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Preliminary analysis of a low-work type supersonic fan.

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Publisher's version / Version de l'éditeur:
https://doi.org/10.4224/40003972
Laboratory Memorandum (National Research Council of Canada. Division of Mechanical Engineering. Engine Laboratory); no. NRC-ENG-42, 1965-03

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SECURITY CLASSIFICATION OPEN

SUBJECT Preliminary Analysis of a Low-Work Type Supersonic Fan.

PREPARED BY U.W. Schaub and G.G. Levy

ISSUED TO Internal

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NATIONAL RESEARCH COUNCIL

DIVISION OF MECHANICAL ENGINEERING

LABORATORY MEMORANDUM

NRC-ENG-42

Summary

A preliminary study of low-work supersonic fans has been made, considering only the isentropic flow case, i.e. neglecting shocks, friction and blade loading losses.

Preliminary Analyses of a Low-Work Type Supersonic Fan

1. Introduction

A preliminary study of possible supersonic fan designs has been made based on a proposal for a low-work ($\Delta C_\theta << U_{tip}$) 1.54 P.R. fan.

Initial consideration showed that the low-work criterion at the tip could not be satisfied when a normal shock existed anywhere inside the fan passage. With a normal shock present, a larger swirl change would be required to ensure compatibility of the velocity triangles.

As a first approximation, only the isentropic flow case (i.e. neglecting shocks, friction and blade loading losses) was solved in this analysis.

2. Input Design Data

The following parameters were derived from the proposed design and used in the analysis:

Fan temperature rise - 69°F
Maximum tip speed - 1695 ft/sec
Axial velocity (constant) - 873 ft/sec

A free-vortex design was specified and hence a constant work input per lb. at all radii.

3. Inlet Configurations

Three inlet configurations were examined:

1. Axial Inlet
2. Pre-swirl Inlet Guide Vanes
3. Counter-swirl Inlet Guide Vanes

Because of the high sub-sonic axial velocity (Mach 0.835), it was necessary to consider supersonic pre-swirl I.G.V.'s to ensure a reasonably adequate response in terms of rotor relative Mach No.

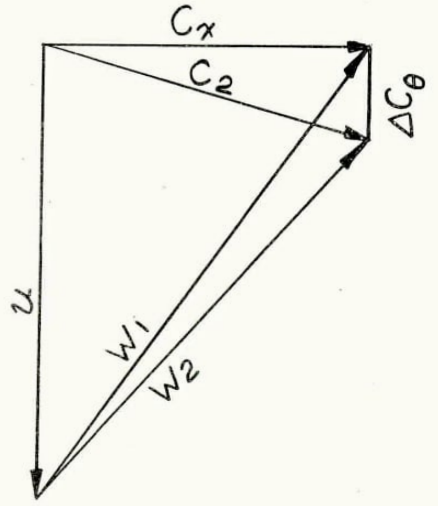
An outlet Mach No. of 1.246 was arbitrarily selected for these vanes.

A Mach No. of 0.9 was chosen as the limiting case for the counter-swirl I.G.V.'s. The above limits were assumed to bracket the region of interest.

4. Results

Rotor relative inlet Mach numbers are plotted in Figure 1 for each of the three inlet configurations, using the ratio of axial velocity to blade speed as the abscissa. The values of C_x/u appropriate to the proposed design are indicated on Figure 2.

Rotor relative exit Mach No., Stator inlet Mach No., rotor deflection angles and stator deflection angles are plotted in Figures 3, 4, 2 and 5, respectively. Velocity diagrams are shown in Figures 6, 7 and 8.



5. Summary of Results

5.1 Blade relative Mach Number

5.1.1 No. I.G.V.'s (Axial Inlet)

The rotor inlet is supersonic for values of C_x/u from 0.5 to 1.4. For values of C_x/u greater than 1.4, it becomes sub-sonic. The rotor exit is supersonic only in the region $C_x/u = 0.5$ to 0.8, and is sub-sonic for larger values of C_x/u. The stator inlet is sub-sonic for small C_x/u values, but is otherwise transonic.

5.1.2 Pre-swirl I.G.V.'s

The rotor inlet is essentially transonic and the stator is strongly supersonic everywhere. The rotor exit is transonic for $C_x/u = 0.5$ to 1.0; but thereafter becomes progressively more supersonic.

5.1.3 Counter-swirl I.G.V.'s

The rotor inlet is entirely supersonic while the stator inlet is sub-sonic. The rotor exit is supersonic for small values of C_x/u and sub-sonic for large C_x/u values.

5.2 Deflection Angles

5.2.1 Rotor

For the axial inlet case considered here, rotor deflection angles vary between 5° and 32.5° at the tip and root, respectively. Although the Pre- and counter-swirl vanes alter the rate of deflection angle change with C_x/u, the tip and root values do not change greatly.

For large values of C_x/u, the rotor deflection angles for the axial inlet and counter-swirl cases approach each other and become increasingly large. In the pre-swirl case, the rate of deflection angle changes with C_x/u, for large values of C_x/u, decreases and tends towards a very small constant value, giving deflections of approximately 32°.

5.2.2 Stator

At all values of C_x/u, significant changes in the stator deflection angles, relative to those attainable with the axial inlet, may be achieved by the use of pre-swirl or counter-swirl I.G.V.'s.

6. General

6.1 It is important to note that not all configurations bracketed in this analysis necessarily lead to practical applications. In some instances, the Mach No. variations inside the passages imply unusual geometrical changes and, also, the blade loadings may become excessively high at large values of C_x/u.

6.2 It is to be noted that most published work to date on this subject has dealt with high-work (i.e. large deflection angles) supersonic compressor stages, while the design considered here is essentially a low-work (i.e. smaller deflection angles) supersonic fan (see Appendix).

7. Conclusions

1. On the basis of the first approximations made in this analysis, it would appear that the low-work supersonic fan represents a valid addition to the family of high by-pass ratio engines, particularly in cases where a reducing gear drive cannot be considered.

2. By using progressively decreasing amounts of counter-swirl from root to tip, maximum velocities could be held below about $M = 1.4$, in spite of the 1695 ft/sec tip speed.

Appendix

1. Some Notes on Low Work and High Work Type Supersonic Fans

Most of the research done on supersonic compressors has dealt with "high work high Mach number" stages and the state of the art at this moment appears to be such that a well performing high efficiency stage of this category can be made by carefully applying available design rules.

Practically all blade rows designed feature high solidities for the simple reason that the open area between blades can then be considered as channels to which supersonic internal flow experience can be applied. The supersonic blade in row has therefore neither connection with isolated airfoil theory nor with subsonic cascade experience. Some supersonic cascades have been built (using the channel design techniques) to check on the magnitude of the centrifugal effects experienced in rotating blade rows. The diffusion limit $(C_2/C_1)_{min.}$ appears to be approximately that of the subsonic diffuser, $(C_2/C_1)_{min.} = 0.72$. The so-called "diffusing type" supersonic blade rows that have design diffusion ratios in excess of 0.72 show, when tested, badly separated flows downstream of the normal shock. The diffusion accomplished by such a blade row is almost entirely due to the velocity decrease across the normal shock. The observation that supersonic blade rows with separated subsonic flows do not necessarily have poor efficiencies has led directly to the cambered wedge blade form where the "would-be" separated flow area is filled in by the blade itself.

The "low-work" blade row is not required to work to the limits of diffusion and hence need have only moderate blade camber. Theoretically, the danger of flow separation should not be as great here as was experienced in "high-work" blade rows. The performance required from a "low-work" supersonic stage is very similar to that obtainable from a good subsonic stage, except that the high rotational speed necessitates supersonic flow (at least in some places) inside the stage passages. Two approaches are indicated now that could be used as a basis for discussion of a fan programme.

2. Method 1

The rotor blade row has a low solidity with the blades set at large stagger angles. Conventional supersonic channel design techniques cannot be used because the passages are much too wide. One might attempt combining appropriate subsonic compressor with isolated supersonic air-foil design methods.

3. Method 2

Another approach to the low-work stage design is to use IGV's. Relative Mach numbers at the rotor blade tips can be reduced by pre-swirling the inlet flow in the peripheral direction. Relative Mach numbers at the rotor blade root can be increased (in order to improve radial matching) by imparting counter-rotating swirl with the IGV roots. When IGV's are used the aerodynamic problems associated with s.s. rotor operation are much more severe (as has been established by high-work s.s. compressor testing) because of interaction between IGV wakes with the rotor shock patterns. Possibly the impulse type s.s. blading would be the most tolerant in passing through the non uniform velocity profile. The stator could be made supersonic or transonic followed by subsonic flow.

4. Specific Problem Areas

It is anticipated that the fan aerodynamics of low-work fans will be quite complicated since it is unlikely that the stage can be tested in component form. There are some specific areas, however, that are more problematical than others (at first glance) and these are indicated below.

5. Low Solidity Rotor

It is most important that no shocks project upstream and this will be difficult to accomplish with a low solidity blade row unless the relative Mach numbers are large. The problem of end wall boundary layer and shock interaction becomes of greater importance. The stator is relied on much more than has been during the past s.s. compressor programmes, because it is required to do more turning.

6. Stage with IGV's.

Here both the rotor and stator blade rows present many design problems. The rotor has to tolerate the unwholesome environment of a defective inlet velocity profile. The stator problems are those of above.

The following references were used:-

1. Further Investigations of a Blunt Trailing Edge Cascade in the S-3 Supersonic Wind Tunnel.
   by P. Herman, Von Karman, **Institute for Fluid Dynamics**, Internal Note 9.
2. Design Data of the R-32 Rotor (A Supersonic Axial Compressor using Blunt Trailing Edge Blades).
   by F. Breugelmans, Training Centre for Experimental Aerodynamics, Internal Note 3.
3. Aerodynamics of Turbines and Compressors.
   Editor, W. R. Hawthorne, Princeton University Press, 1964.
4. Résumé of the Supersonic-Compressor Research at NACA Lewis Laboratory.
   Ward W. Wilcox, Edward R. Tysl, Melvin J. Hartmann, ASME Paper No. 58-A177.
5. A Review of Supersonic Compressor Development.
   J. F. Klapproth, Flight Propulsion Division, General Electric Co., Cincinnati, Ohio.
   ASME Paper No. 60-WA-294.

FIG 1

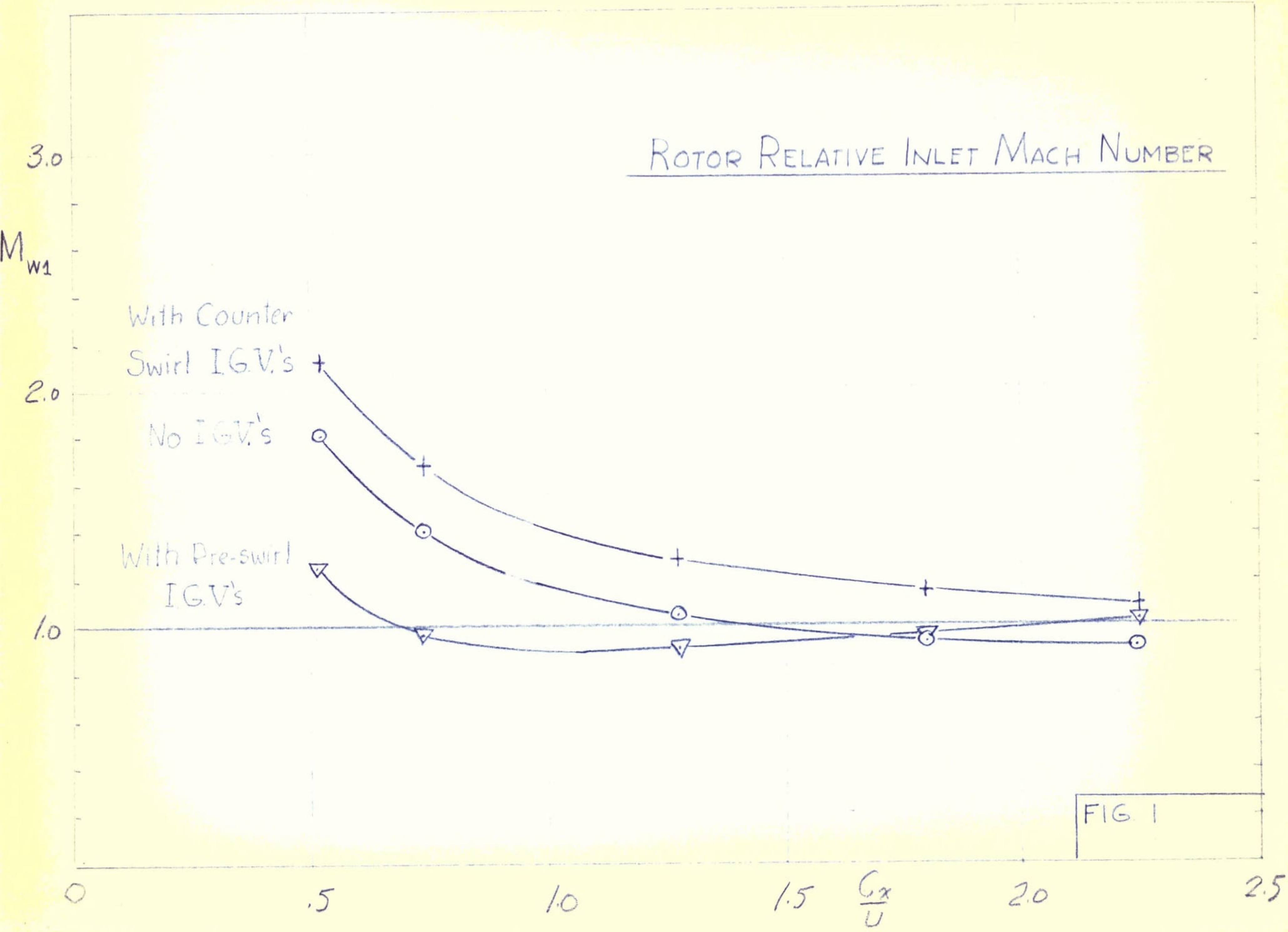
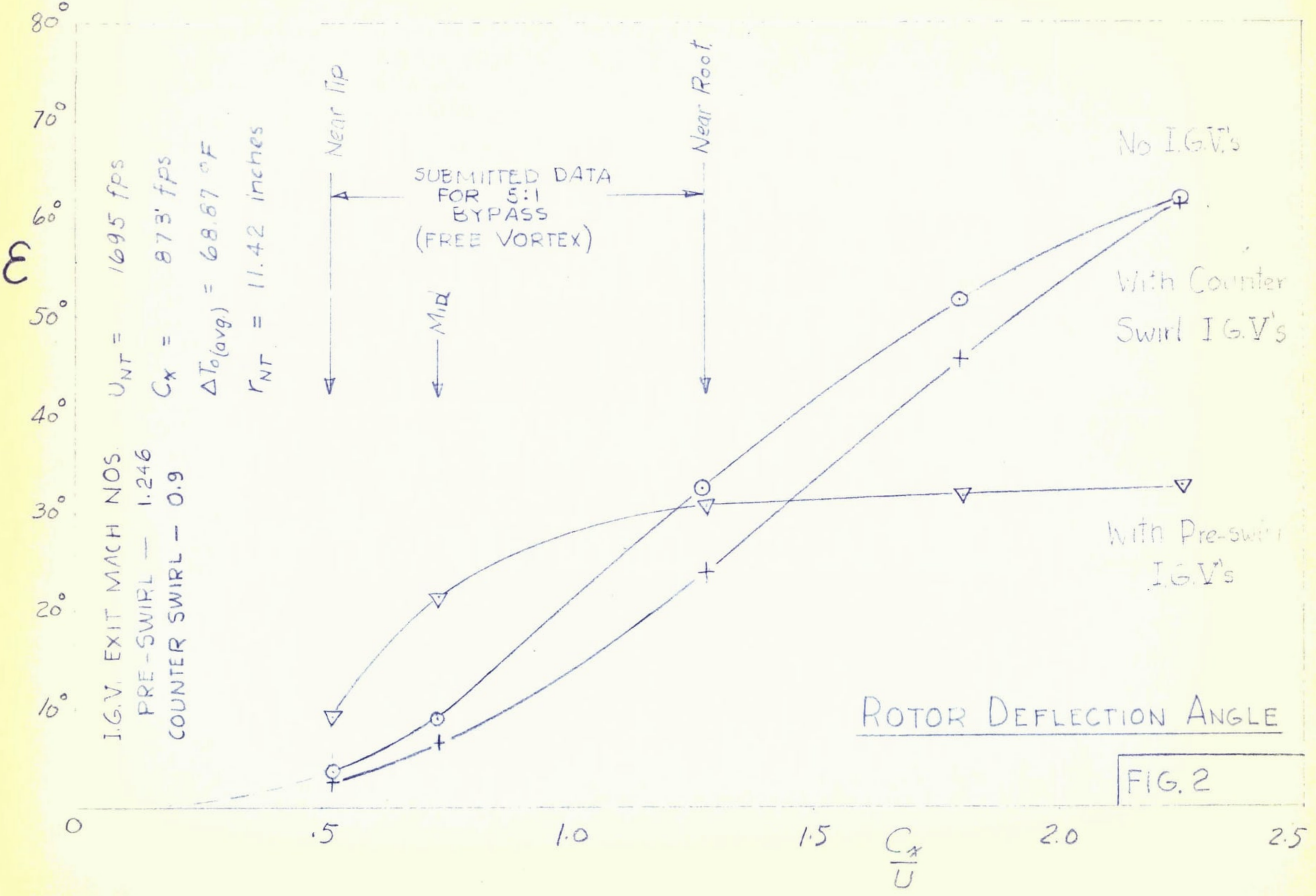

ROTOR RELATIVE INLET MACH NUMBER
M_{W1}
3.0
2.0
1.0
With Counter Swirl I.G.V.'s
No I.G.V.'s
With Pre-swirl I.G.V.'s
0
.5
1.0
1.5
2.0
2.5
$\frac{C_x}{U}$

FIG 1



ROTOR DEFLECTION ANGLE

FIG. 2

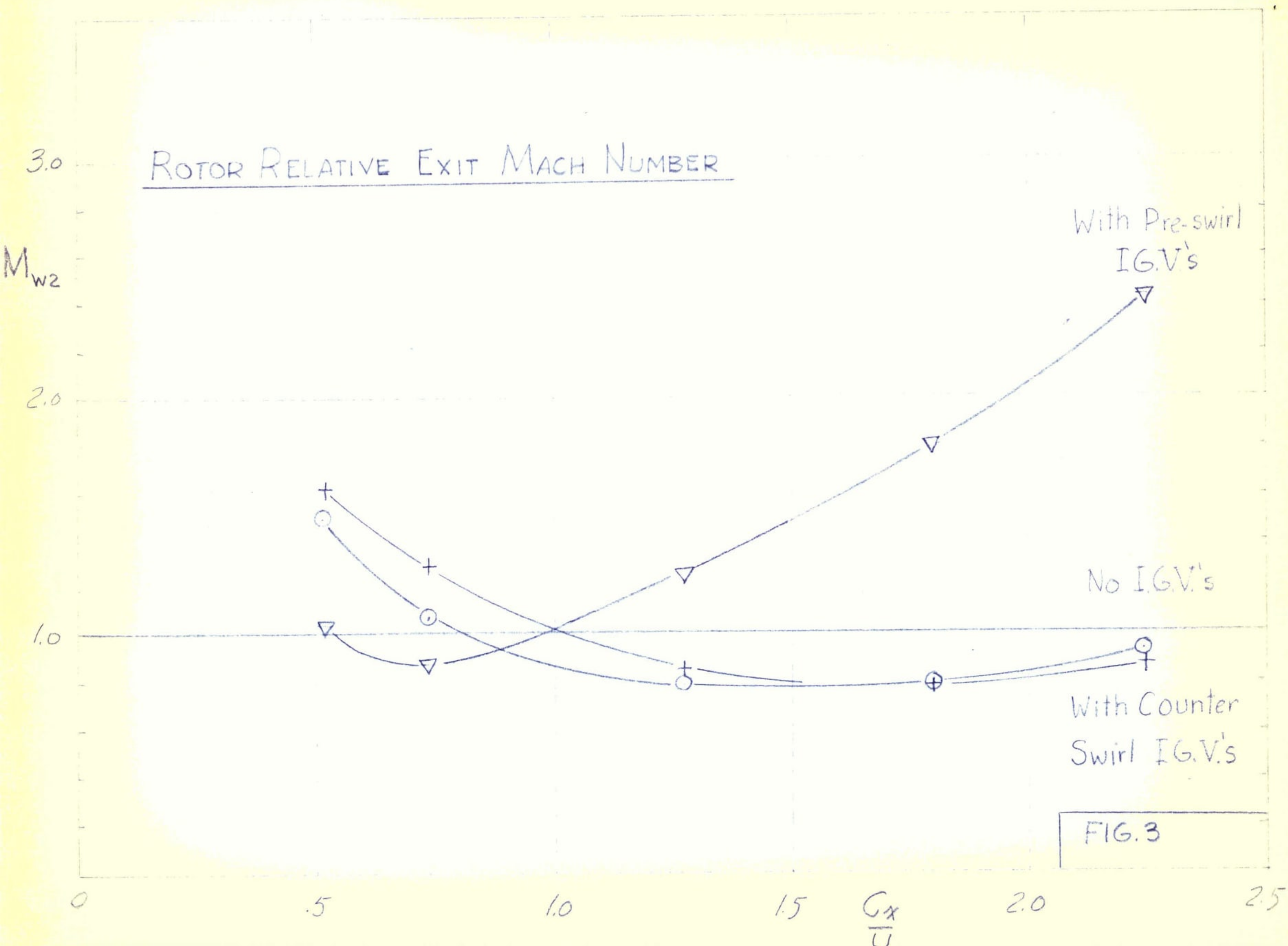

ROTOR RELATIVE EXIT MACH NUMBER
M_{w2}
3.0
2.0
1.0
0
.5
1.0
1.5
2.0
2.5
$\frac{C_x}{U}$
With Pre-swirl I.G.V's
No I.G.V's
With Counter Swirl I.G.V's

FIG. 3

FIG 4

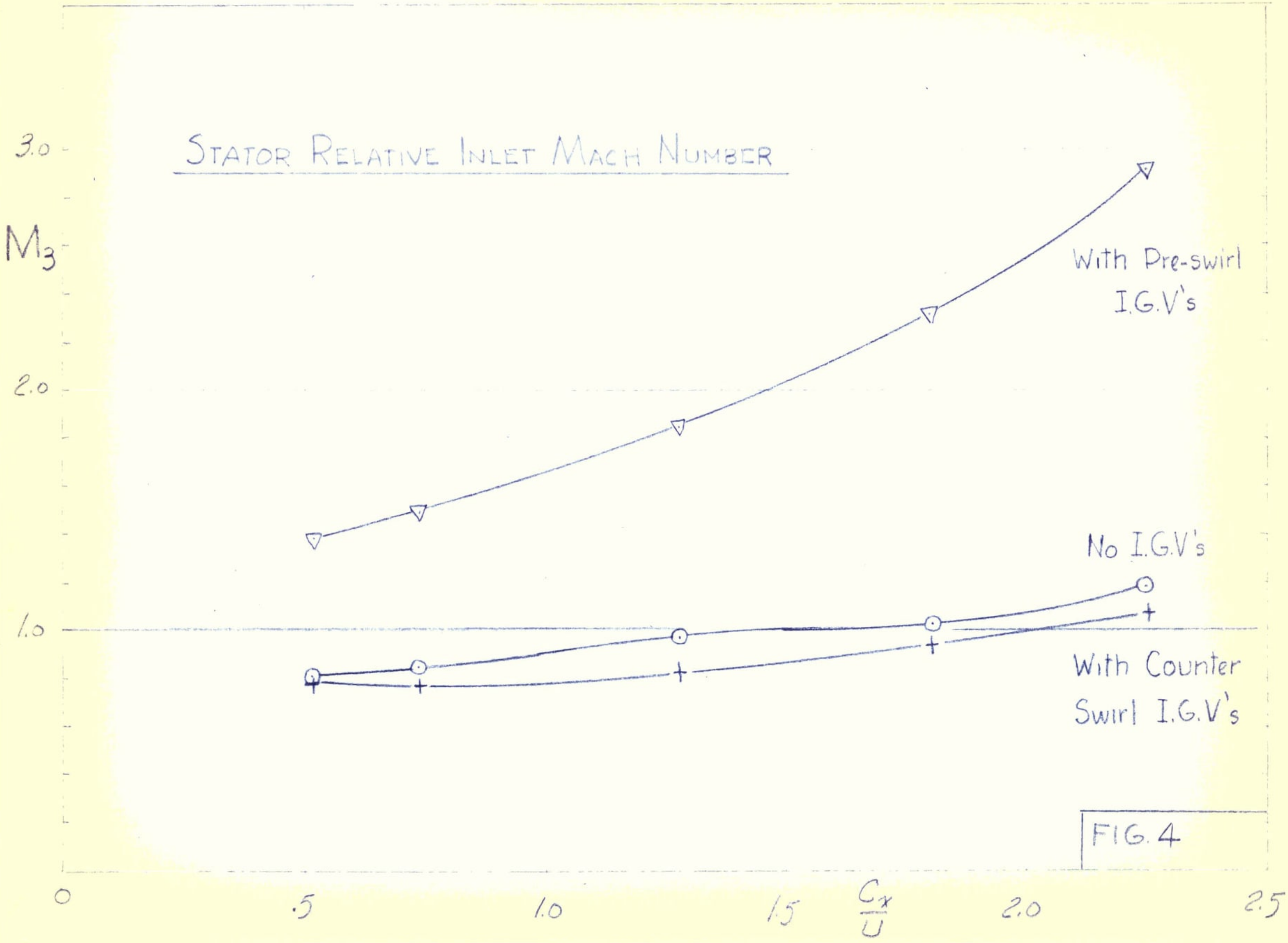
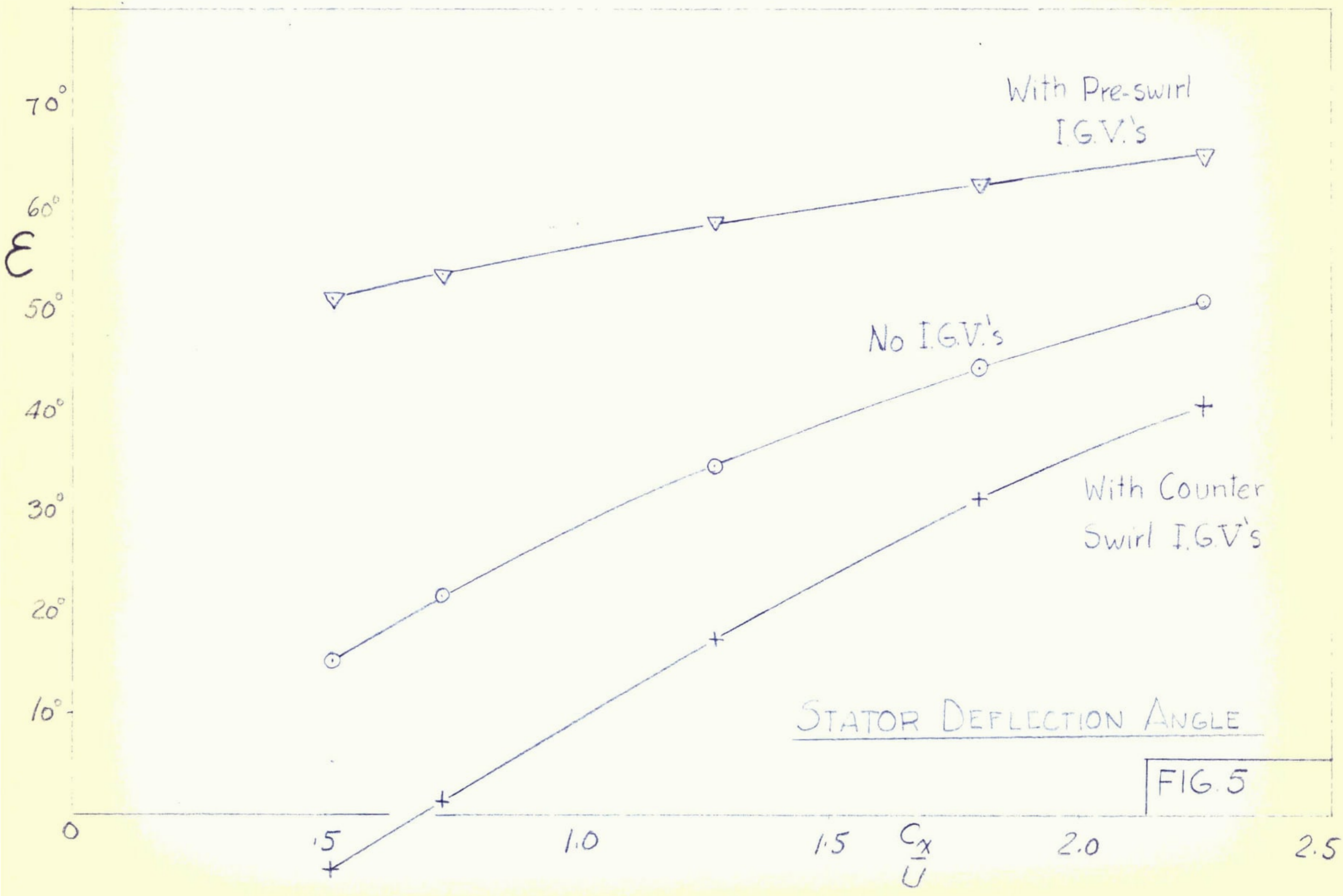
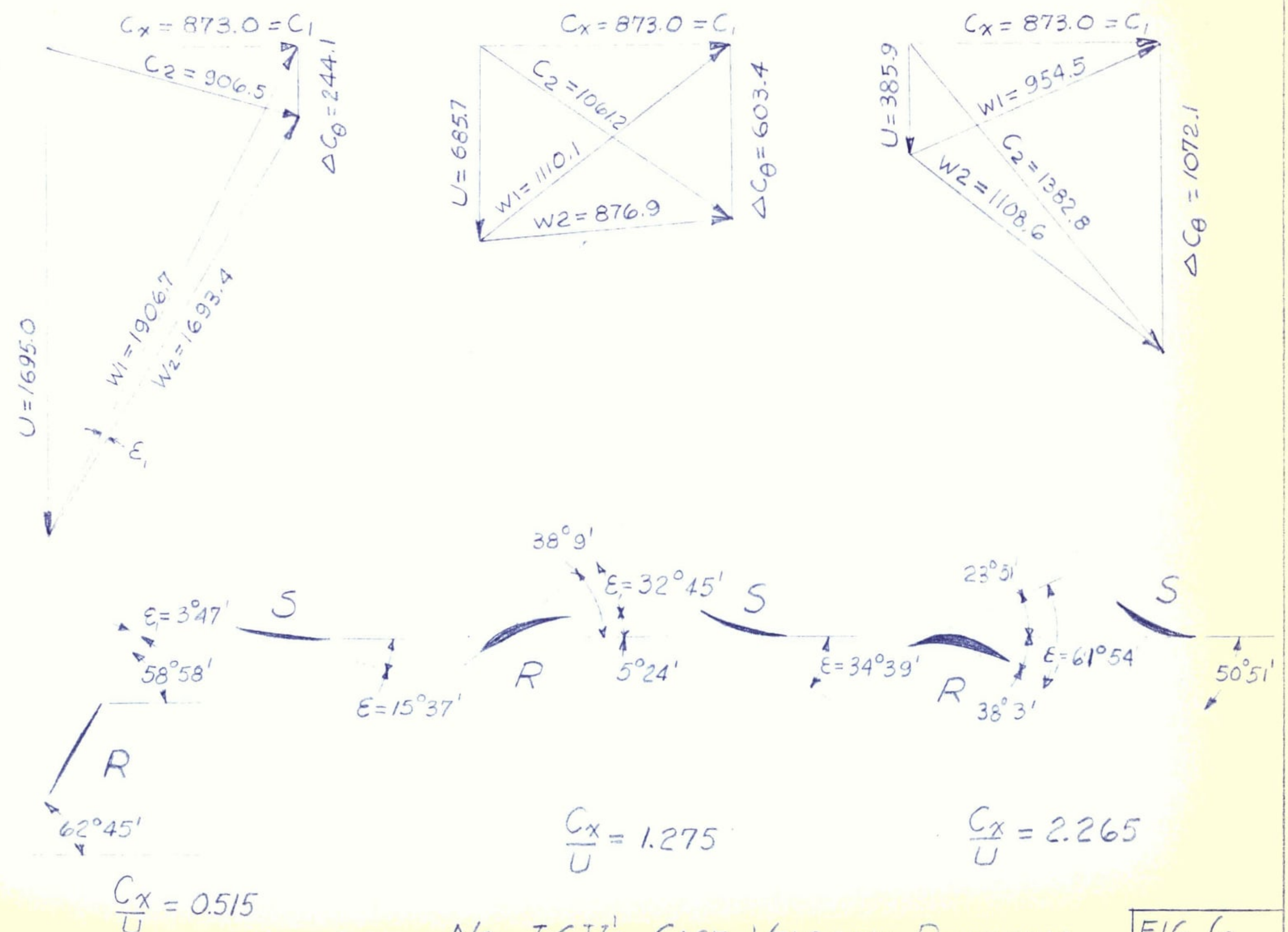

STATOR RELATIVE INLET MACH NUMBER
M_3
3.0
2.0
1.0
0
.5
1.0
1.5
$\frac{C_x}{U}$
2.0
2.5
With Pre-swirl I.G.V's
No I.G.V's
With Counter Swirl I.G.V's

FIG. 4



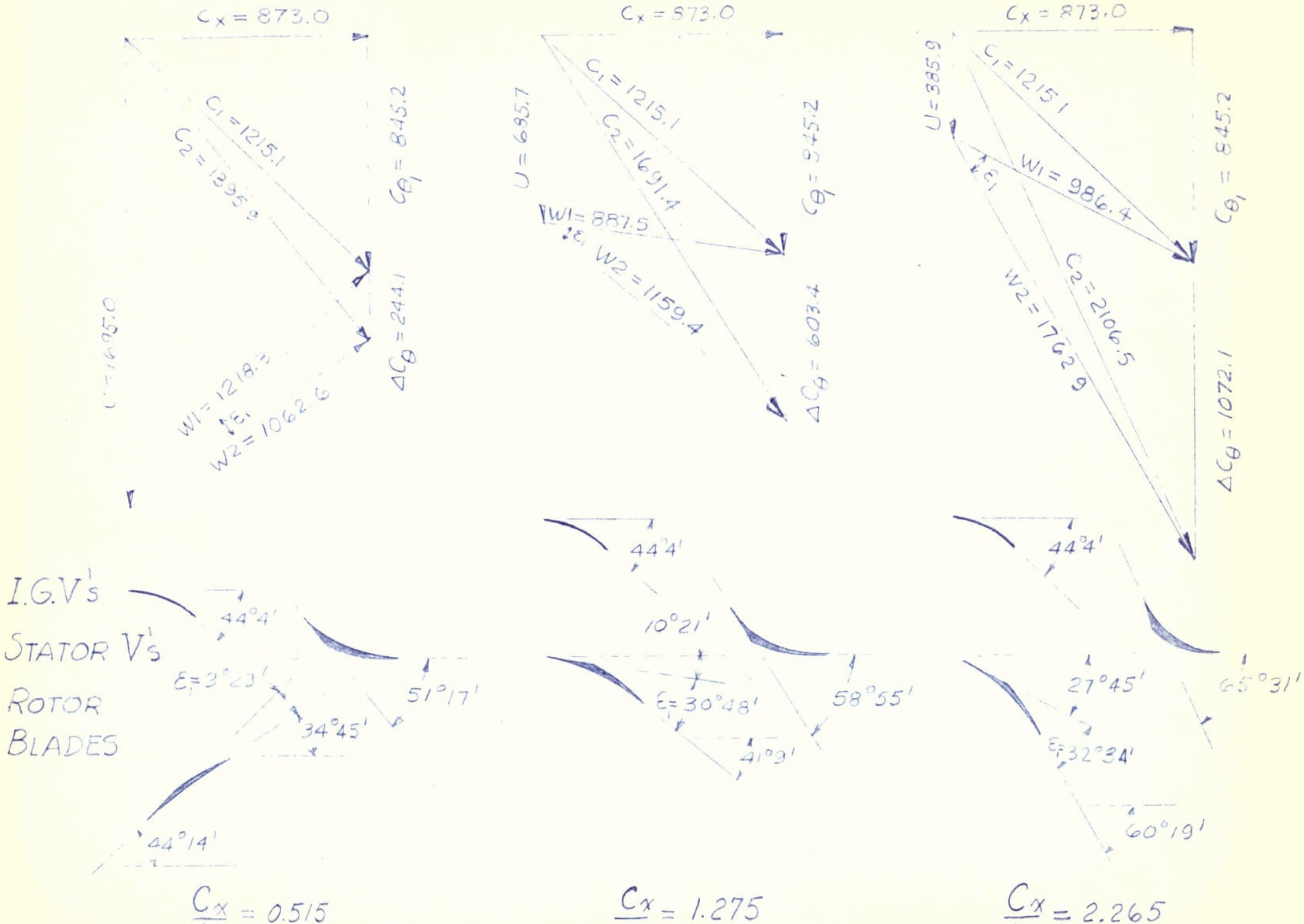
STATOR DEFLECTION ANGLE

FIG. 5



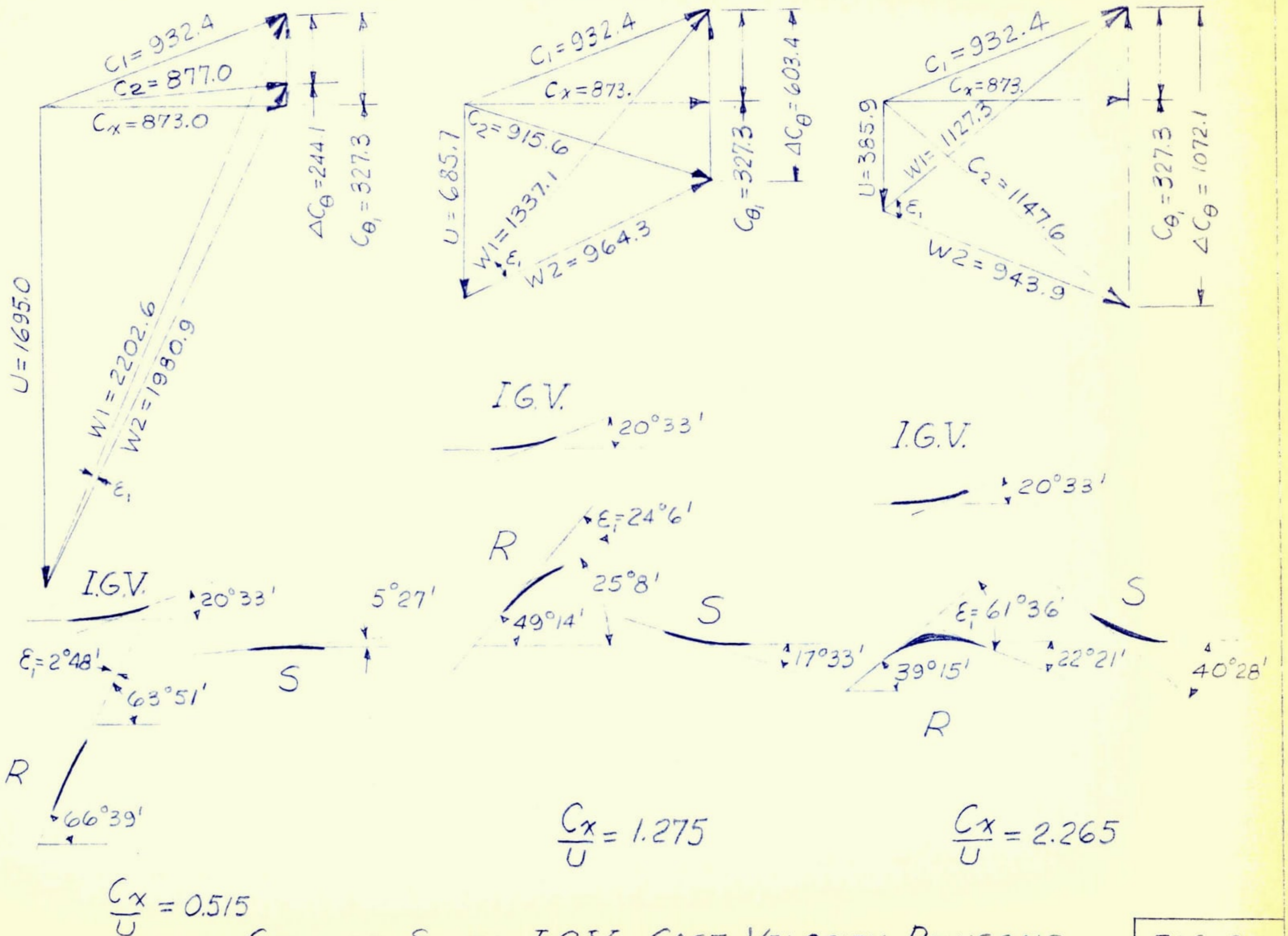
No I.G.V's CASE VELOCITY POLYGONS

FIG. 6



PRE-SWIRL I.G.V. CASE VELOCITY POLYGONS

FIG.7



COUNTER-SWIRL I.G.V. CASE VELOCITY POLYGONS

FIG. 8