong	Experimental investigation of the stalled flow of a single stage axial compressor. A.R.C.17,280. November, 1954.
7	M. D. Wood	Stall propagation in axial flow compressors. Cambridge University Ph.D. Thesis 1955.
8	A. R. Kriebel, B. S. Seidel and R. G. Schwind	Stall propagation in cascade of airfoils. NASA TR R-61, 1960.

WS

APPENDIX

Rapid-Response Pressure Transducer

Ref. 4 is being prepared for publication; this note is added to make the present paper self-contained.

The instrument used to observe instantaneous flows was a single hole pitot tube, with a transducer arranged to display, on an oscillograph, a signal proportional to the instantaneous pressure. The pressure registered by a pitot tube is a known (directly calibrated) function of the angle between the direction of the flow ("air angle") and the direction in which the pitot hole is pointed ("yaw angle"), so that pressure readings at a range of yaw angles, as in Fig. 32, enable the stagnation pressure, static pressure, and air angle, and hence velocity, to be deduced. In a steady flow, this method is much slower than using a 3-hole tube. In a periodically fluctuating flow, on the other hand, the 3-hole tube cannot be used owing to changes in air angle, but the single hole tube method remains possible.

FIG. 1. COMPRESSOR.

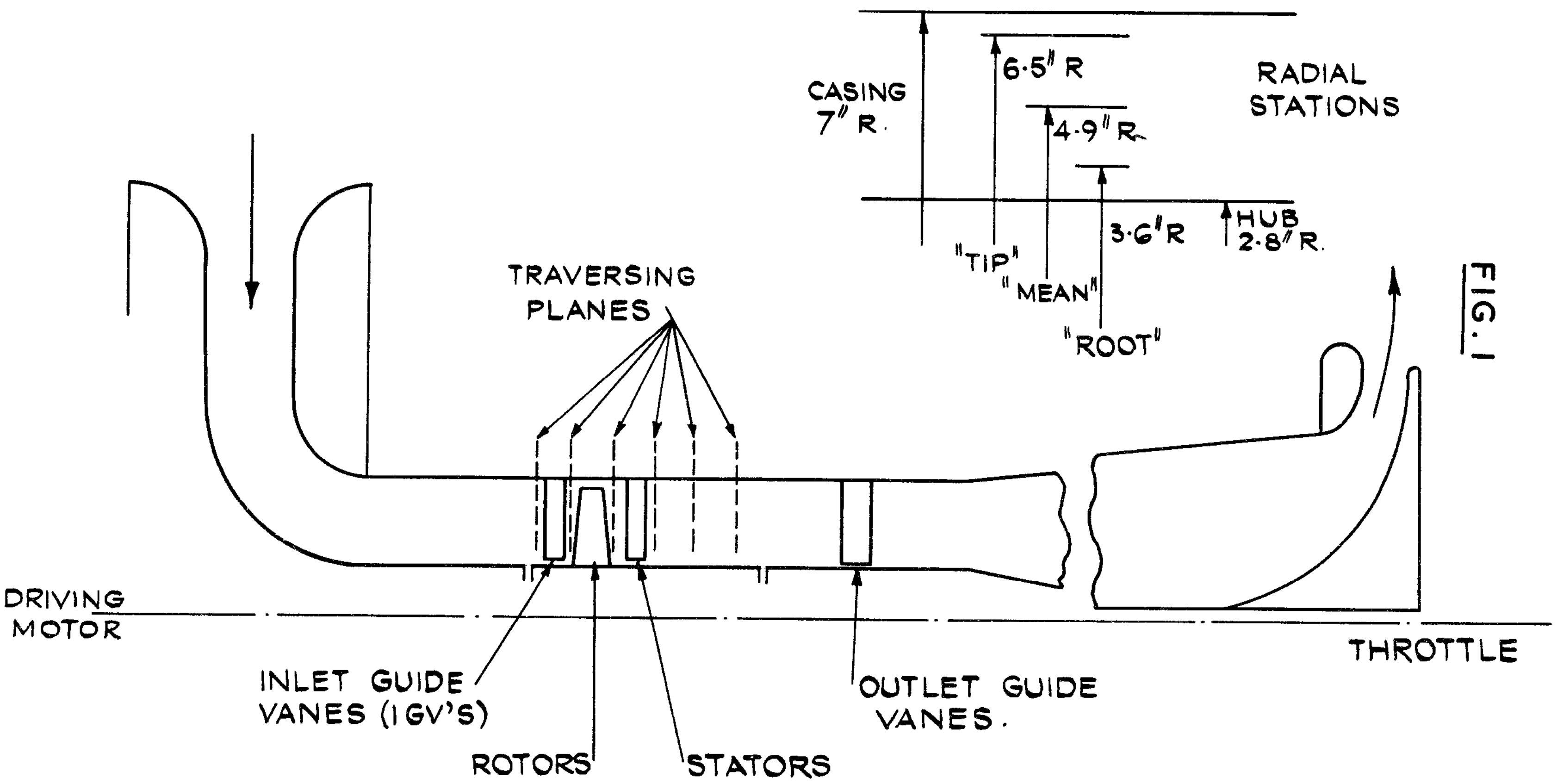
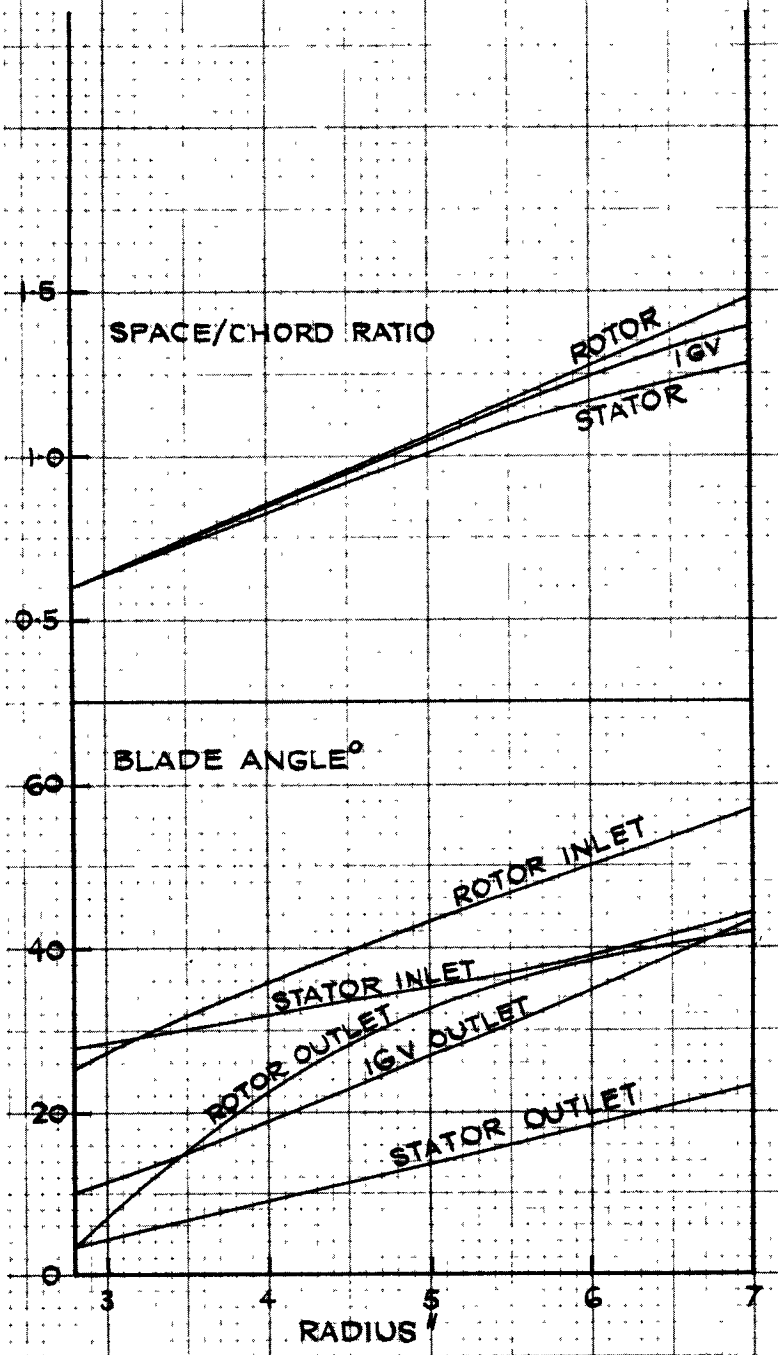


FIG. 1

AFTER REF. 5.

FIG. 2. BLADING



FROM REF. 5.

FIG 3. OVERALL CHARACTERISTICS.

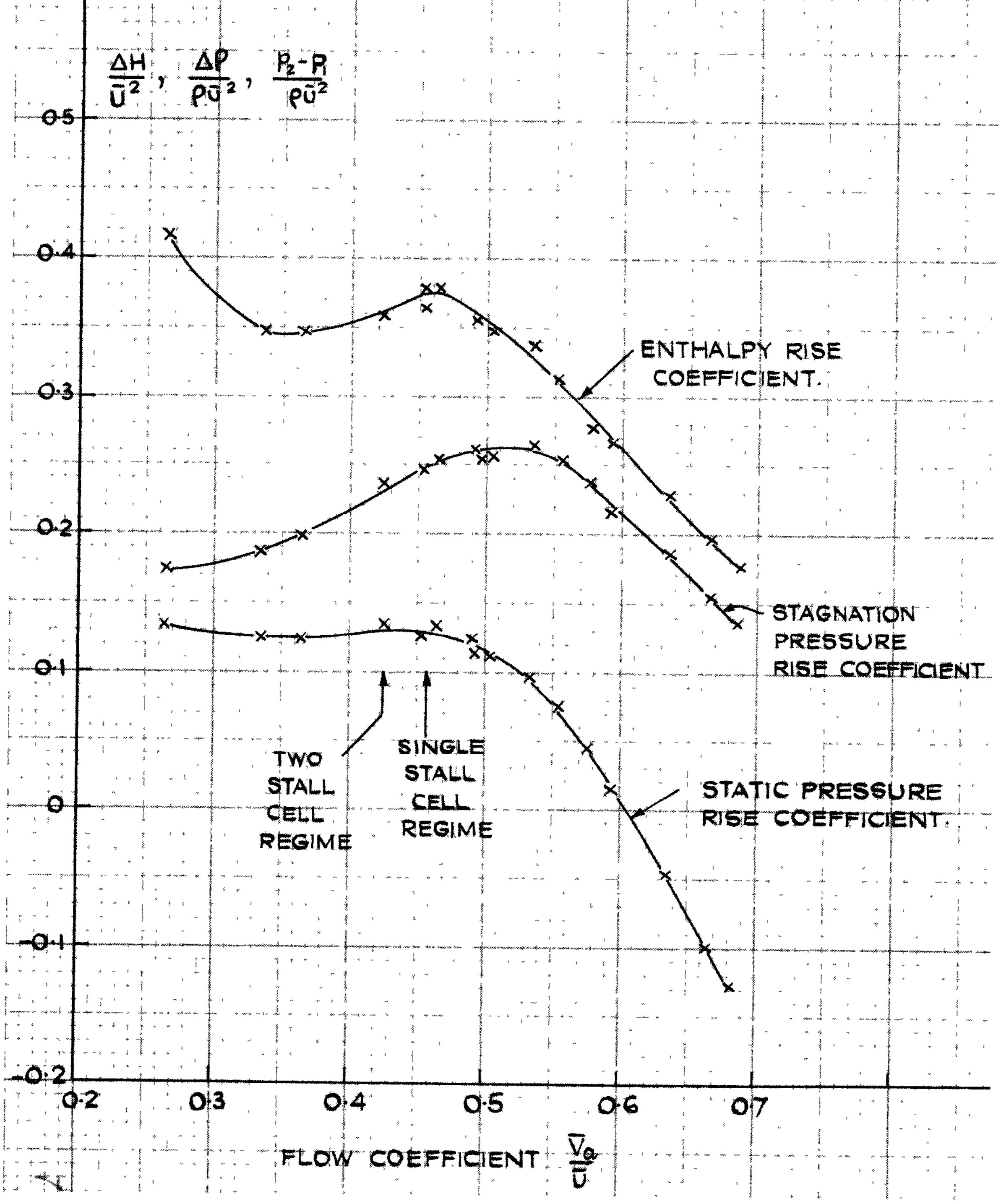
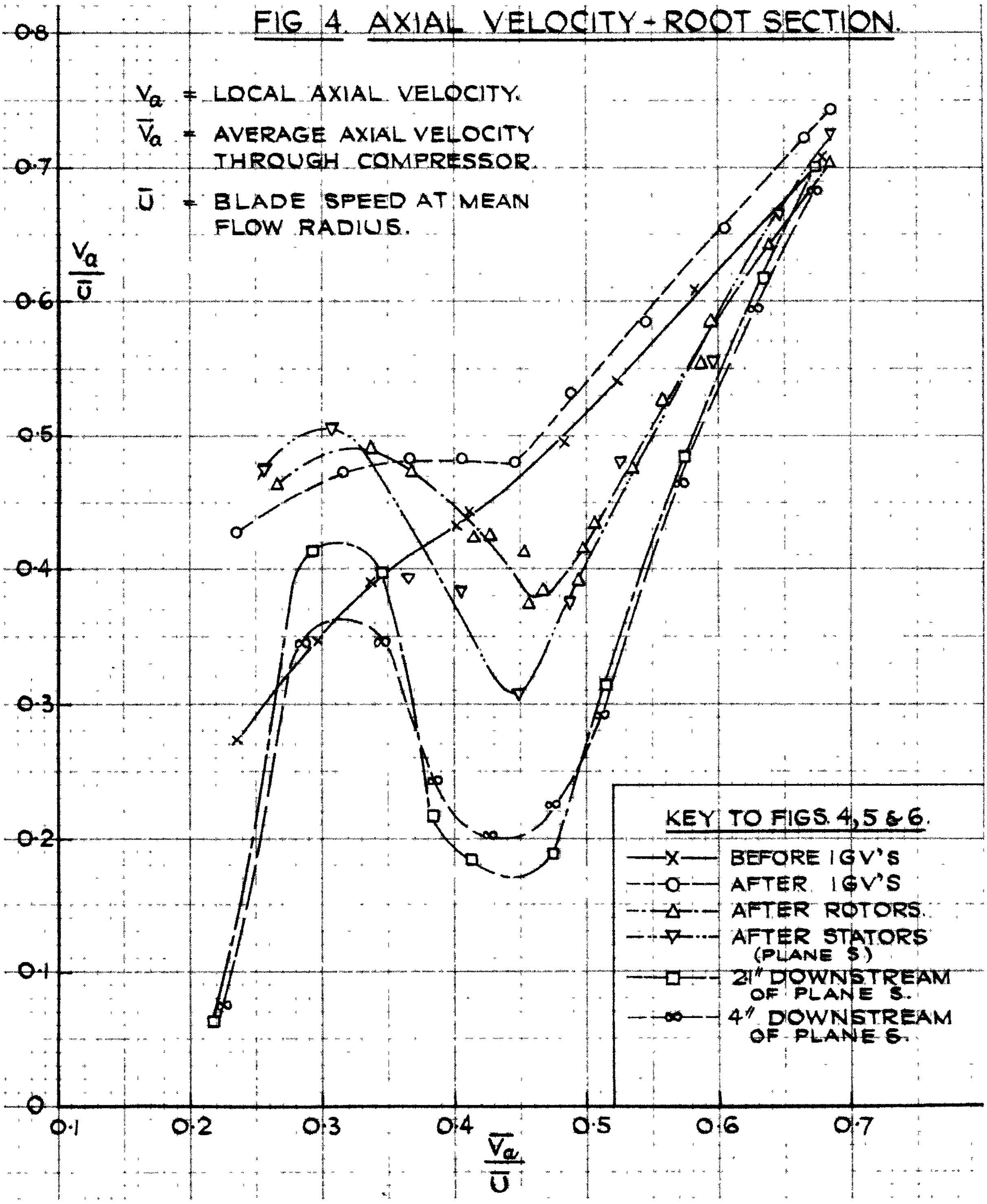


FIG 4. AXIAL VELOCITY - ROOT SECTION.



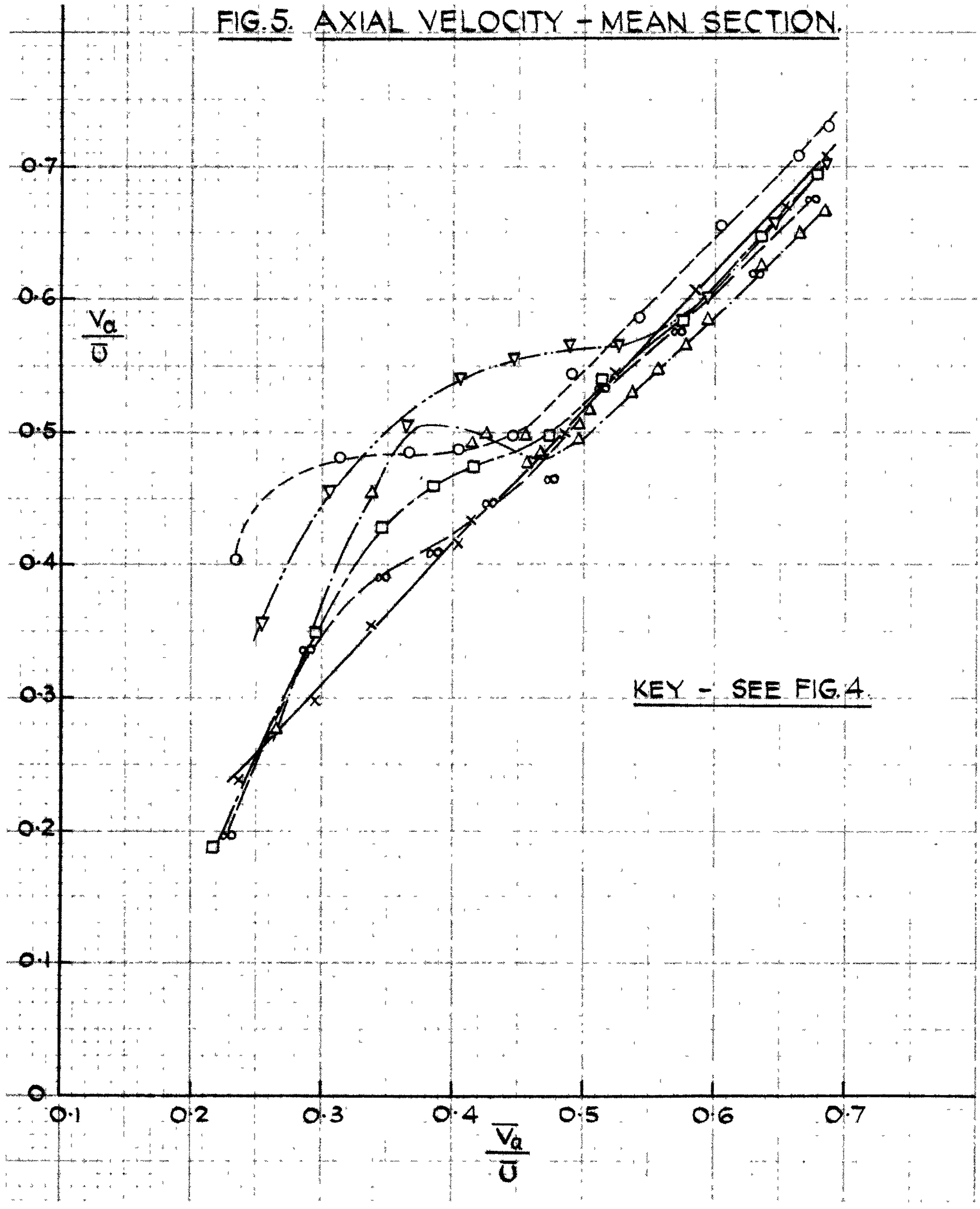


FIG. 5. AXIAL VELOCITY - MEAN SECTION.
$\frac{V_a}{U}$
0·7
0·6
0·5
0·4
0·3
0·2
0·1
0
0·1
0·2
0·3
0·4
0·5
0·6
0·7
$\frac{\overline{V_a}}{U}$
KEY - SEE FIG. 4.

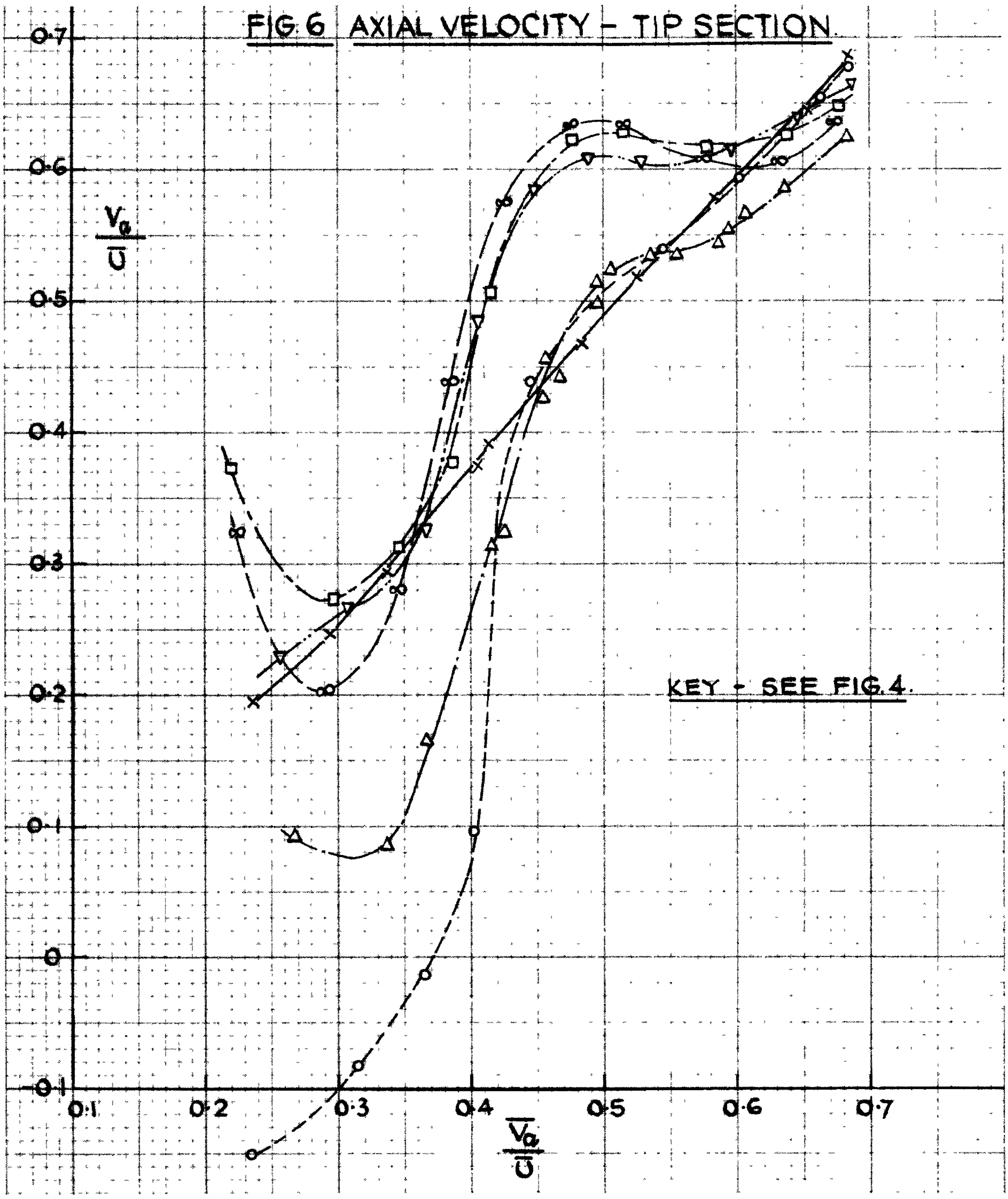


FIG 6 AXIAL VELOCITY – TIP SECTION.

KEY – SEE FIG. 4.

KEY TO FIGS. 7 - 30.

$\frac{V_a}{\bar{U}}$ = $\frac{\text{LOCAL AXIAL VELOCITY}}{\text{BLADE SPEED AT MEAN FLOW RADIUS}}$

$\frac{P}{\rho\bar{U}^2}, \frac{p}{\rho\bar{U}^2}$ = STAGNATION AND STATIC GAUGE PRESSURES IN NON-DIMENSIONAL FORM.

"ROOT" SECTION RADIUS 3·6"
"MEAN" SECTION RADIUS 4·9"
"TIP" SECTION RADIUS 6·5"
} SEE FIG. 1.

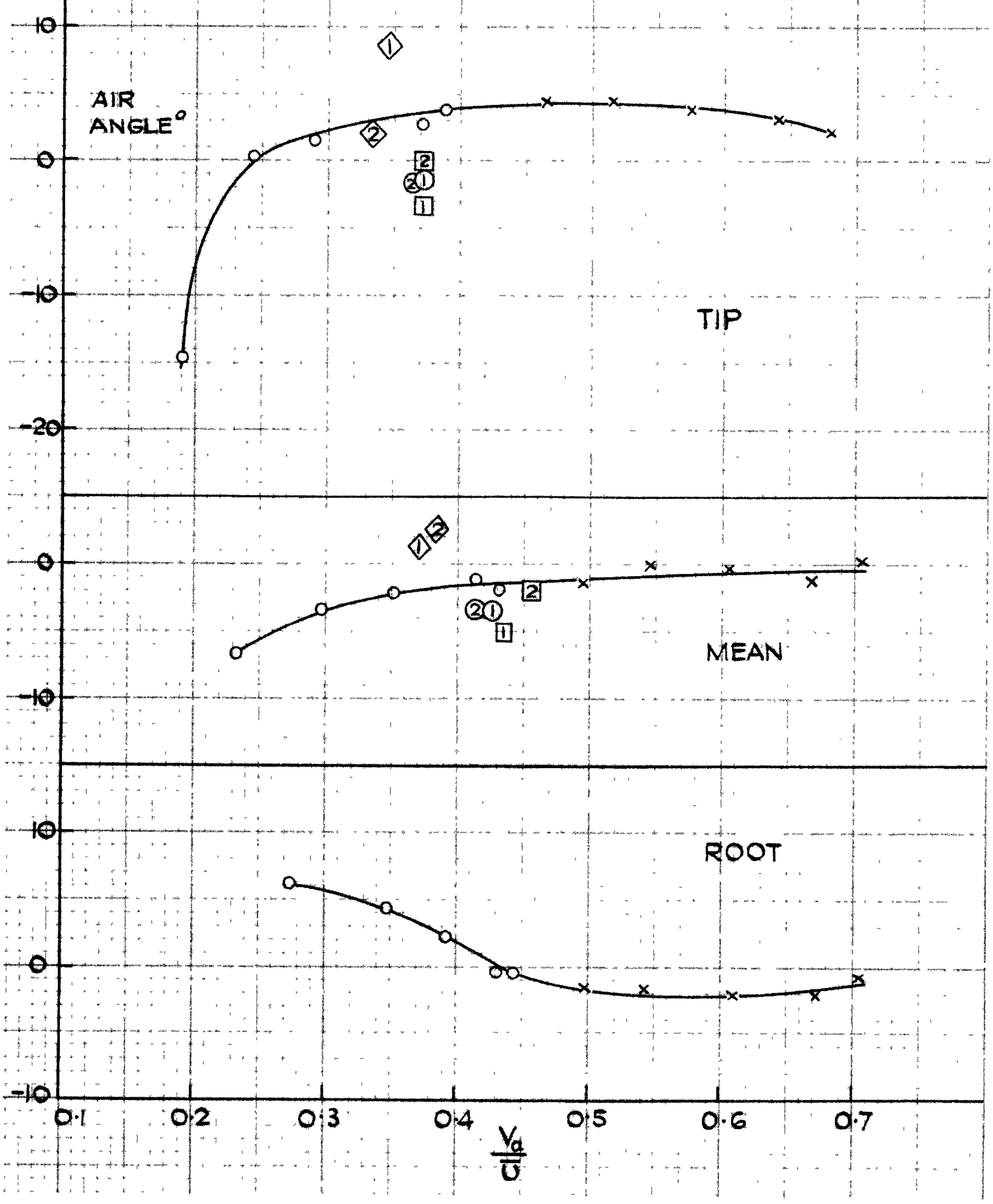
× ○ } TIME AVERAGE READINGS, 3-HOLE TUBE MANOMETER.

× ROTOR TIP UNSTALLED
○ ROTOR TIP STALLED
} JUDGED BY COMPRESSOR NOISE ONLY.

SINGLE HOLE TUBE READINGS		
ONE STALL CELL REGIME.	TWO STALL CELLS REGIME.	
①	②	TIME AVERAGE (MANOMETER)
$\boxed{1}$	$\boxed{2}$	INSTANTANEOUS FLOW OUTSIDE STALL CELL.
◇1	◇2	INSTANTANEOUS FLOW INSIDE STALL CELL.

NO STEADY STALL CELLS WERE FOUND AT THE ROOT SECTION.

FIG. 7. AIR ANGLES BEFORE 1 GV's.



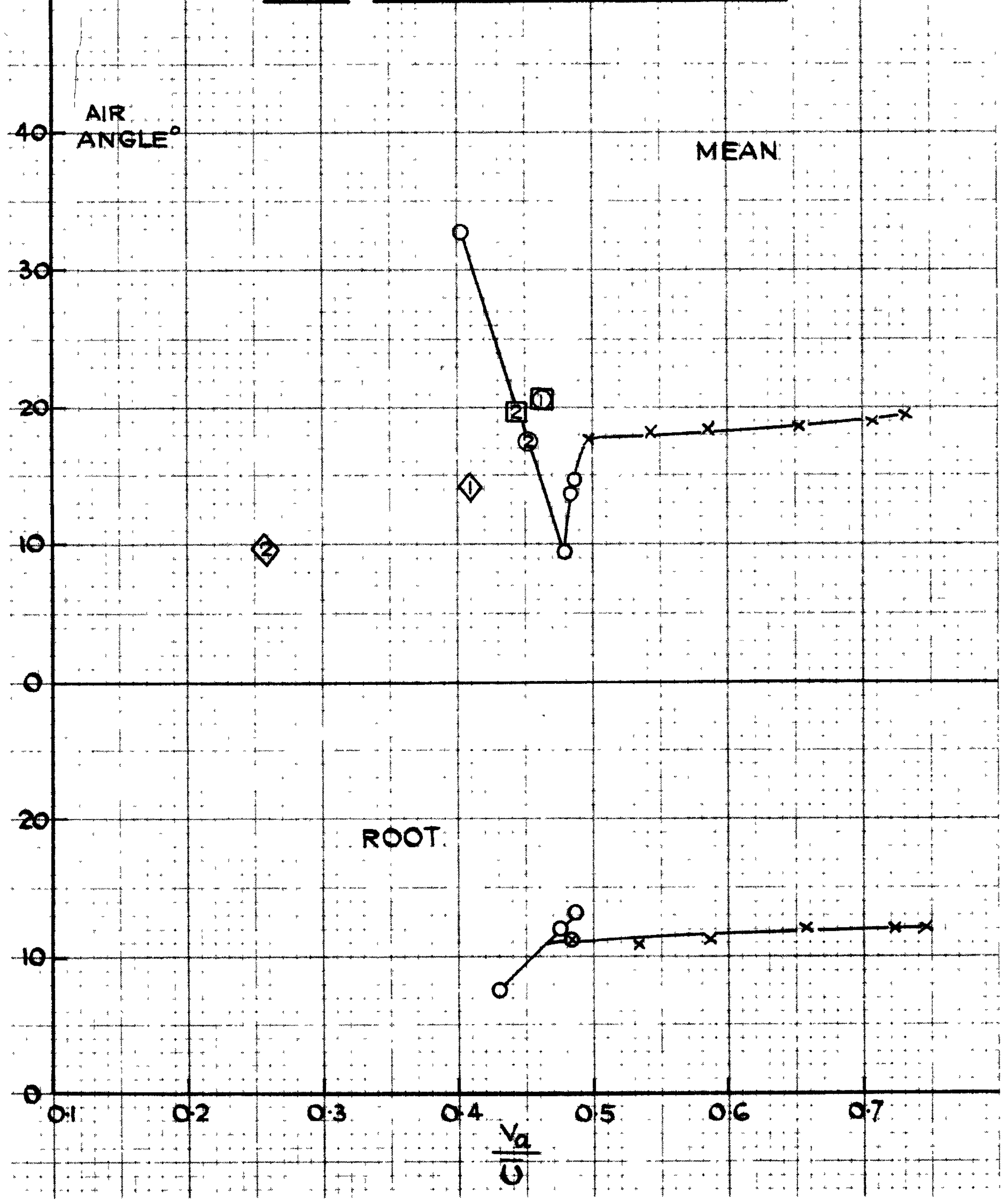


FIG. 8. AIR ANGLES AFTER IGV'S

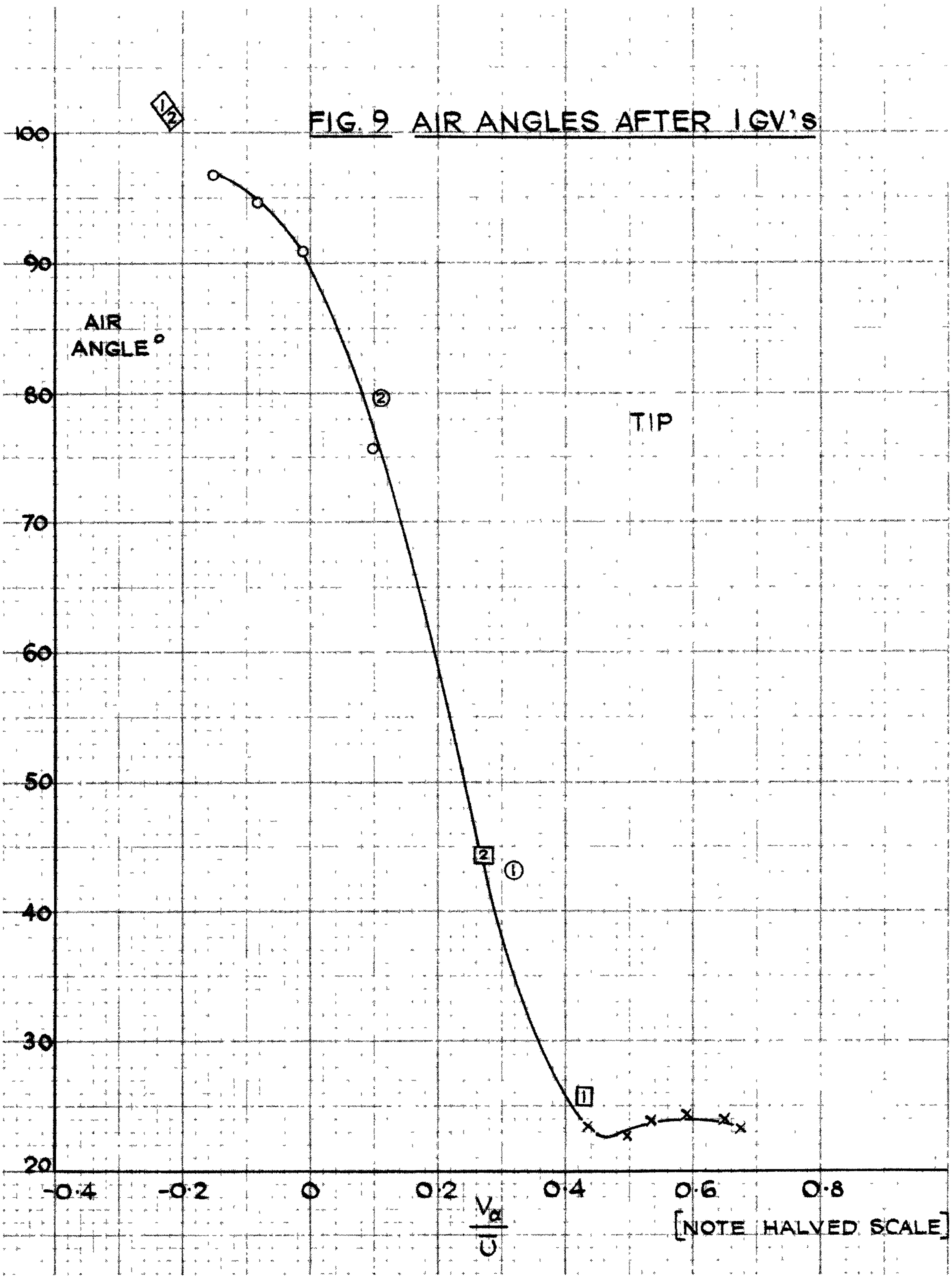


FIG. 9 AIR ANGLES AFTER IGV's

FIG 10. AIR ANGLES AFTER ROTORS.

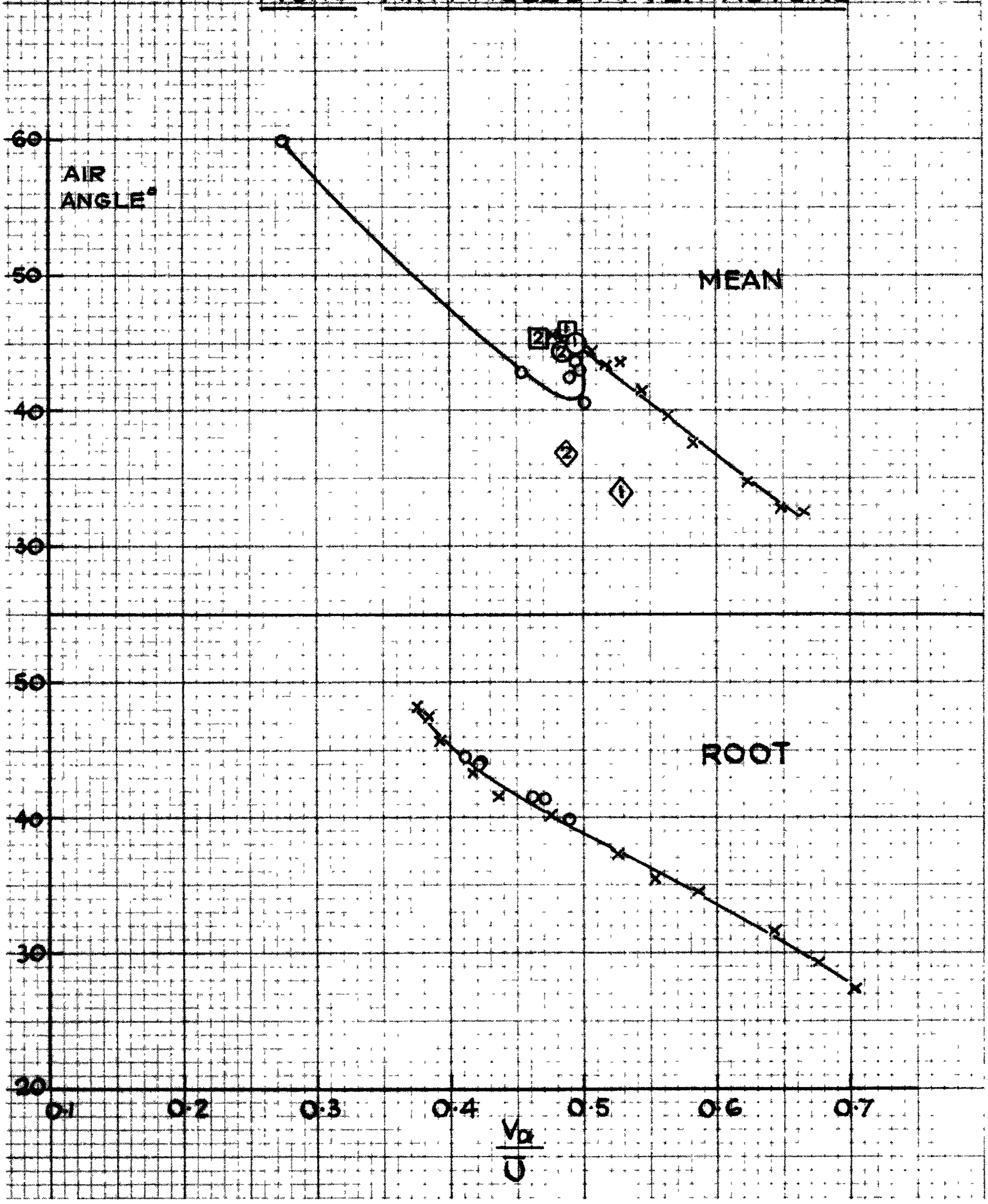


FIG 11. AIR ANGLES AFTER ROTORS.

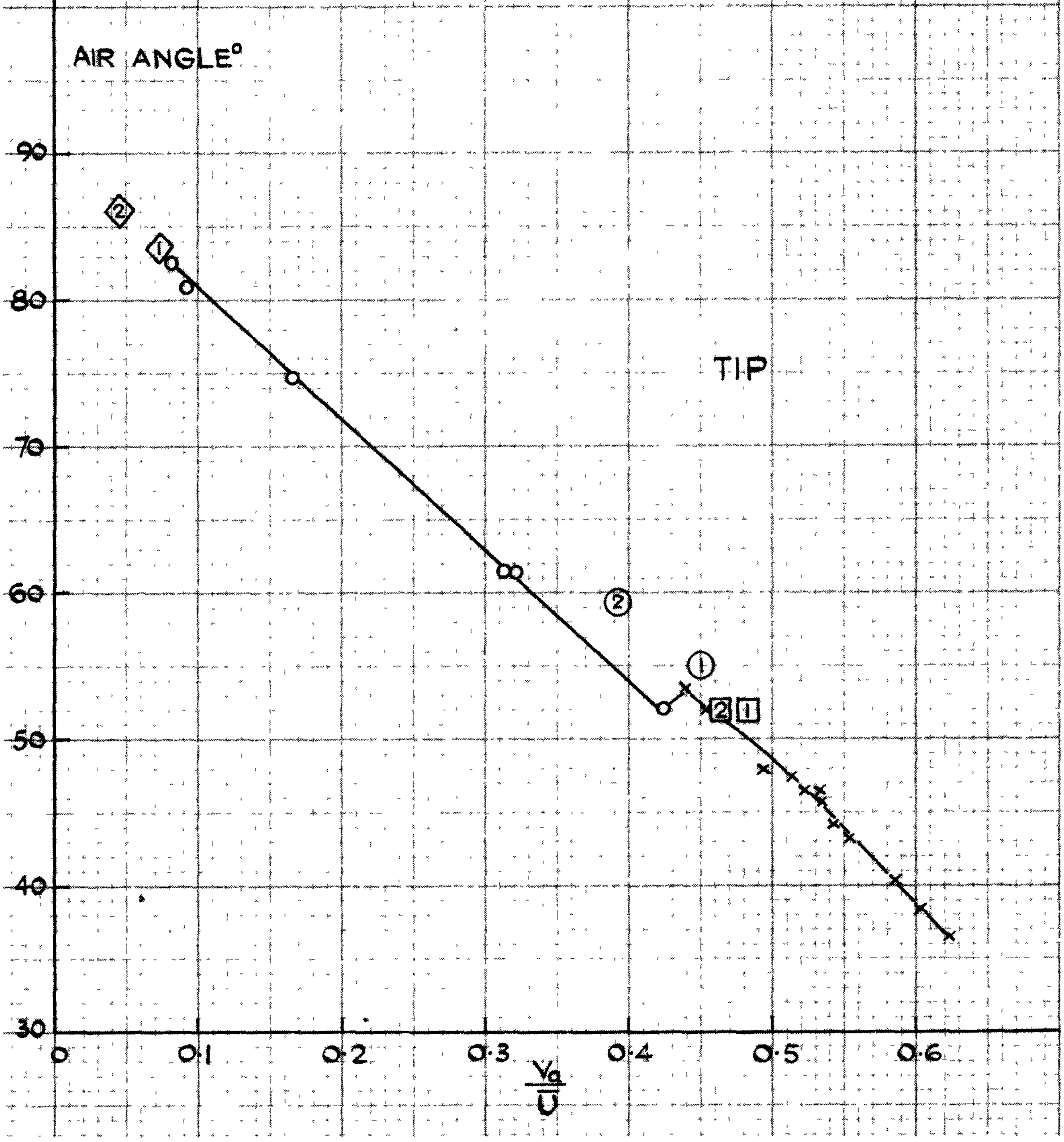


FIG. 12. AIR ANGLES AFTER STATORS.

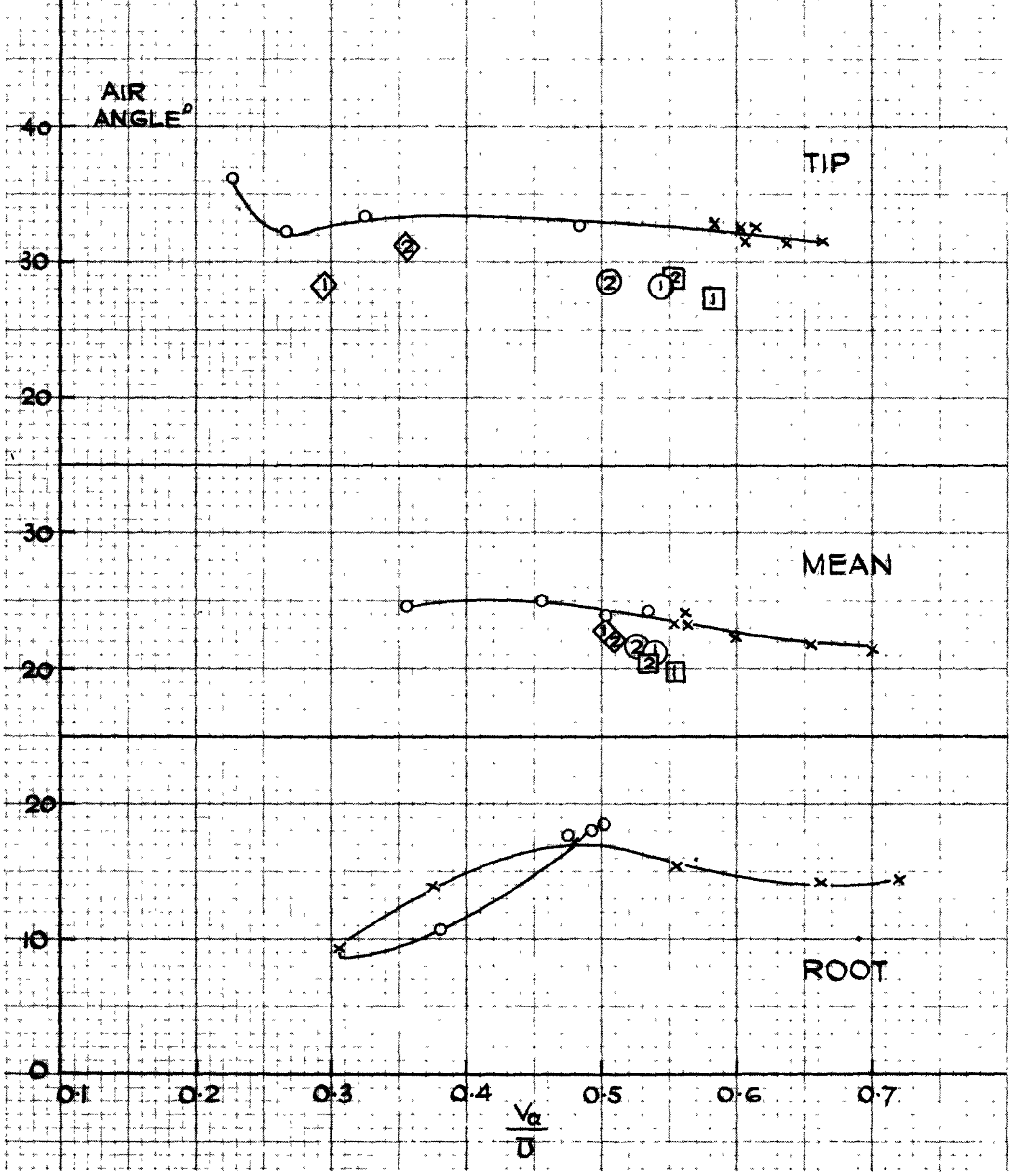


FIG. 13. AIR ANGLES 2·1" FURTHER DOWNSTREAM THAN "AFTER STATORS."

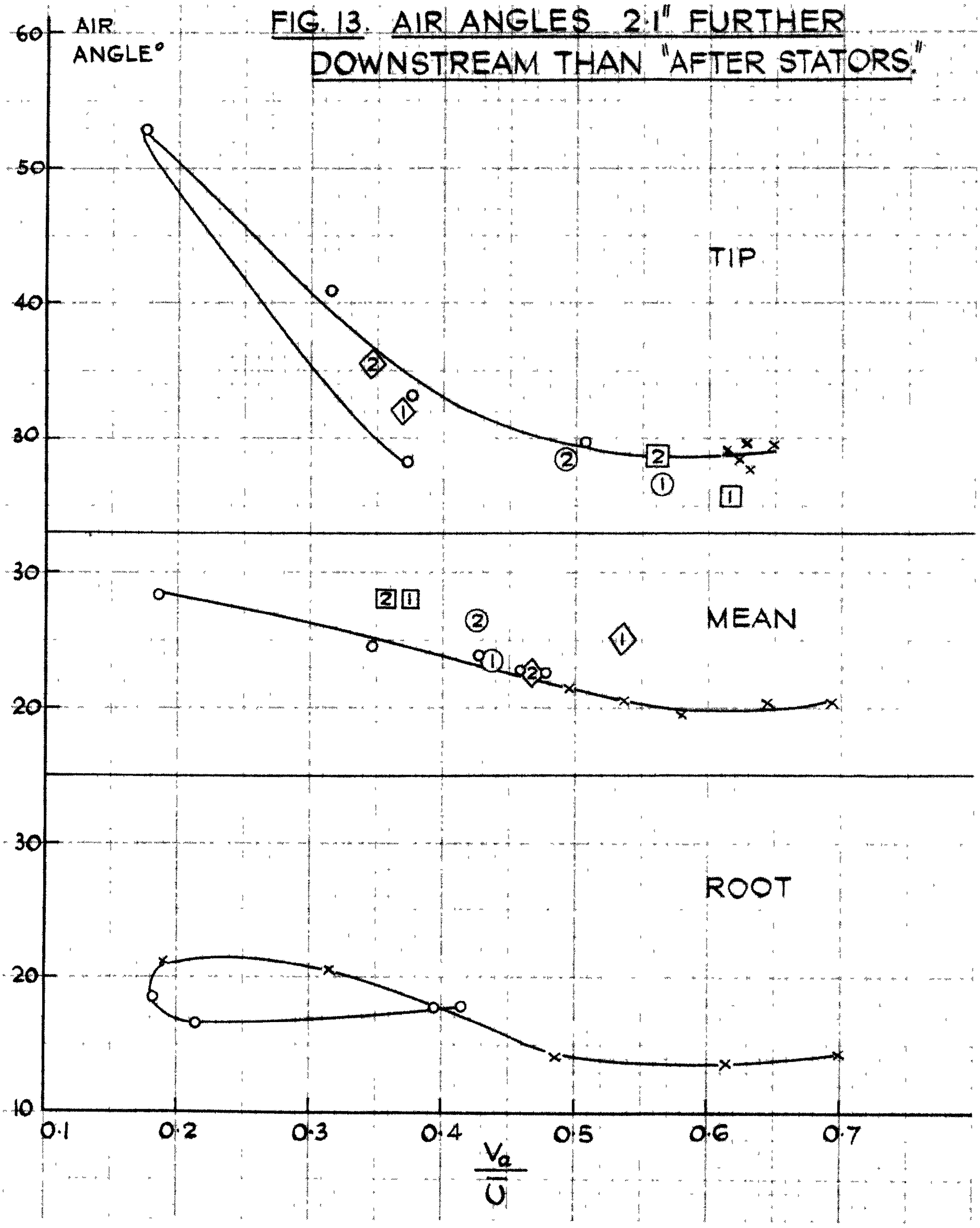


FIG. 14. AIR ANGLES 4" FURTHER DOWNSTREAM THAN 'AFTER STATORS'.

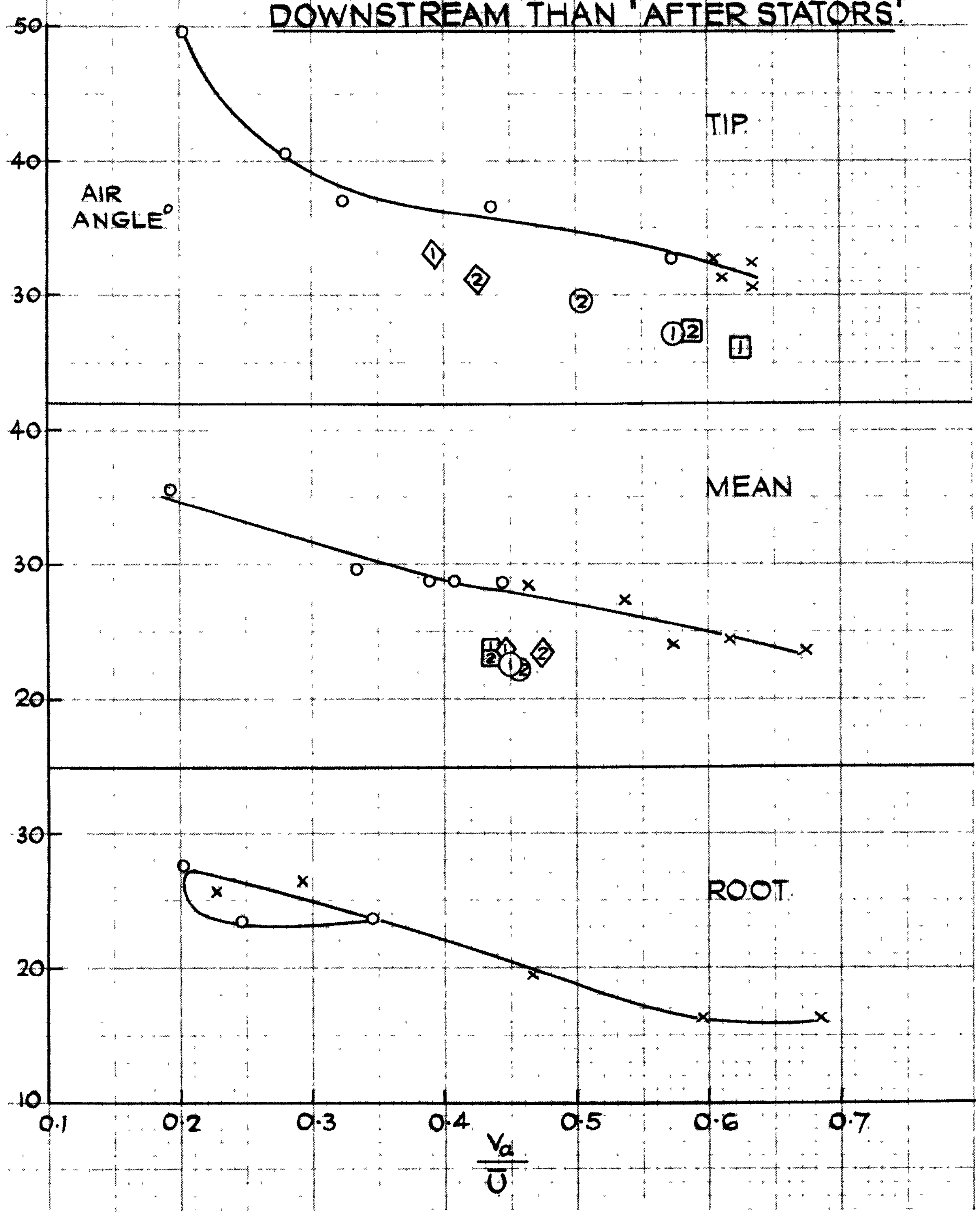


FIG. 15. PRESSURES BEFORE I GV'S.

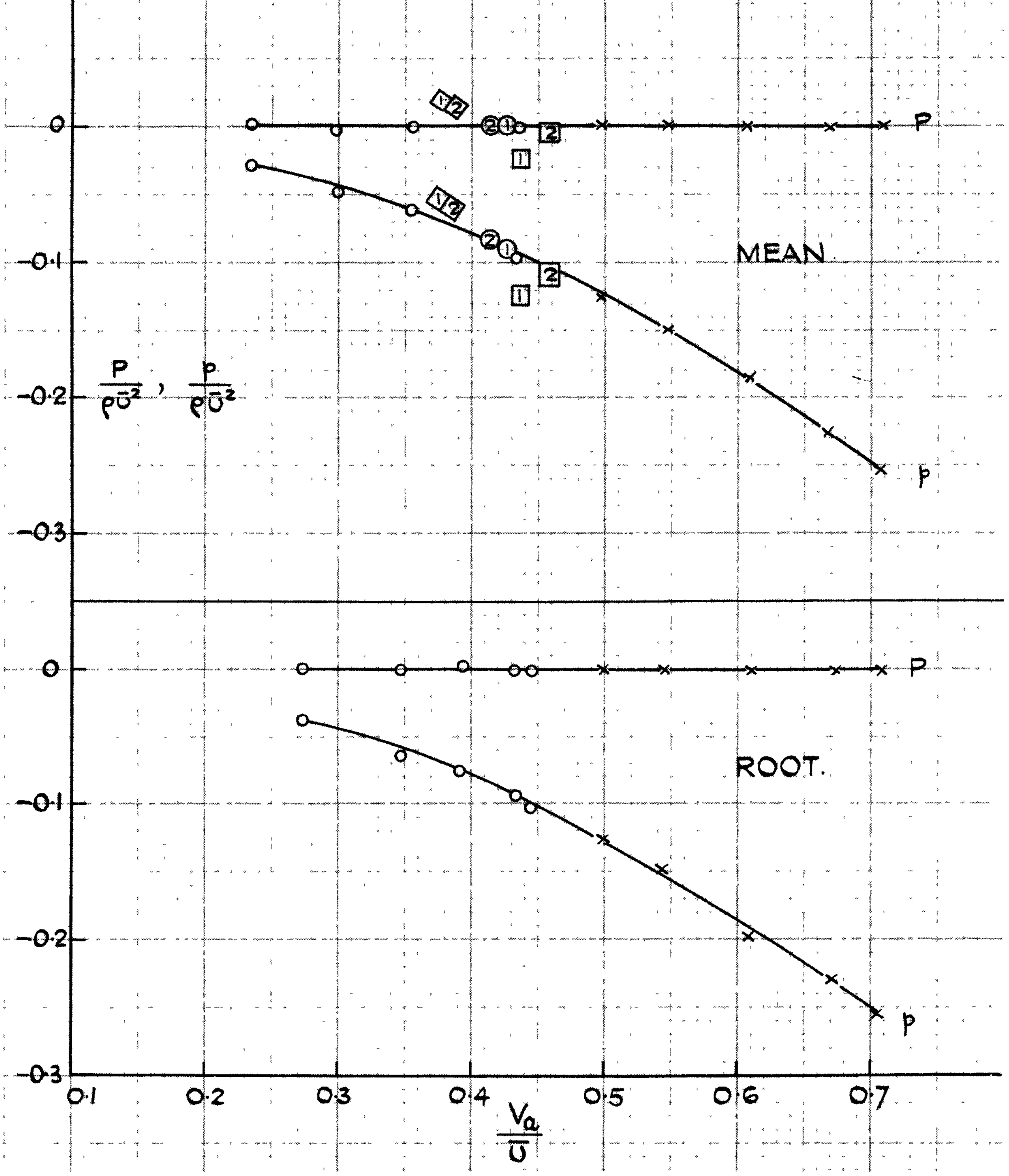


FIG 16. PRESSURES BEFORE I GV's.

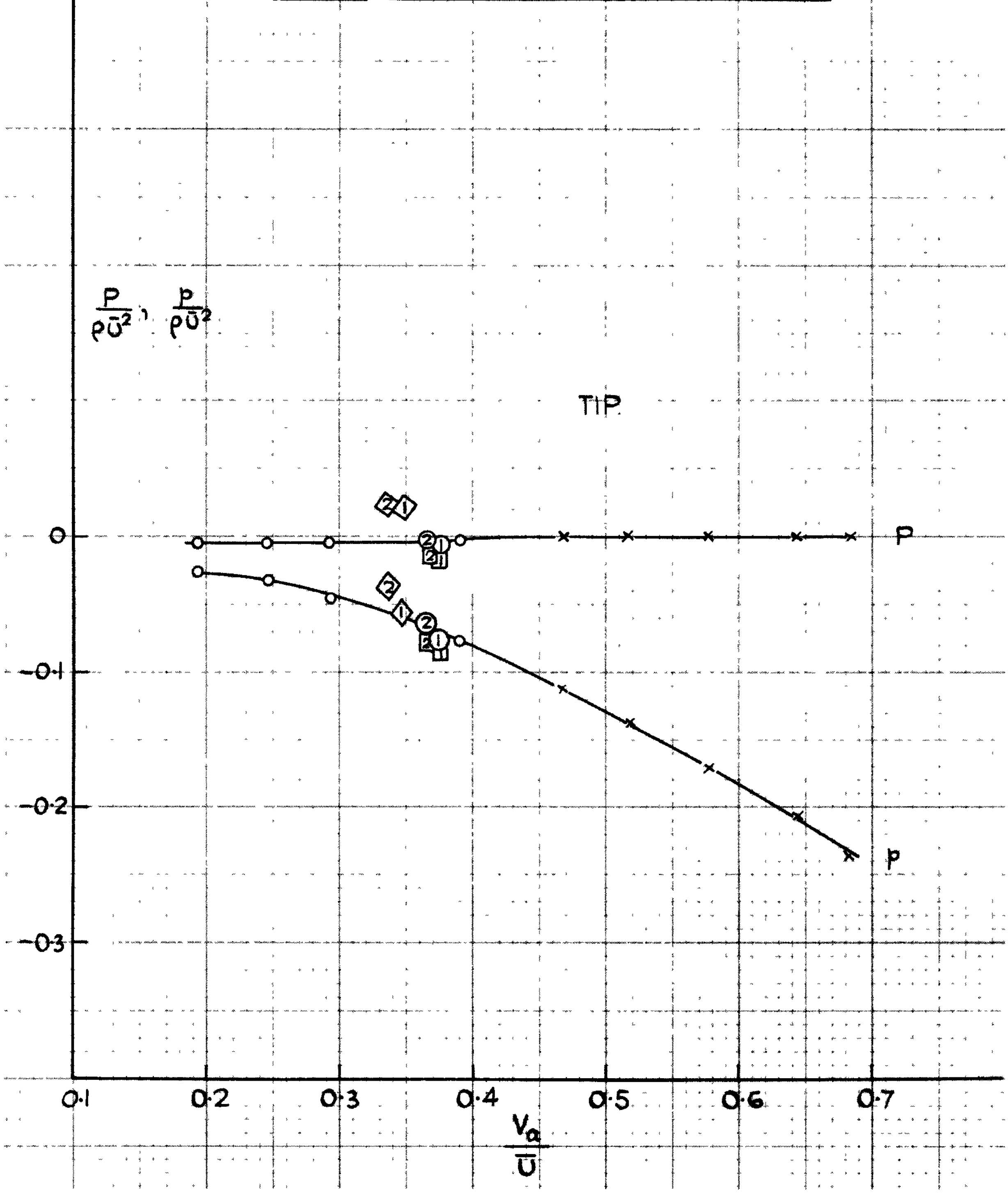


FIG. 17 PRESSURES AFTER I GV's

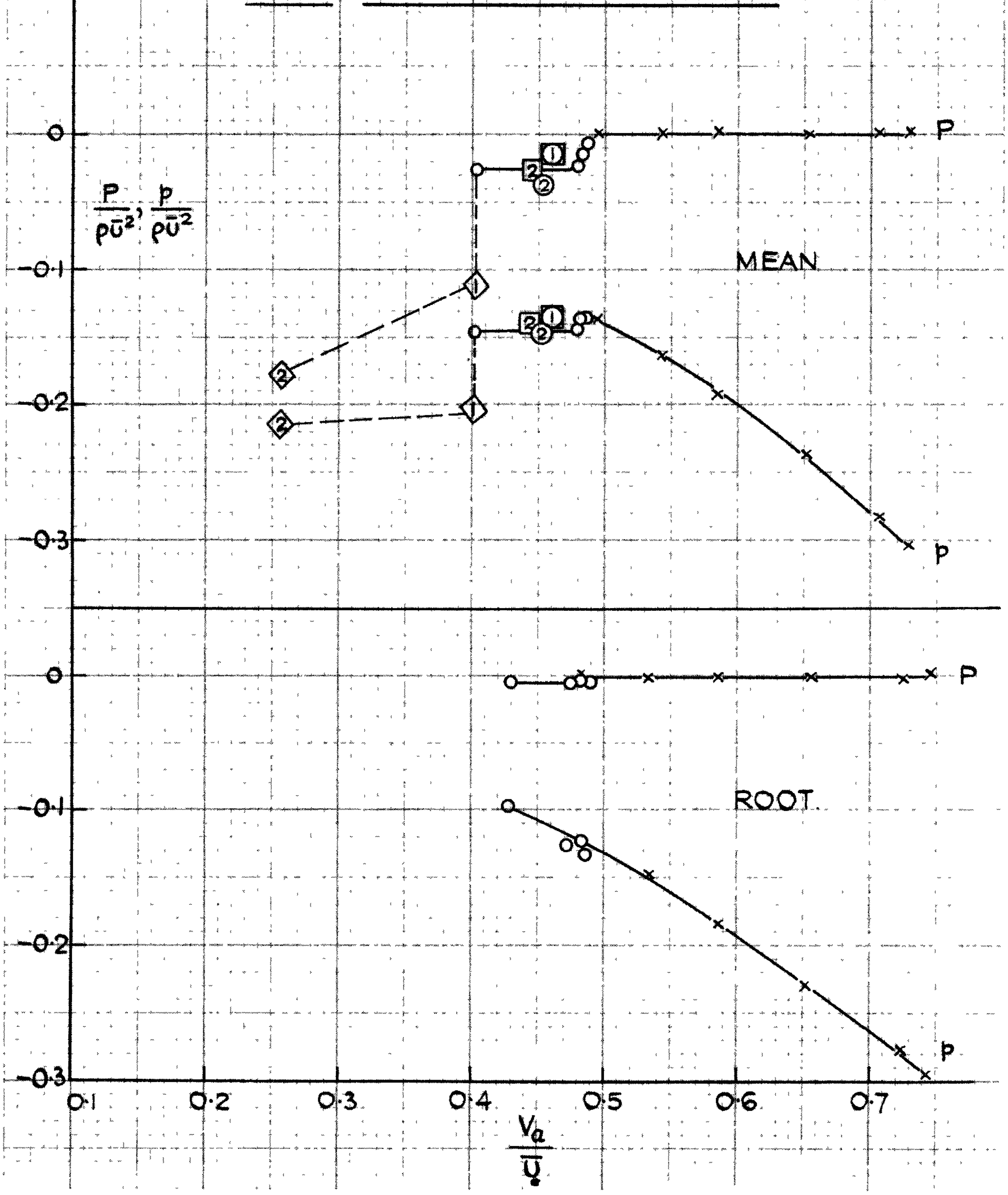


FIG. 18. PRESSURES AFTER IGV'S.

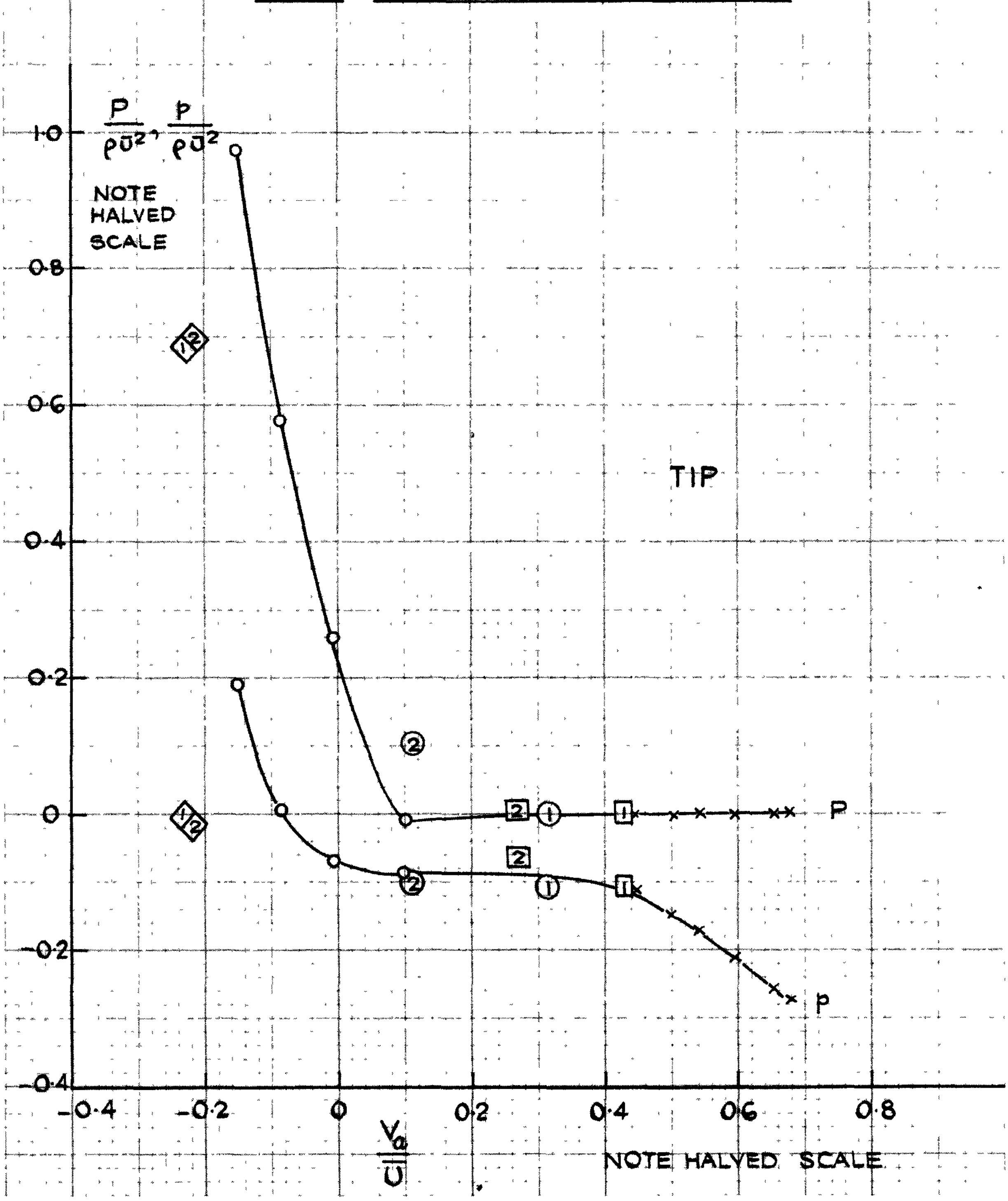


FIG. 19 PRESSURES AFTER ROTOR.

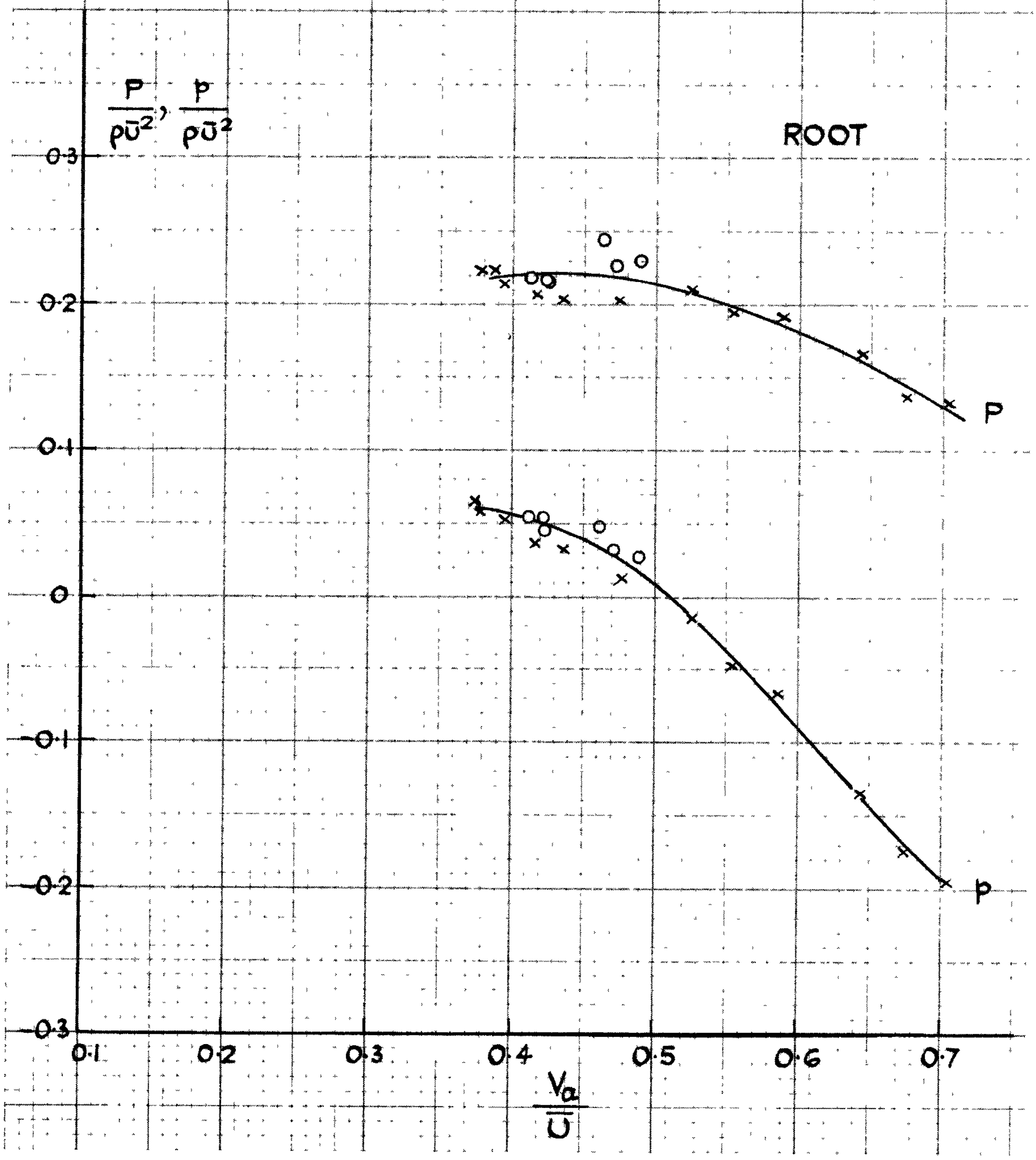


FIG. 20. PRESSURES AFTER ROTORS.

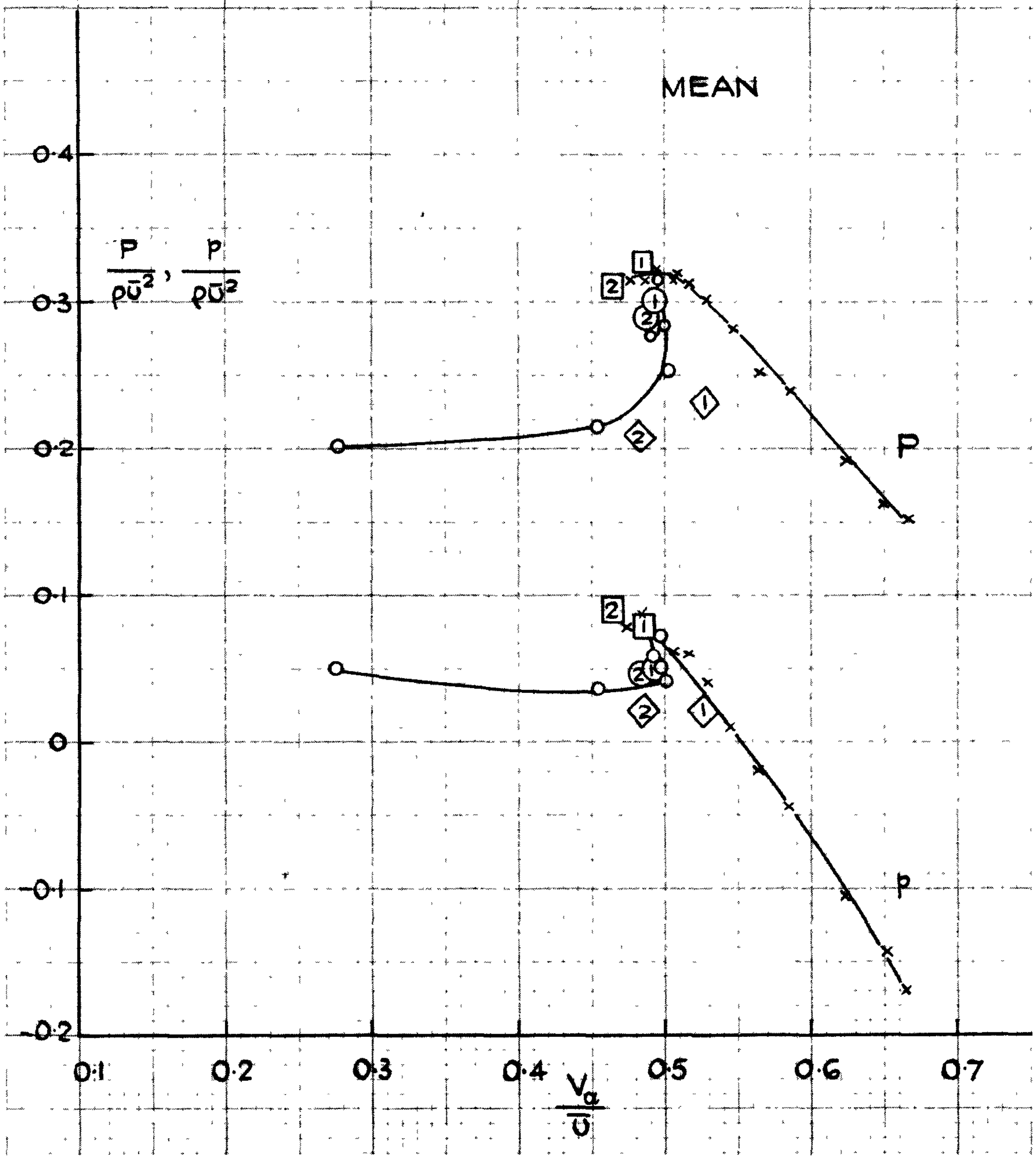


FIG 21. PRESSURES AFTER ROTORS.

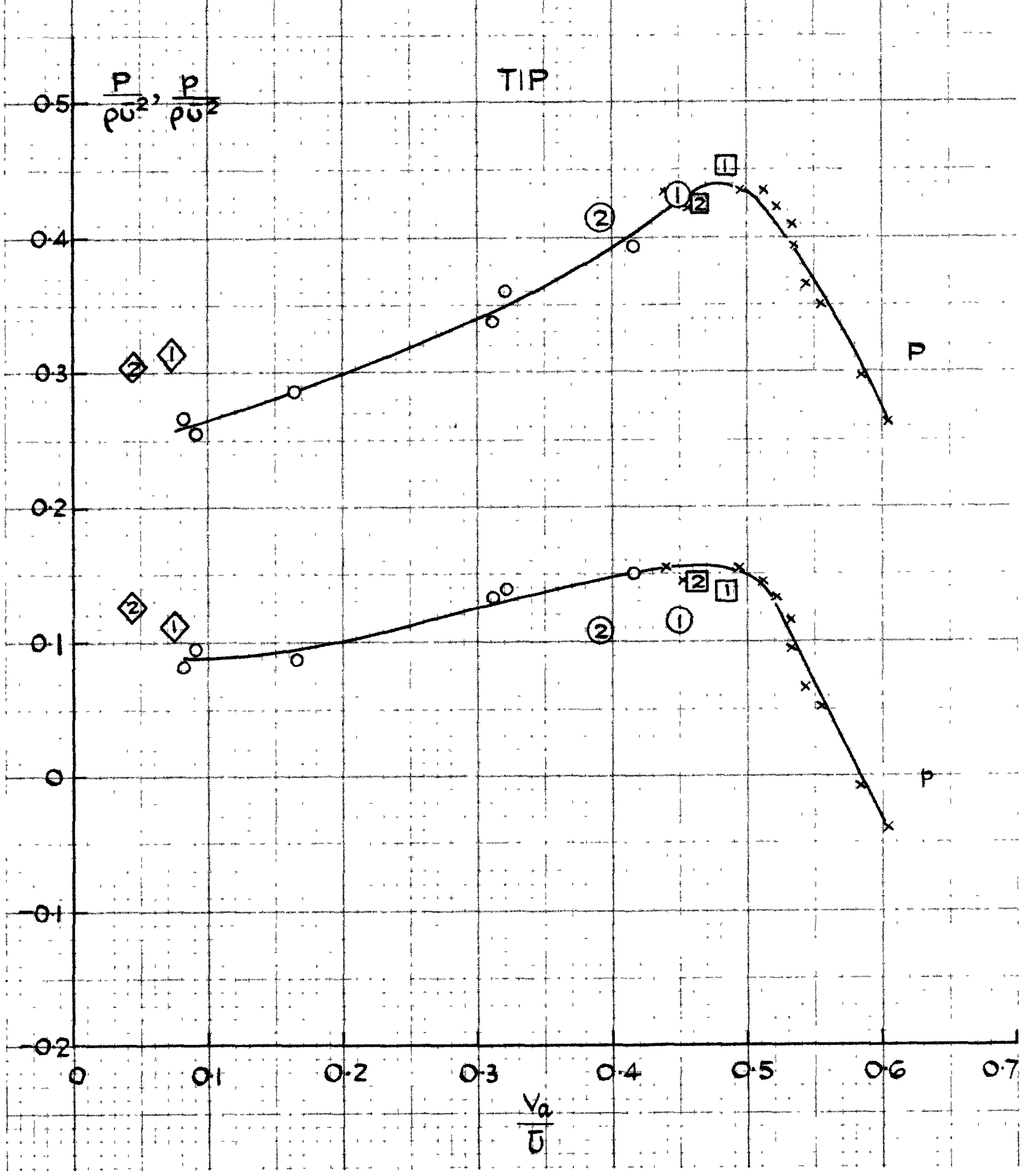


FIG. 22. PRESSURES AFTER STATORS.

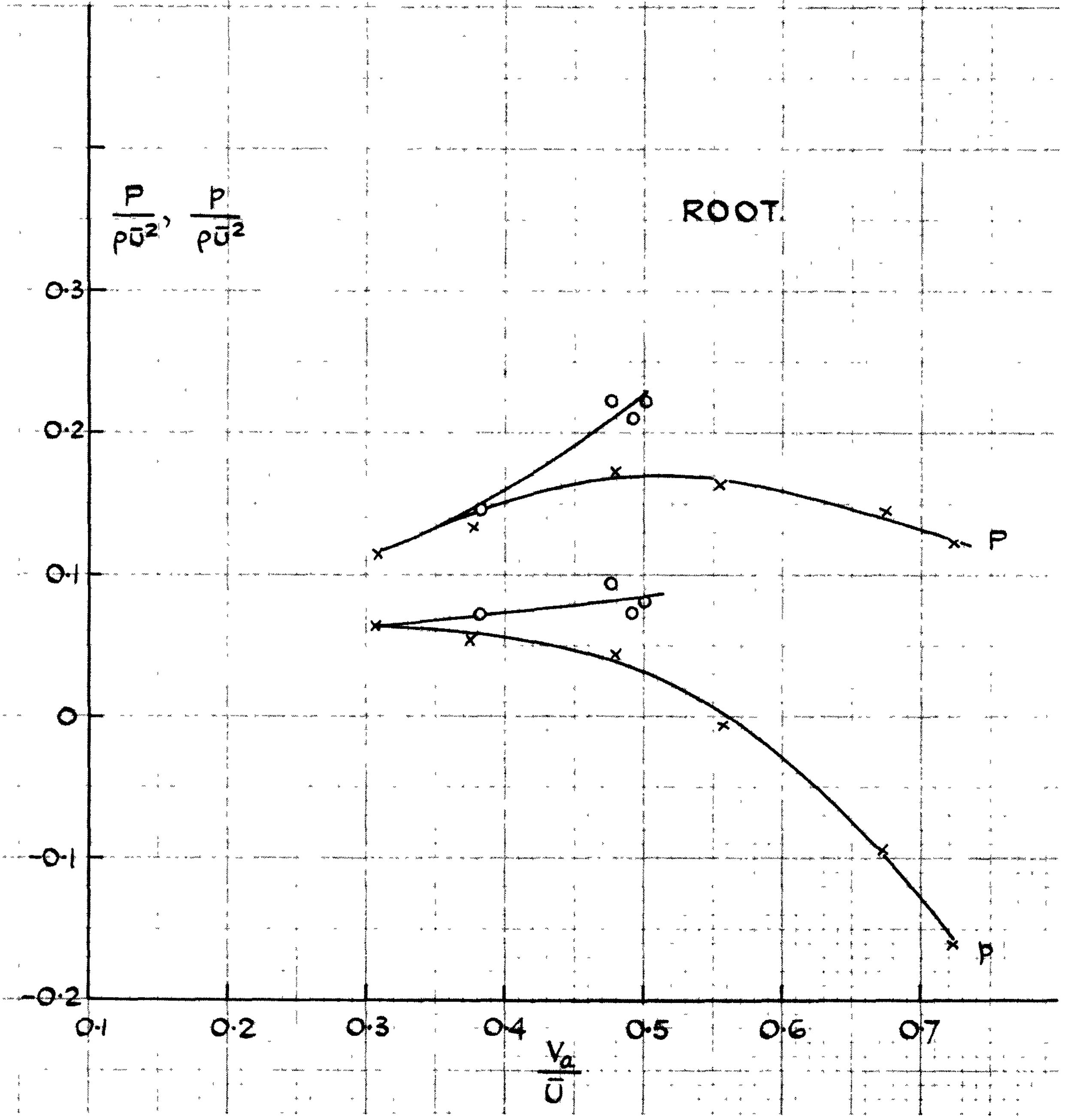


FIG. 23. PRESSURES AFTER STATORS.

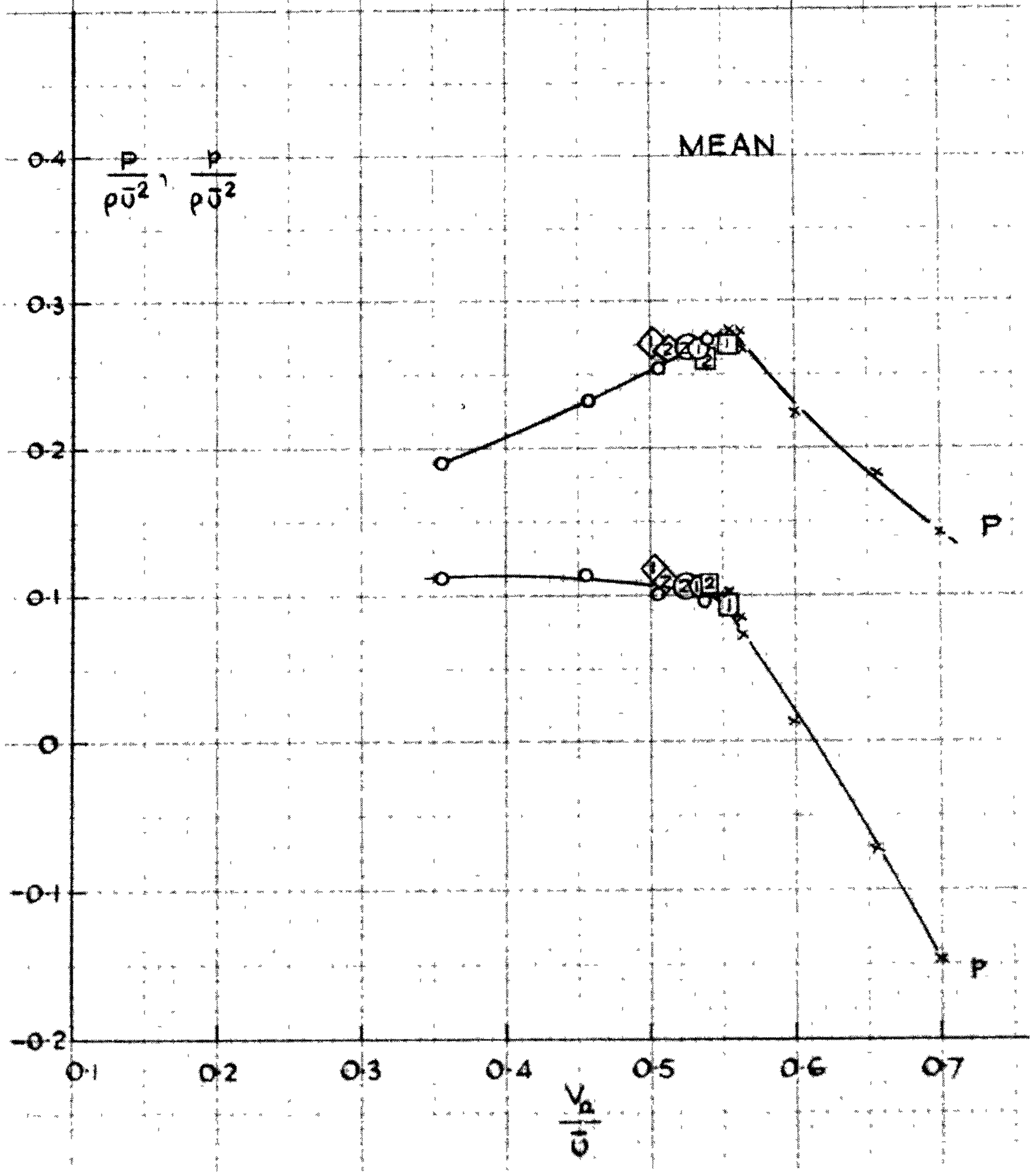
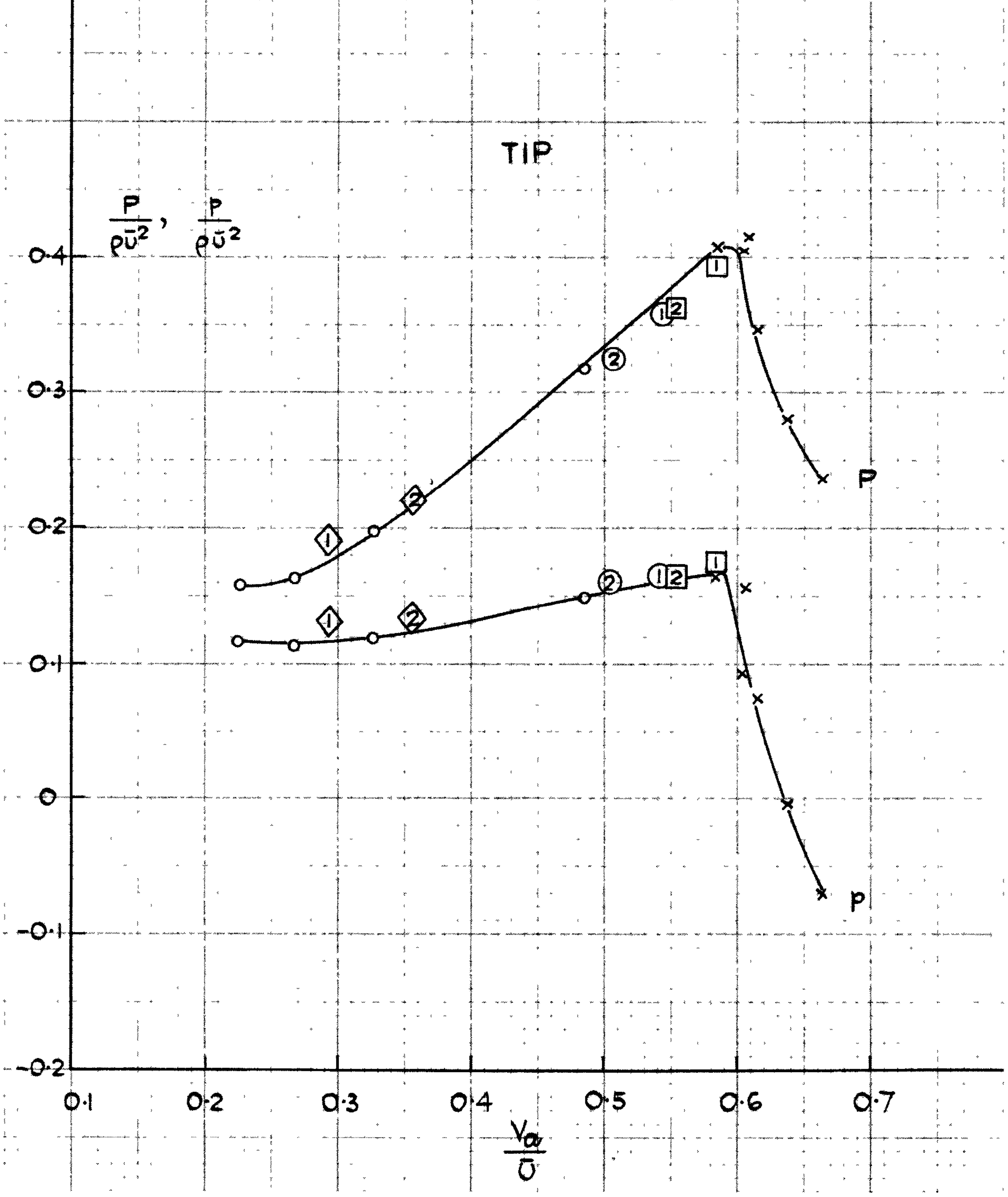


FIG 24. PRESSURES AFTER STATORS.



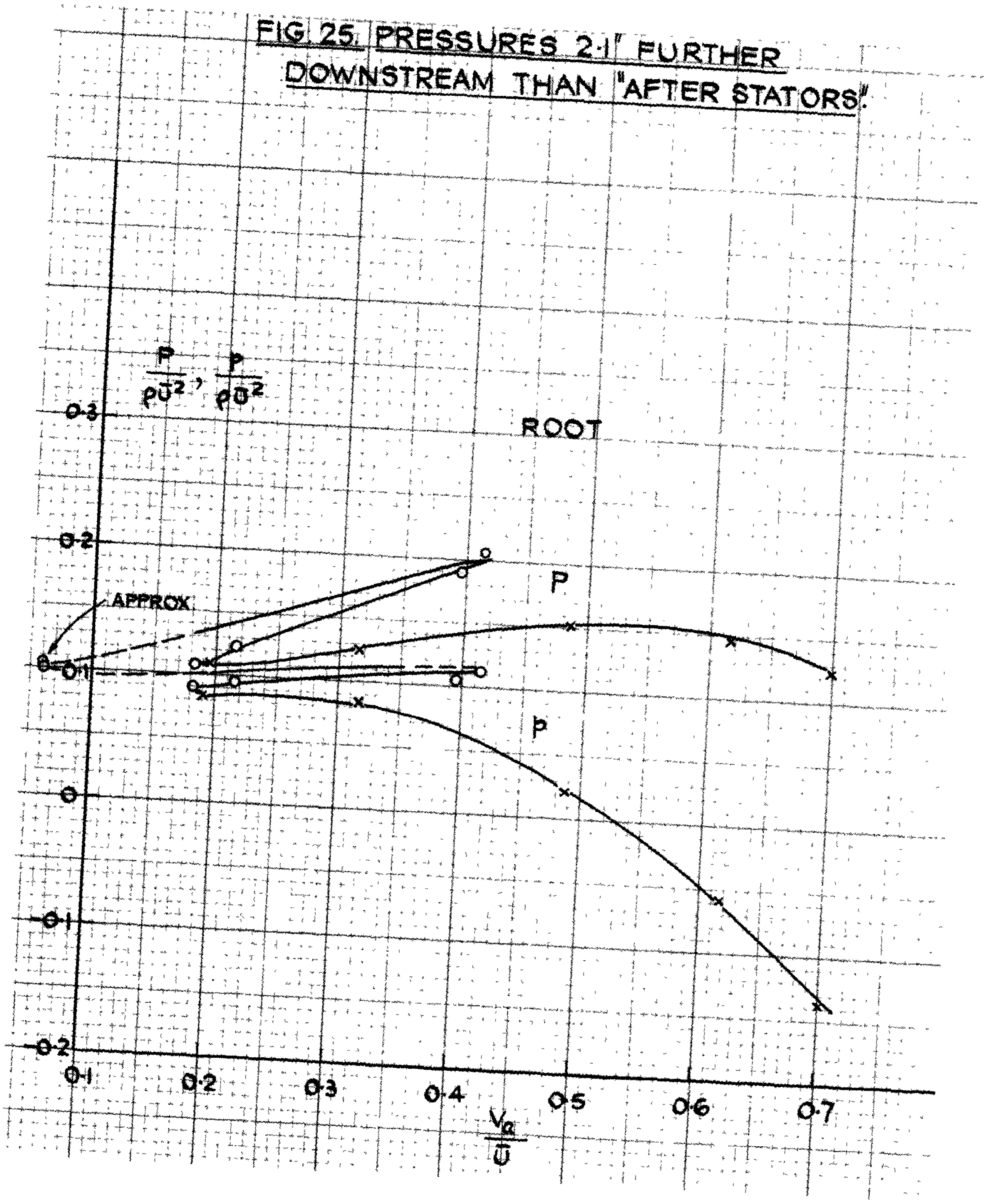


FIG. 25. PRESSURES 2·1" FURTHER DOWNSTREAM THAN "AFTER STATORS".

FIG. 26. PRESSURES 2·1" FURTHER DOWNSTREAM THAN 'AFTER STATORS'

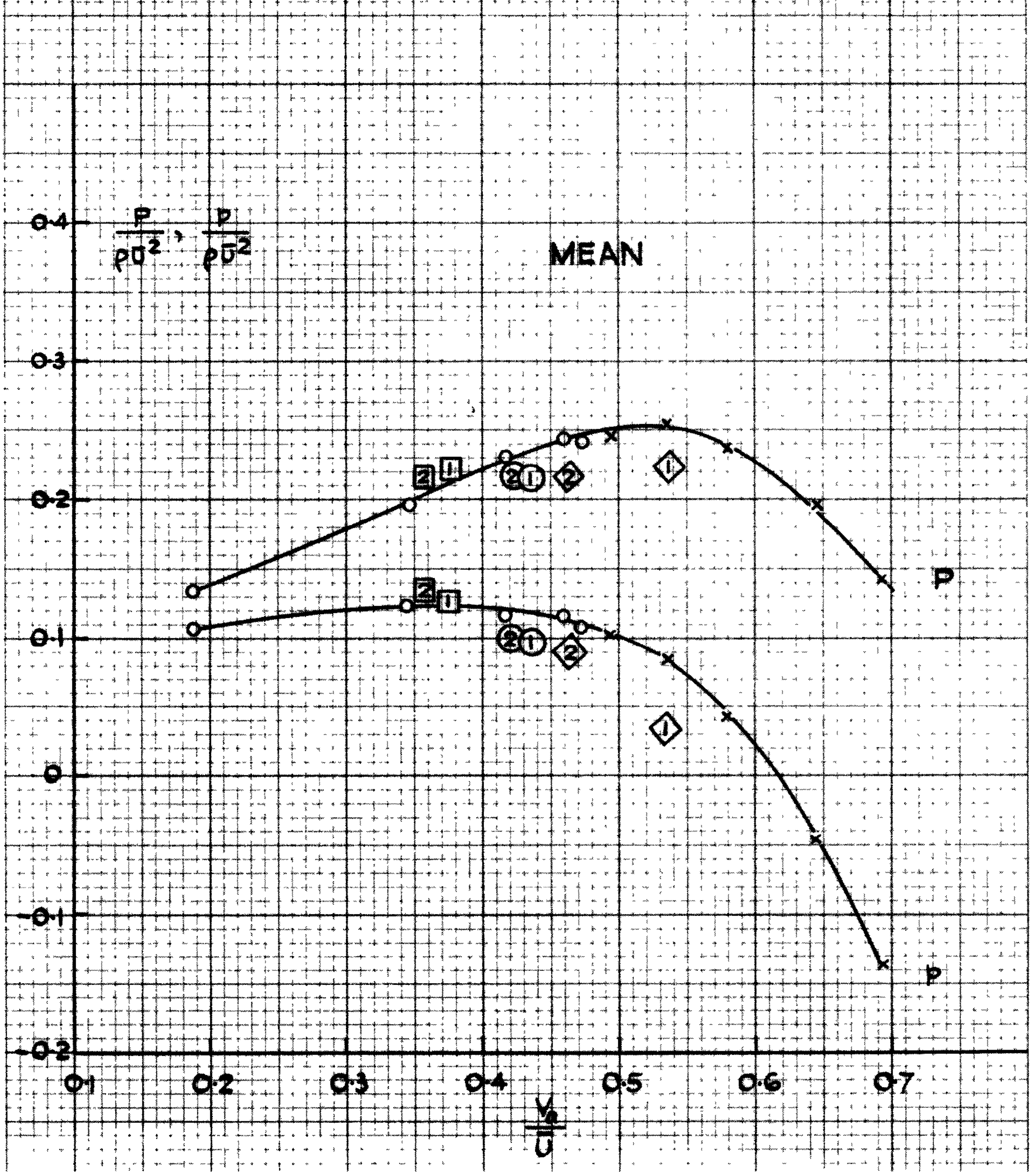


FIG. 27. PRESSURES 2·1" FURTHER DOWNSTREAM THAN "AFTER STATORS."

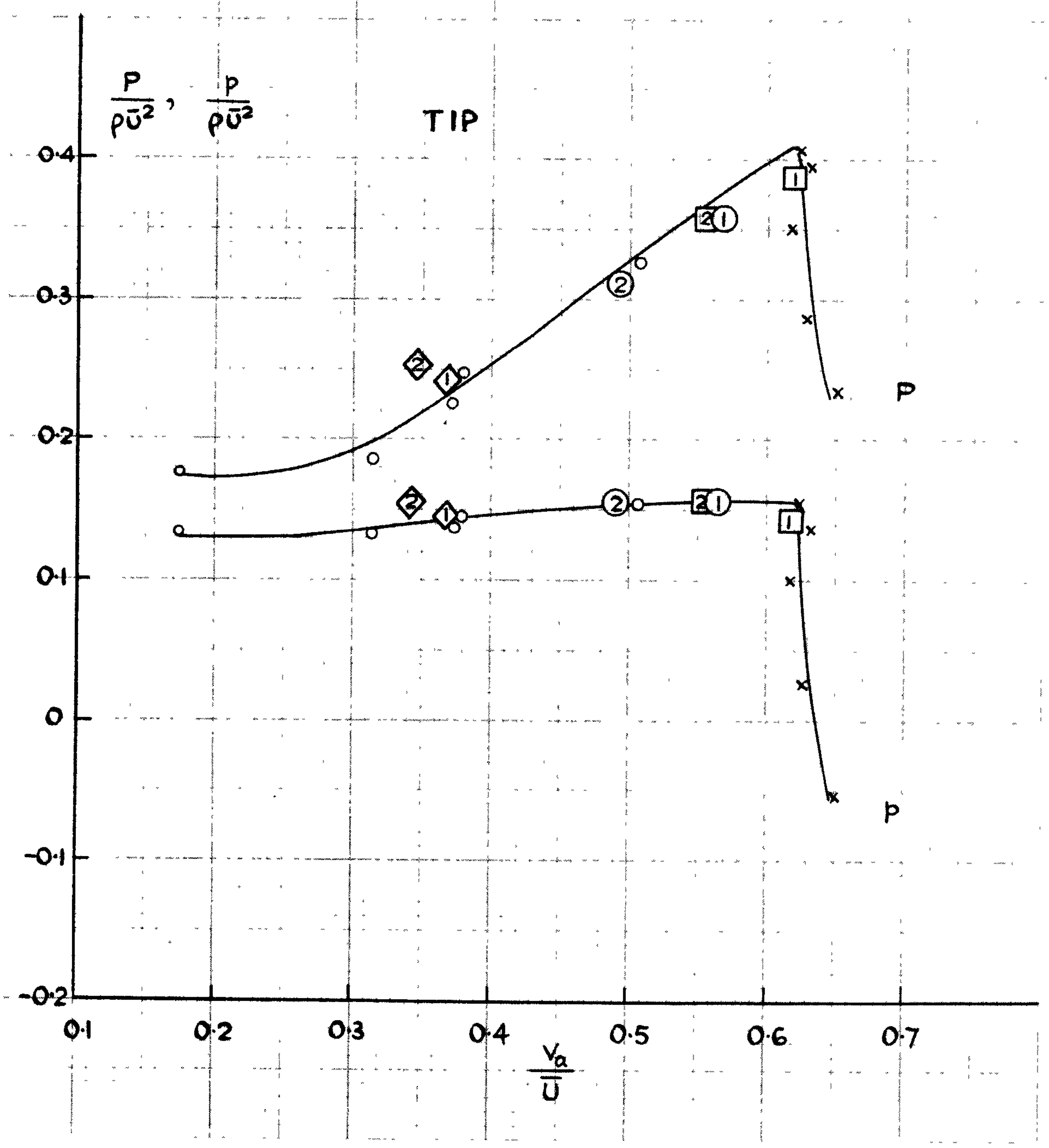


FIG 28. PRESSURES 4' FURTHER DOWNSTREAM THAN 'AFTER STATORS'

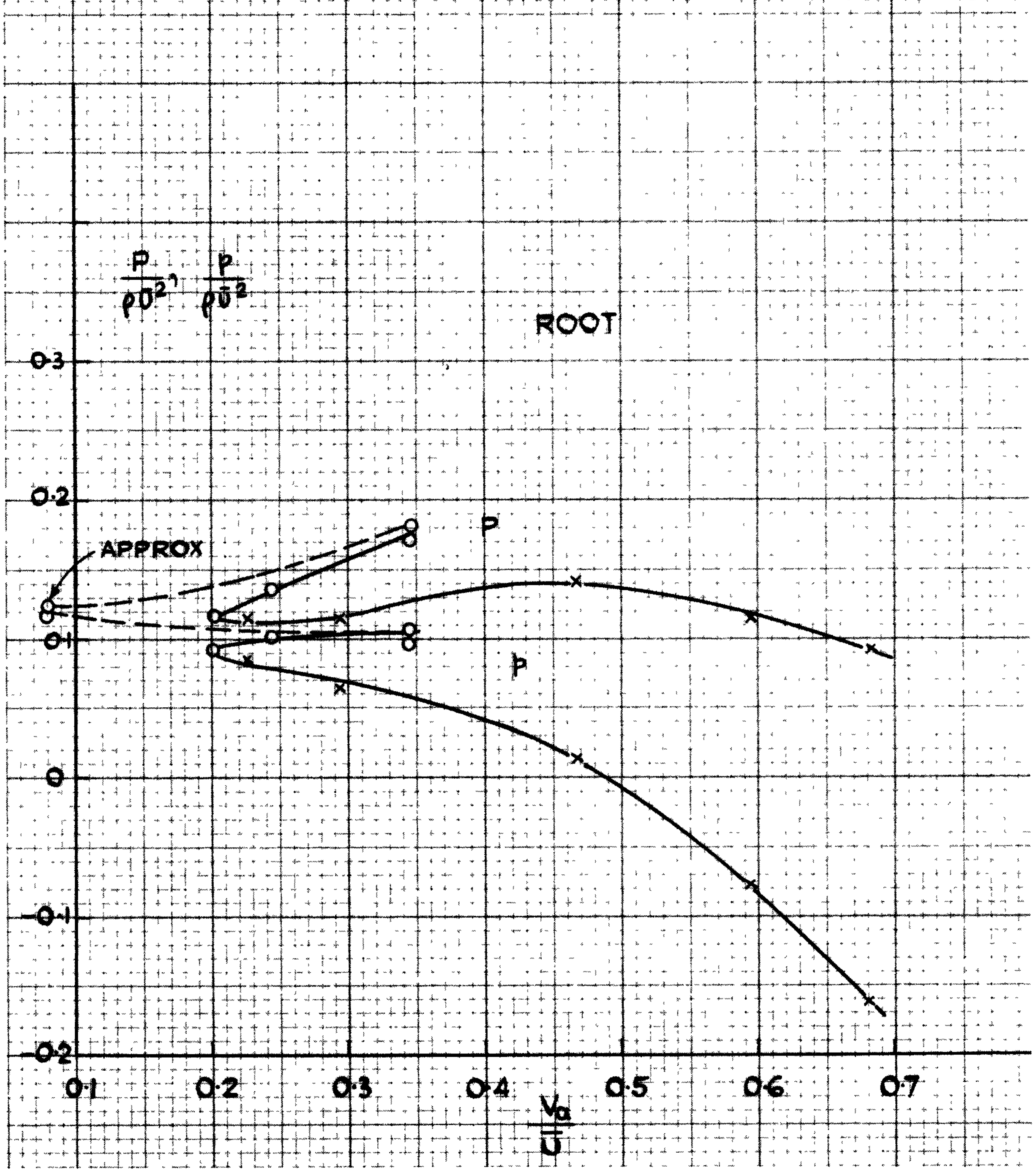


FIG. 29. PRESSURES 4" FURTHER DOWNSTREAM THAN "AFTER STATORS"

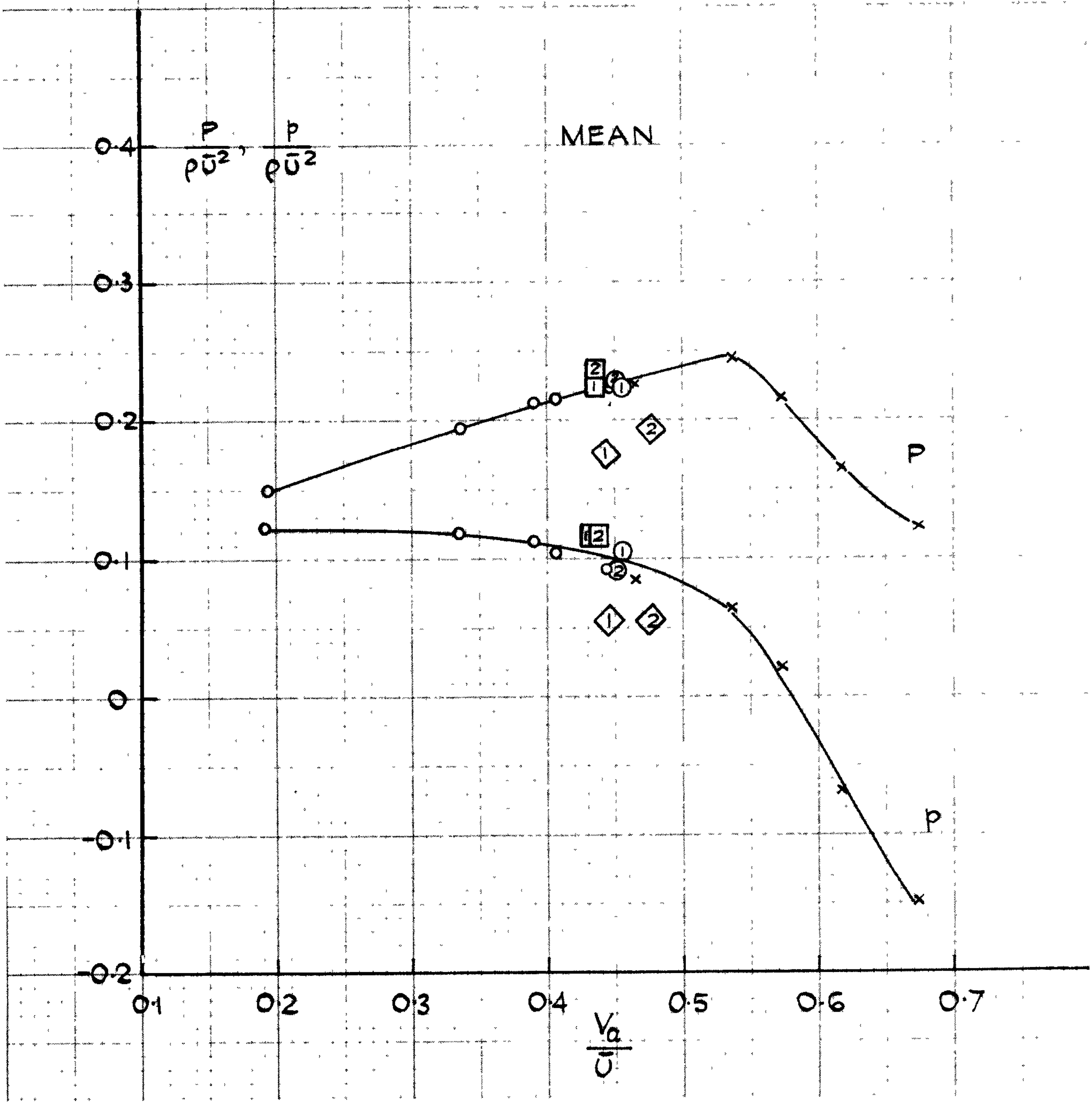


FIG 30. PRESSURES 4" FURTHER DOWNSTREAM THAN 'AFTER STATORS'

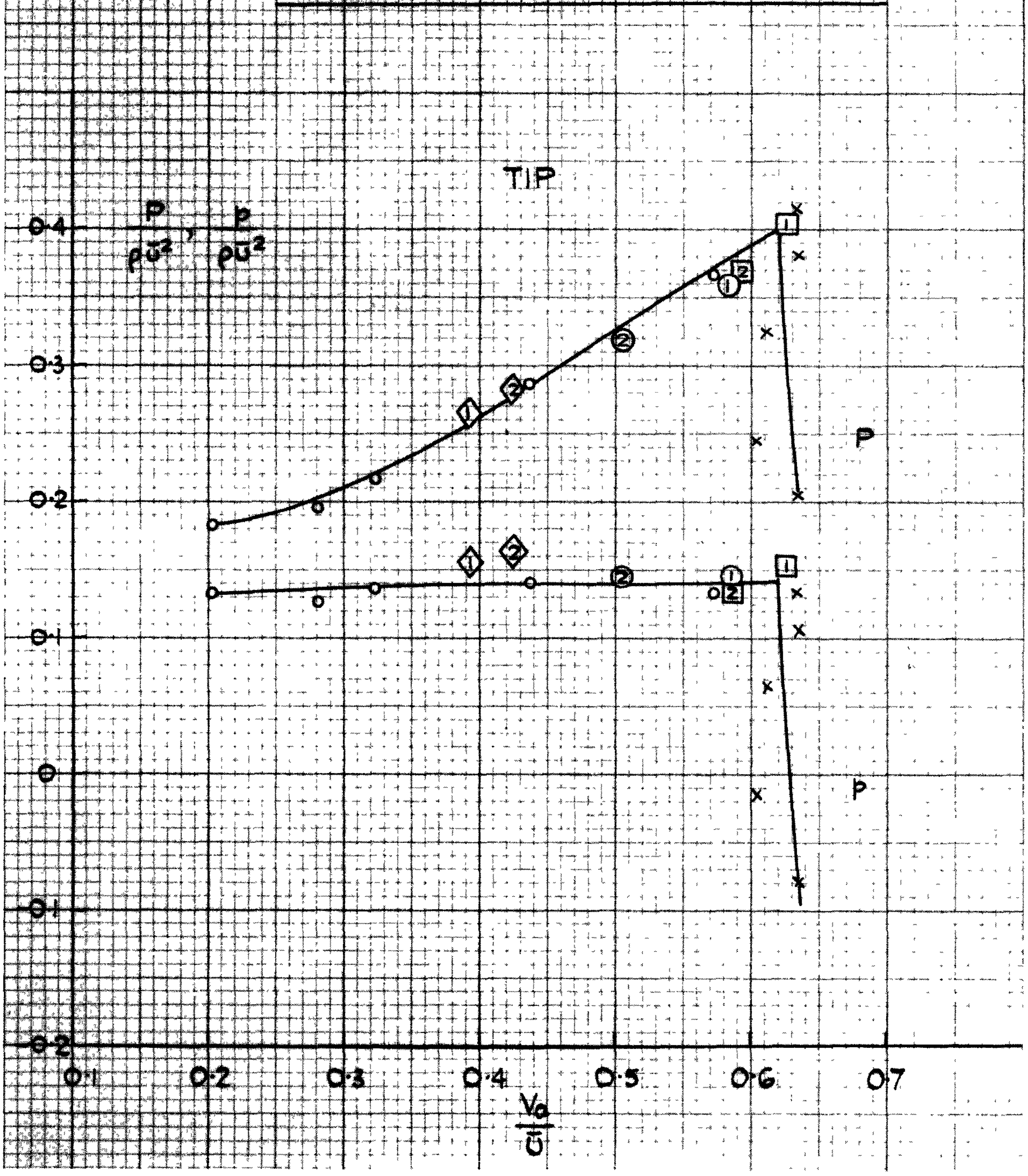
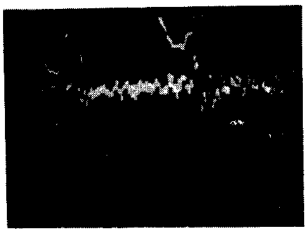


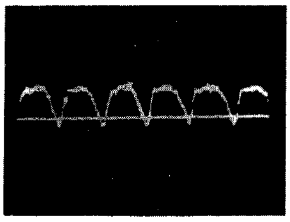
FIG. 31. OSCILLOGRAPH FILMS OF PRESSURE FLUCTUATIONS BEHIND ROTOR TIP

SINGLE STALL CELL
YAW ANGLE 30°

SINGLE STALL CELL YAW ANGLE 90°, SHOWING HOW TURBULENCE GIVES RISE TO A SPURIOUS READING WHEN THE STALLED AND UNSTALLED PRESSURES ARE EQUAL. (SEE FIG. 32)
(UPPER TRACE IS A REFERENCE SIGNAL)



SINGLE STALL CELL YAW ANGLE 15°,
(EXTRA DAMPING IN TRANSDUCER)



TWO STALL CELLS YAW ANGLE 30°,
(SAME EXTRA DAMPING)

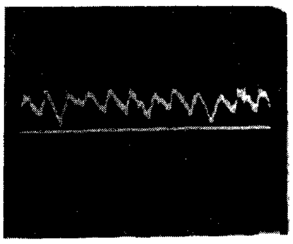


FIG. 32 PRESSURE MEASUREMENTS BEHIND ROTOR TIP

(SINGLE STALL CELL).

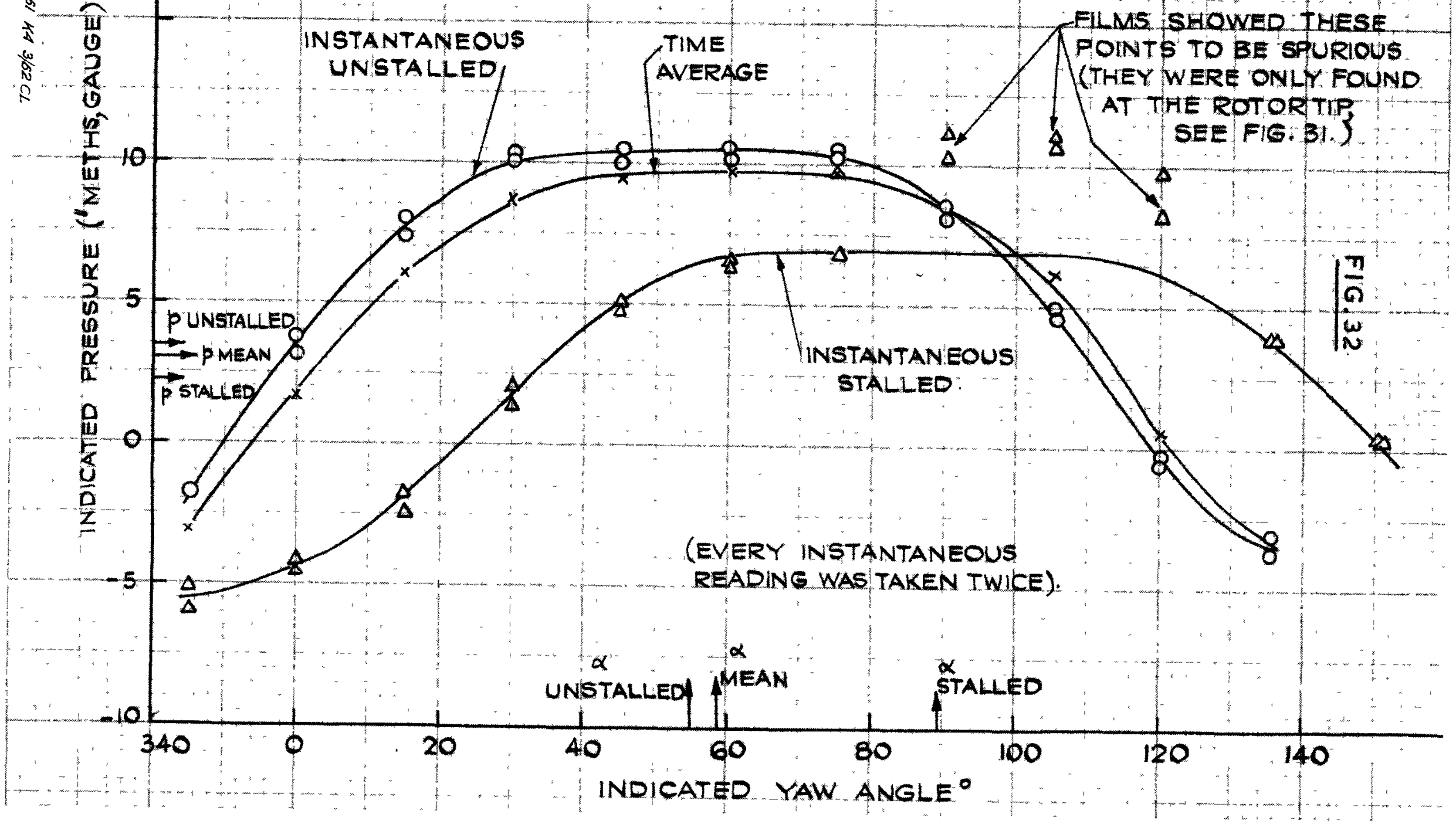


FIG. 32

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Measurements have been made of the instantaneous values of the pressure, velocity, and direction of the flow in a single stage axial compressor. During stall propagation, the flow appears to switch from a point on the unstalled characteristic towards a point on the fully stalled characteristic and back again.

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