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by

J. H. Horlock and E. C. Deverson

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An Experiment to Determine the Position of an Equivalent Actuator Disc Replacing a Blade Row of a Turbomachine

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SUMMARY

One difficulty encountered in the application of actuator disc theory to analyse turbomachine performance is that the axial location of the equivalent disc replacing the blade row has not been satisfactorily determined, analytically or experimentally. This paper describes an experiment in which axial velocity profiles have been measured at many axial locations upstream and downstream of a moving row. Changes in axial velocity outside the row are compared with the exponential decay of axial velocity perturbations predicted by simple actuator disc theory. It is found that the simple theory gives adequate prediction of the observed axial velocities if the disc is located near the axial centre line of the blades.

Introduction

A simple approximate analysis for the changes in axial velocity (C_X) that take place in the flow through an actuator plane from upstream infinity (station 1) to downstream infinity (station 2) has been given by Hawthorne and is reproduced in Reference 1.

The axial velocity at a distance x upstream of such a disc is

$$C_x = C_{x_1} + \frac{(C_{x_2} - C_{x_1})}{2} e^{kx/\ell}$$

The axial velocity at a distance x downstream of such a disc is

$$C_x = C_{x_2} - \frac{(C_{x_2} - C_{x_1})}{2} e^{-kx/\ell}$$

where C_{x_1}, C_{x_2} are the axial velocities at the same radius far upstream and far downstream of the disc.

ℓ is the blade height,

k is a constant which depends upon the hub-tip ratio of the disc. (For a hub-tip ratio of 0.4, $k = 3.22$; for hub-tip ratios approaching 1.0, $K \doteqdot \pi$).

If such an analysis is to be used to predict the flow through a blade row, then the axial location of the equivalent disc has to be determined. Marble (Reference 2) has suggested that this location should

be/

be the centroid of the tangential force acting on the blade. In most calculations using actuator disc theory (Reference 3), the disc has been placed at the axial centre line of the blade row.

Experimental Results

A single rotor row of an axial flow compressor stage of 0.4 hub-tip ratio was used in the experiments. The stage design was of the type in which the exit absolute air angle from the rotor is constant with radius. Details of the rotor blading and the compressor test rig are given in Reference 3. No guide vanes or stators were used.

The rotor was first placed at a forward axial station on the compressor shaft and a series of readings taken with a long exit section of constant annulus area. The experiment was repeated with the rotor placed in a rearward axial location, with a long entry section available. Results from these two experiments were combined by plotting observations relative to the axial location of the rotor.

Static pressures on the outer wall were measured at several axial locations upstream and downstream of the rotor. Static pressures were also recorded on a stationary "dummy" hub which fitted over the rotating hub, upstream and downstream of the rotor. The rotor roots were filled in up to the radius of the dummy hub. Total pressure and yaw angle surveys were made in the main stream at axial locations corresponding to the static pressure tappings.

Initially the rotor was run at 4500 r.p.m. with the maximum flow rate possible (C_{x_1} = 192 ft/sec) but it was found that larger changes in axial velocity profiles were obtained at the same r.p.m. but at a lower flow (C_{x_1} = 125 ft/sec). The rotor remained unstalled. Static pressure distributions along hub and tip are shown for this throttled condition in Figure 1. The rotor produces a small increase in the axial velocity at the tip section and a large decrease in axial velocity at the root section. Not all the changes are produced within the blade row and the variations in static pressure upstream and downstream of the row are proof that radial equilibrium does not exist at the leading and trailing edges.

The axial velocity changes at the tip section, although measurable, were too small to give an accurate assessment of the position of an equivalent disc. The axial velocities at points outside the hub boundary layer region (at a radius of one half of the tip radius) are plotted against axial location in Figure 2, for both the full flow and throttled tests. Approximately 60% of the axial velocity change takes place outside the blade row. The axial velocity distributions are compared with the predictions of the analysis outlined in the introduction.

Discussion

To assess the validity of the simple theory the axial velocity distributions of Figure 2 have been replotted in the form

$$\psi = \log_e \frac{2(C_x - C_{x_1})}{(C_{x_2} - C_{x_1})} \quad \text{against } x, \text{ upstream,}$$

$$\psi = \log_e \frac{2(C_{x_2} - C_x)}{C_{x_2} - C_{x_1}} \quad \text{against } x, \text{ downstream}$$

The/

The straight lines on Figure 3 show the predictions of the analysis based on two axial locations of the disc, one at the centre line and one at 70% of the chord from the leading edge. The slope of these lines is $\pm \frac{k}{\ell} = \pm \frac{3.22}{4.0}$ (since the effective blade length was 4.0 inches), and they meet at $\psi = 0$, where $C_X = (C_{X_1} + C_{X_2})/2$. the experimental results show the expected exponential decay near the blades, but a more rapid attainment of radial equilibrium than that predicted at some 2-3 inches from the blade. It appears that the actuator plane should be located to the rear of the axial centre line for the root section of this particular rotor, possibly at 60%-70% of the chord from the leading edge.

Conclusions

It has been shown experimentally that the simple analysis based on actuator disc theory gives an adequate prediction of the variation in axial velocity through the rotor row tested if the disc is located at some 60%-70% of the chord from the leading edge.

References

No.	Author(s)	Titles, Etc.
1	J. H. Horlock	Some actuator disc theories for the flow of air through axial flow turbo-machines. R. & M. 3030. December, 1952.
2	F. E. Marble	The flow of a perfect fluid through an axial turbo-machine with predescribed blade loading. Journal of Aeronautical Sciences. August, 1948.
3	J. H. Horlock	Experimental and theoretical investigations of the flow of air through two single stage compressors. R. & M. 3031. March, 1955.

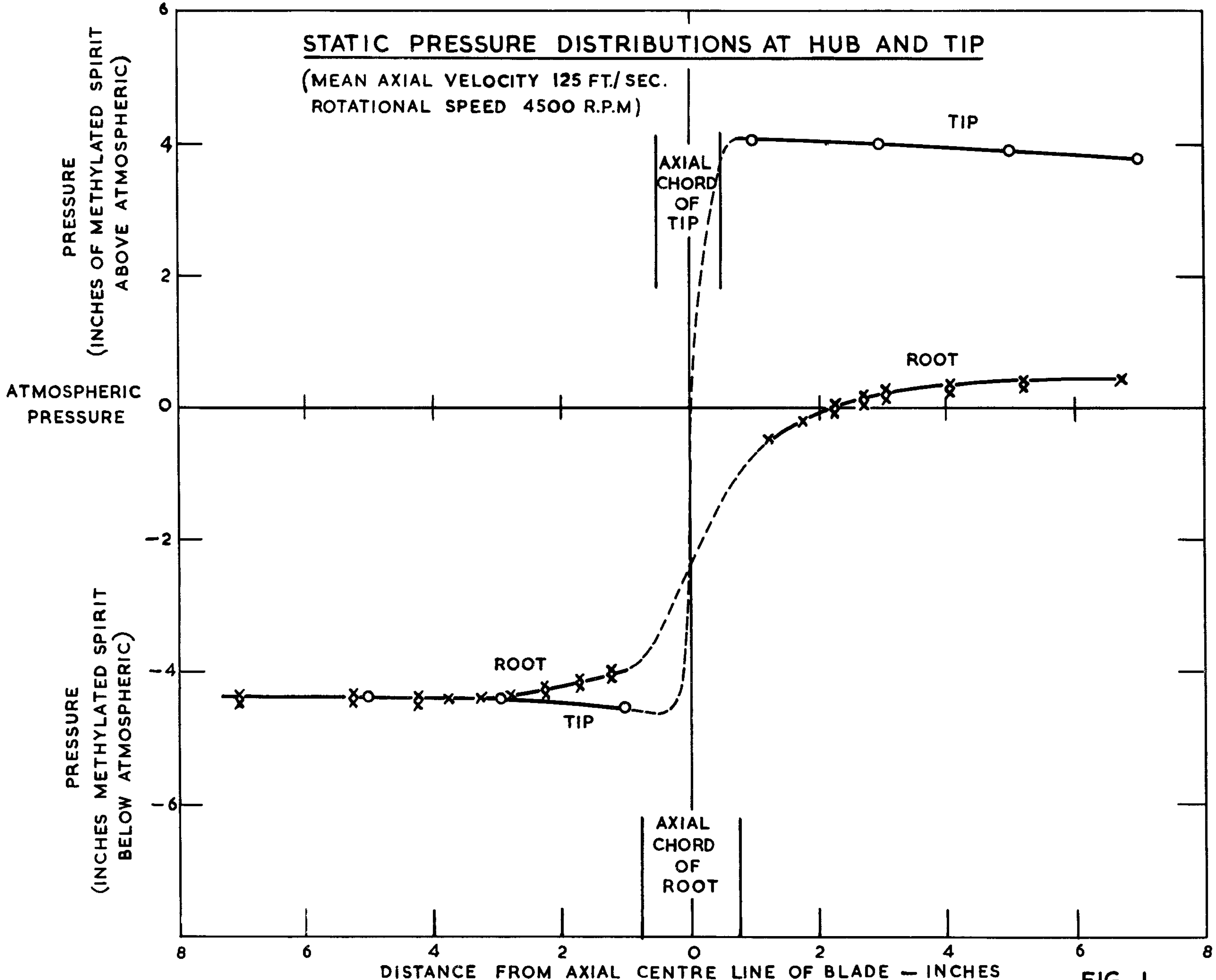
STATIC PRESSURE DISTRIBUTIONS AT HUB AND TIP
(MEAN AXIAL VELOCITY 125 FT./SEC.
ROTATIONAL SPEED 4500 R.P.M)
PRESSURE (INCHES OF METHYLATED SPIRIT ABOVE ATMOSPHERIC)
PRESSURE (INCHES METHYLATED SPIRIT BELOW ATMOSPHERIC)
ATMOSPHERIC PRESSURE
AXIAL CHORD OF TIP
AXIAL CHORD OF ROOT
TIP
ROOT
ROOT
TIP
6
4
2
0
-2
-4
-6
8
6
4
2
0
2
4
6
8
DISTANCE FROM AXIAL CENTRE LINE OF BLADE — INCHES

FIG. 1.

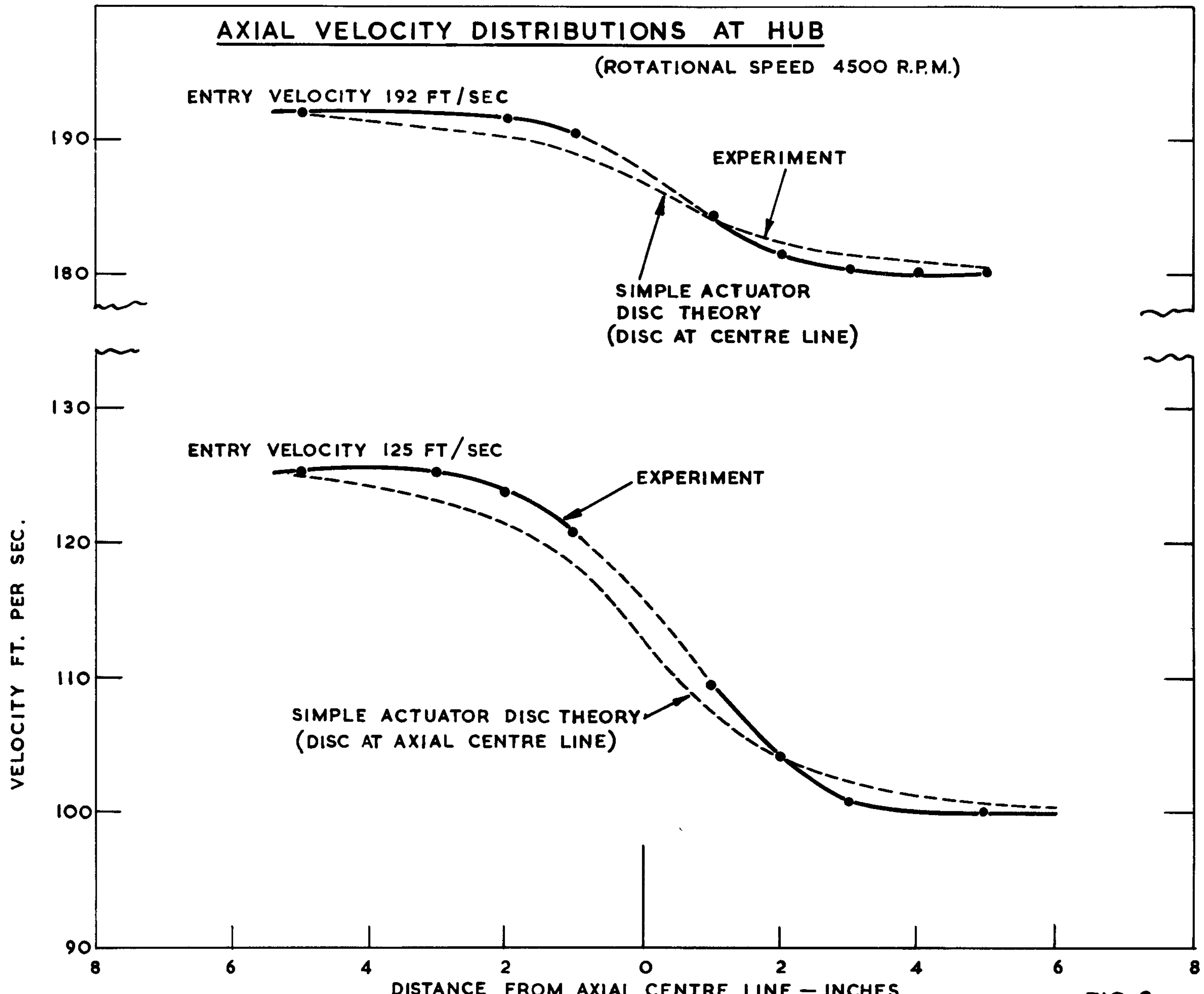
AXIAL VELOCITY DISTRIBUTIONS AT HUB
(ROTATIONAL SPEED 4500 R.P.M.)
ENTRY VELOCITY 192 FT/SEC
EXPERIMENT
SIMPLE ACTUATOR
DISC THEORY
(DISC AT CENTRE LINE)
ENTRY VELOCITY 125 FT/SEC
EXPERIMENT
SIMPLE ACTUATOR DISC THEORY
(DISC AT AXIAL CENTRE LINE)
VELOCITY FT. PER SEC.
190
180
130
120
110
100
90
8
6
4
2
0
2
4
6
8
DISTANCE FROM AXIAL CENTRE LINE — INCHES

FIG. 2.

LOCATION OF ACTUATOR DISC

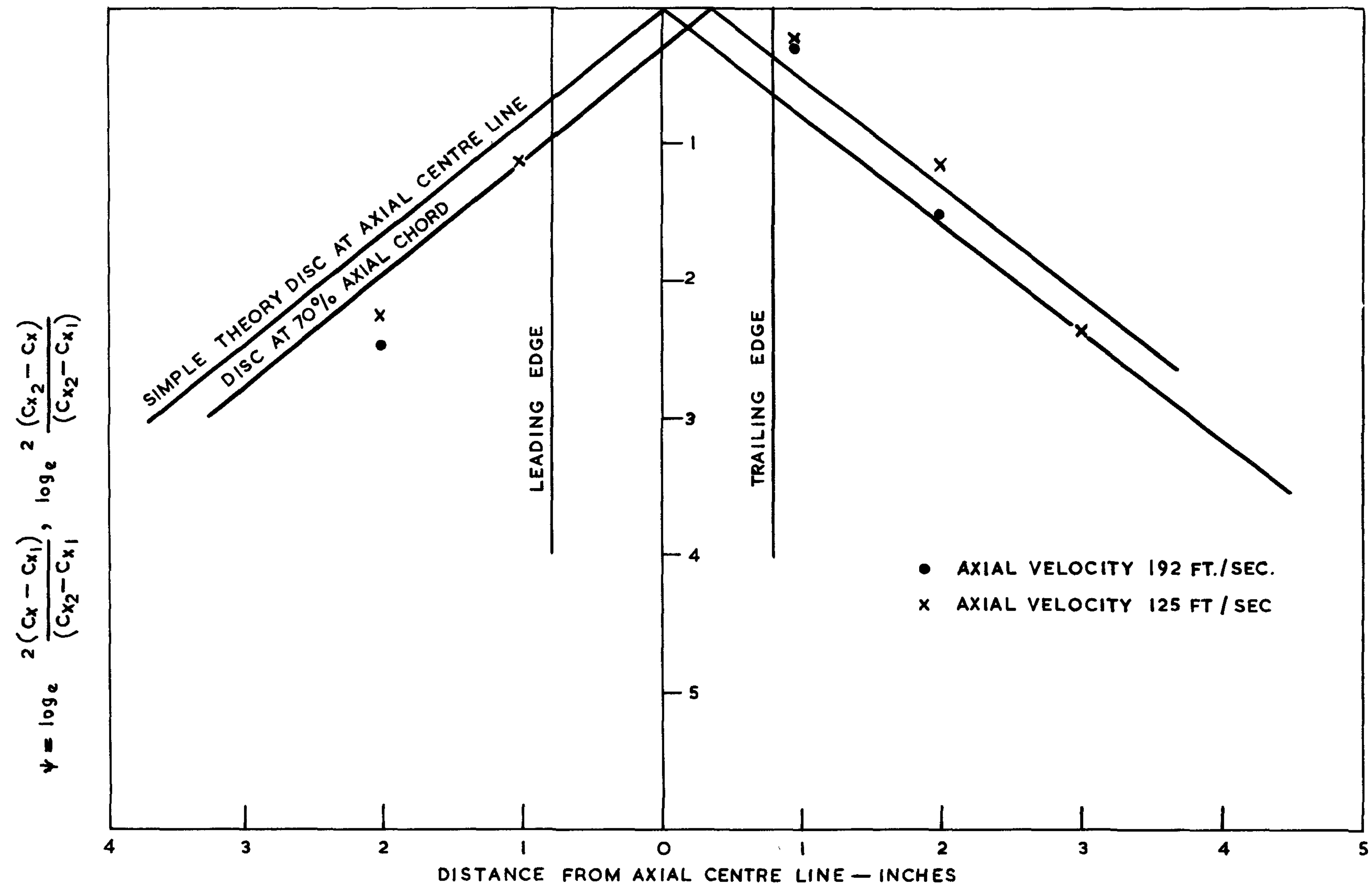

FIG. 3.

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