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AN INVESTIGATION OF THE FEASIBILITY OF ACTIVE BOUNDARY LAYER THICKENING FOR AIRCRAFT DRAG REDUCTION

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AN INVESTIGATION OF THE FEASIBILITY OF ACTIVE BOUNDARY LAYER THICKENING FOR AIRCRAFT DRAG REDUCTION

By

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ABSTRACT

The feasibility of using a forward mounted windmilling propeller to extract momentum from the flow around an axisymmetric body to reduce total drag has been studied. Numerical calculations indicate that a net drag reduction is possible when the energy extracted is returned to an aft mounted pusher propeller. However, net drag reduction requires very high device efficiencies.

Results of an experimental program to study the coupling between a propeller wake and a turbulent boundary layer are also reported. The experiments showed that a complex coupling exists and simple modes for the flow field are not sufficiently accurate to predict total drag.

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INTRODUCTION

This project was concerned with investigating the feasibility of using propeller systems to reduce total drag on an axisymmetric body. Net drag reductions of up to 10 percent have been predicted by Löbert (Refs. 1, 2) for bodies of revolution with dimensions similar to the fuselage of a large transport aircraft travelling at subsonic speeds. Those predictions were based on simple models for the propeller wakes and for the turbulent boundary layer beneath the wakes. Since this drag reduction scheme could have applications in general aviation, remotely piloted vehicles, torpedo and submarine systems, the reliability of the early estimates of Löbert needed to be demonstrated. In order to assess its potential for drag reduction, an accurate model of the flow field was required along with some level of experimental verification.

Combined numerical and experimental investigation were undertaken in the present study. The computational effort used a potential flow code (Ref. 3) and a boundary layer code (Ref. 4) to estimate skin friction and pressure drag over a body with dimensions similar to a transport aircraft. Experiments were conducted using a cylindrical body in a low-speed wind tunnel to investigate the coupling between a windmilling propeller wake and a fully turbulent boundary layer.

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NUMERICAL STUDY

A typical body of revolution is shown in Fig. 1 (at zero angle of attack). Several locations and propeller sizes were examined for the for-

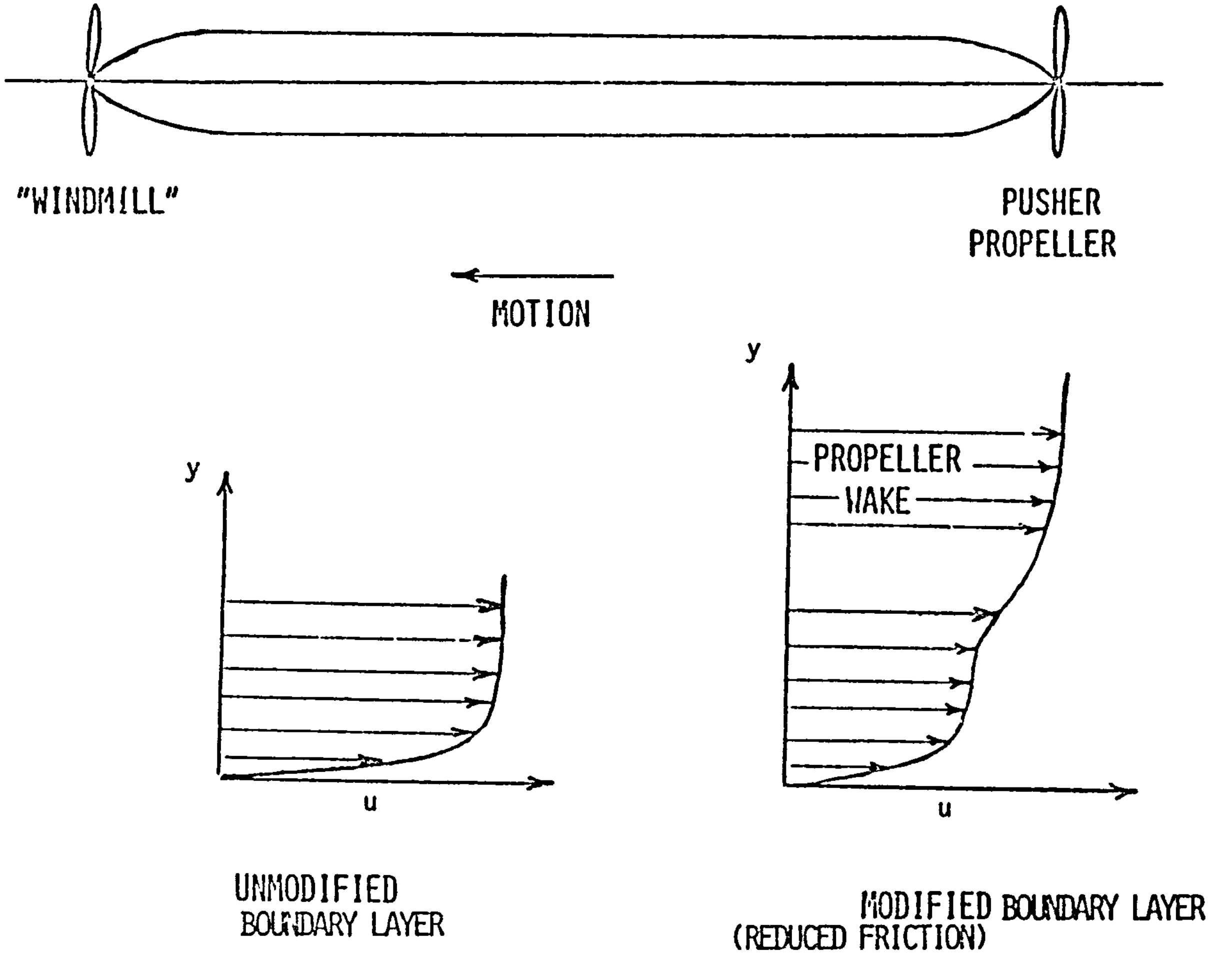


Figure 1. Strategy for active boundary layer thickening.

ward-mounted windmill propeller. The locations and blade lengths considered are tabulated in Table 1.

Table 1. Typical Numerical Results.

CASE	SKIN FRICTION	PRESSURE DRAG	TOTAL DRAG	PROPULSIVE POWER REQD	TURBINE POWER
No Turbine	5887 lb	2181 lb	8068 lb	6.42 M $\frac{\text{ft-lb}}{\text{sec}}$	0
Wind Turbine	3914	6061*	9976	7.94 M $\frac{\text{ft-lb}}{\text{sec}}$	2.18 M $\frac{\text{ft-lb}}{\text{sec}}$

*Pressure drag includes drag of turbine fan.

Since the velocity distribution produced by the propeller wake was three-dimensional and dependent upon the number of propeller blades, rotational speed, forward speed, and propeller blade geometry, it was impossible to develop either an optimized mean wake velocity profile or an optimized propeller location and geometry. After numerous trial and error attempts at producing a realistic propeller wake velocity profile, the boundary layer velocity profile was assumed to take a one seventh power law form and the wake profile was assumed to be in the form:

$$u = C_0 + C_1\, y + C_2\, (y-a)^2.$$

That profile was sufficient to allow coupling between the wake and the turbulent boundary layer using the Beckwith-Bushnell code (Ref. 4). Furthermore, it was possible to calculate the power extracted by the propeller and the pressure drag due to the power extraction.

The performance of the aft-mounted pusher propeller has not been considered in any detail. The difficulty associated with that element is the trade-off between improved performance due to the availability of low-momentum fluid ahead of the propeller and increased drag resulting from acceleration of the low momentum fluid through the propeller. The drag increase is caused by a pressure reduction on the contoured afterbody, which results directly in an increased pressure drag.

It was assumed that the flow in the afterbody region could be maintained as attached and the pressure coefficient could be controlled similar to the distribution shown in Fig. 2. A test case was run on the model shown in Fig. 3 where the aft-mounted propeller was assumed to be configured and mounted to produce the pressure distribution shown in Fig. 2. A free stream velocity of 796 ft/sec (243 m/sec) was assumed. The performance results tabulated in Table 1 can be considered as typical.

Based on the numerical calculations, it can be seen that while the predicted skin friction drag can be decreased by about 33 percent, the total drag increases by about 24 percent. The drag increase is due to the drag associated with the wind turbine and the pressure drag increase on the afterbody. However, an ideal wind turbine can produce 2.18×10^6 ft-lb$_f$/sec (2.96 MW) which can more than offset the drag penalty. Alternatively, if 1.52×10^6 ft-lb$_f$/sec (2.06 MW) can be returned through the aft mounted propeller as propulsive power, the overall system breaks even. Hence, if the overall device efficiencies (the product of windmill efficiency, power transmission efficiency and propeller efficiency) exceed 70 percent, a net drag reduction can be accomplished. This translates to windmill and propeller efficiency requirements of approximately 85 percent each. These relatively high efficiency requirements show how important accurate models of the flow field must be to predict reliably an overall drag reduction. The authors of this report believe the flow field predictions do not capture the

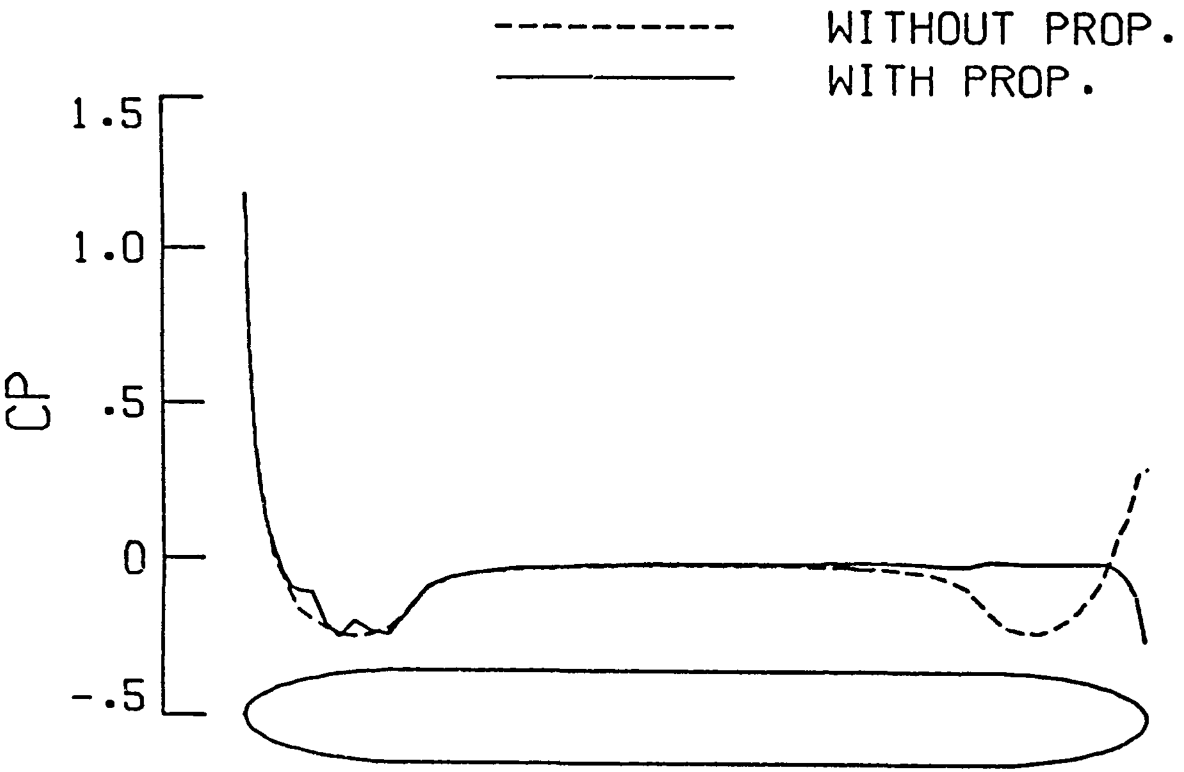
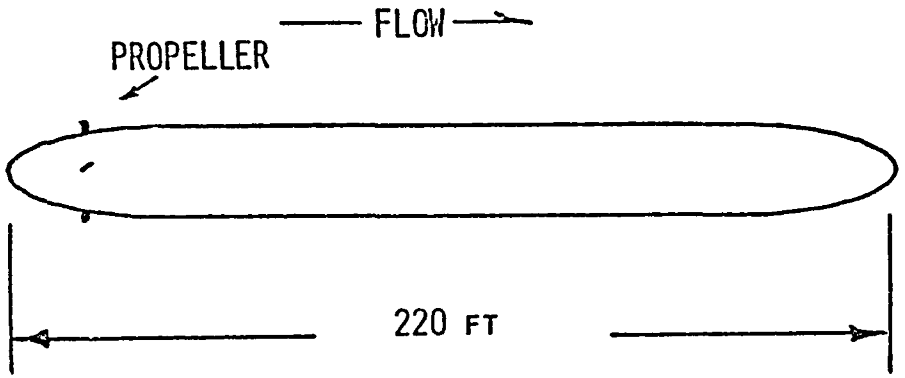


Figure 2. Predicted coefficient distribution over an axisymmetric body without propellers and with forward and aft-mounted propellers.

REPRESENTATIVE BODY USED IN COMPUTER STUDIES



MAXIMUM BODY DIAMETER: 24 FT

PROP. BLADE LENGTH: 1 FT

Figure 3. Representative model dimensions for computational study. (Aft mounted propeller not shown).

flow physics to the extent that net drag reduction can be translated into precise device efficiency requirements and this led to the experimental phase of the investigation.

EXPERIMENTAL MEASUREMENTS

The low speed wind tunnel at Old Dominion University was used to study the coupling between turbulent boundary layer velocity profiles and the flow field behind a windmilling propeller. The wind tunnel has a 3 (0.914 m) by 4 (1.219 m) feet test section and can be operated at speeds up to 175 ft/sec (53.3 m/sec).

An axisymmetric model 2.37 inches (6.02 cm) in diameter and 55.75 inches (1.42m) long with an elliptic nose and a blunt base was mounted in the wind tunnel test section. The model was designed to accommodate a propeller, 27 inches (68.6 cm) behind the nose as shown in Fig. 4. The model was held in place by a vertical airfoil strut located 7 inches (17.28 cm) from the nose and an adjustable sting attached to the aft end of the model. The sting could be adjusted to eliminate angle of attack problems and both supports were adjusted to minimize any bowing of the model. A 2 watt D.C. motor/generator was attached to the propeller shaft to vary the propeller load and thereby control propeller speed. The motor was too small to produce any significant thrust and thus precludes measurements on the coupling between a turbulent boundary layer and a propulsive propeller.

A fully developed turbulent boundary layer was produced by employing a 0.08 inch (2mm) diameter wire trip located 3 inches (7.62 cm) from the nose at the shoulder. Pitot probe boundary layer surveys were made along the model to establish the quality of the turbulent boundary layer. The propeller slot was sealed to prevent any disturbances and typical boundary layer velocity surveys are shown in Fig. 5. The boundary layer thickness varied

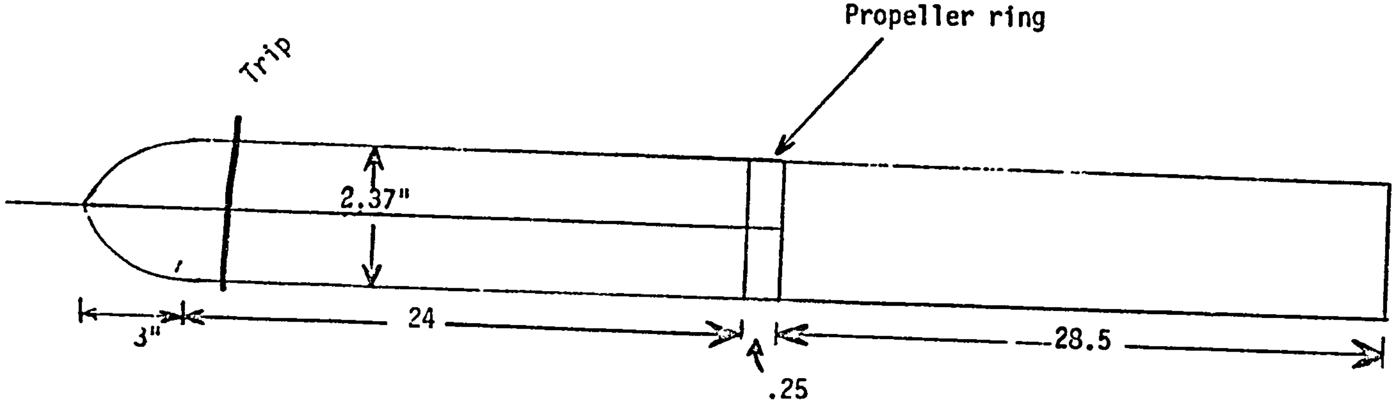


Figure 4. Schematic diagram of the wind tunnel model showing dimensional data (in inches).

Distance from model nose tip = x

N = index in the power law $\frac{u}{u_\infty} = (\frac{y}{\delta})^{1/N}$

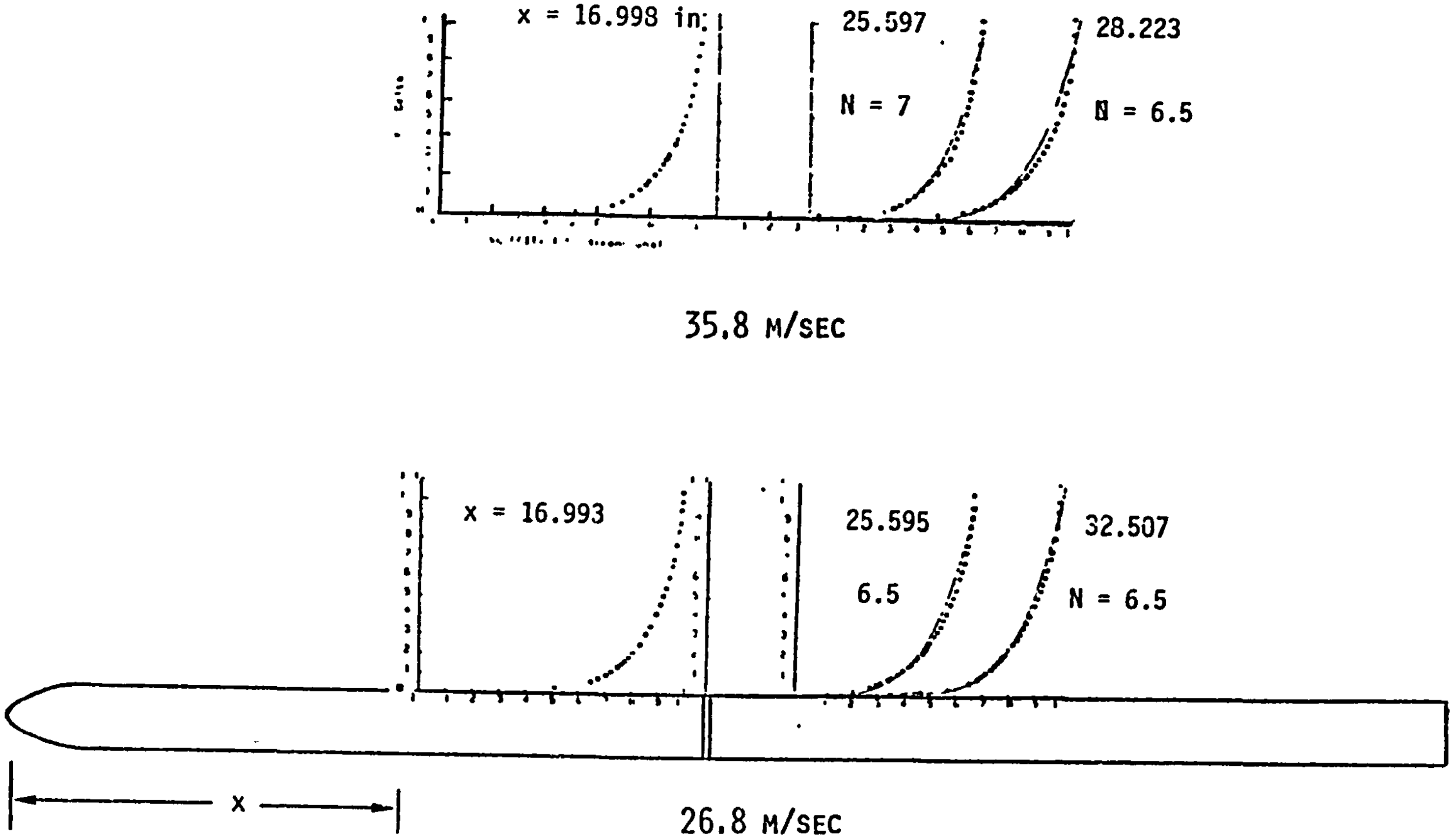


Figure 5. Reference turbulent boundary development.

between .61 inches (1.55 cm) and .703 inches (1.79 cm) at a speed of 88 ft/sec (26.8 m/sec) and between .555 inches (1.41 cm) and .609 inches (1.55 cm) at a speed of 117 ft/sec (35.8 m/sec).

A 10 inch (25.4 cm) diameter two bladed, wooden model airplane propeller with a 6:1 pitch has been used in the preliminary phase of the experiments. The D.C. motor generator was used to control the windmilling speed of the propeller when different loadings were considered. In all cases, the propeller speed was measured using a strobe light.

The free-wheeling or unloaded propeller velocity profiles are shown in Fig. 6. The apparent hysteresis effect in one of the 117 ft/sec (35.8 in/sec) velocity profiles was due to a plotting error and should be ignored. The influence of loading on the velocity profiles is shown in Fig. 7 for a free-stream velocity of 88 ft/sec (26.8 m/sec).

DISCUSSION

The experiments have shown thus far that the velocity profiles behind a windmilling propeller are not necessarily modelled by a simple coupling between a wake and a turbulent boundary layer of the type assumed in the numerical analysis (as sketched in Fig. 1). Obviously, the vortical components of the propeller wake can account for the inflectional properties of the outer velocity profile but the flow field between the helical vortices and the boundary layer suggests other complex flow phenomena are present.

Questions concerning whether a model airplane propeller operating as a windmill produces a generic flow field must be addressed, along with more detailed measurements. Those experiments are continuing at this time.

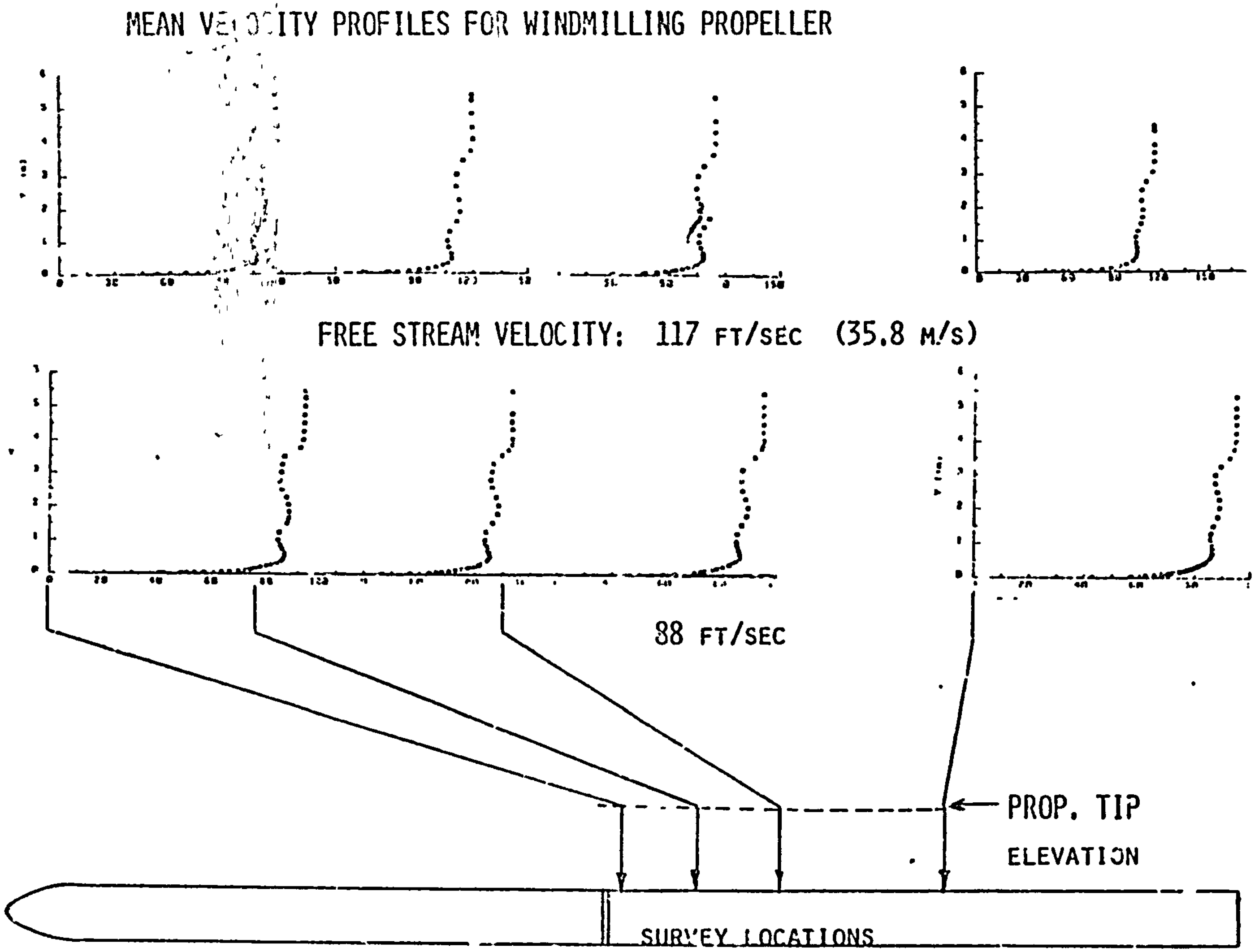


Figure 6. Velocity profiles.

INFLUENCE OF WINDMILL LOADING ON VELOCITY PROFILES AT 88 FT/SEC (26.8 M/S)

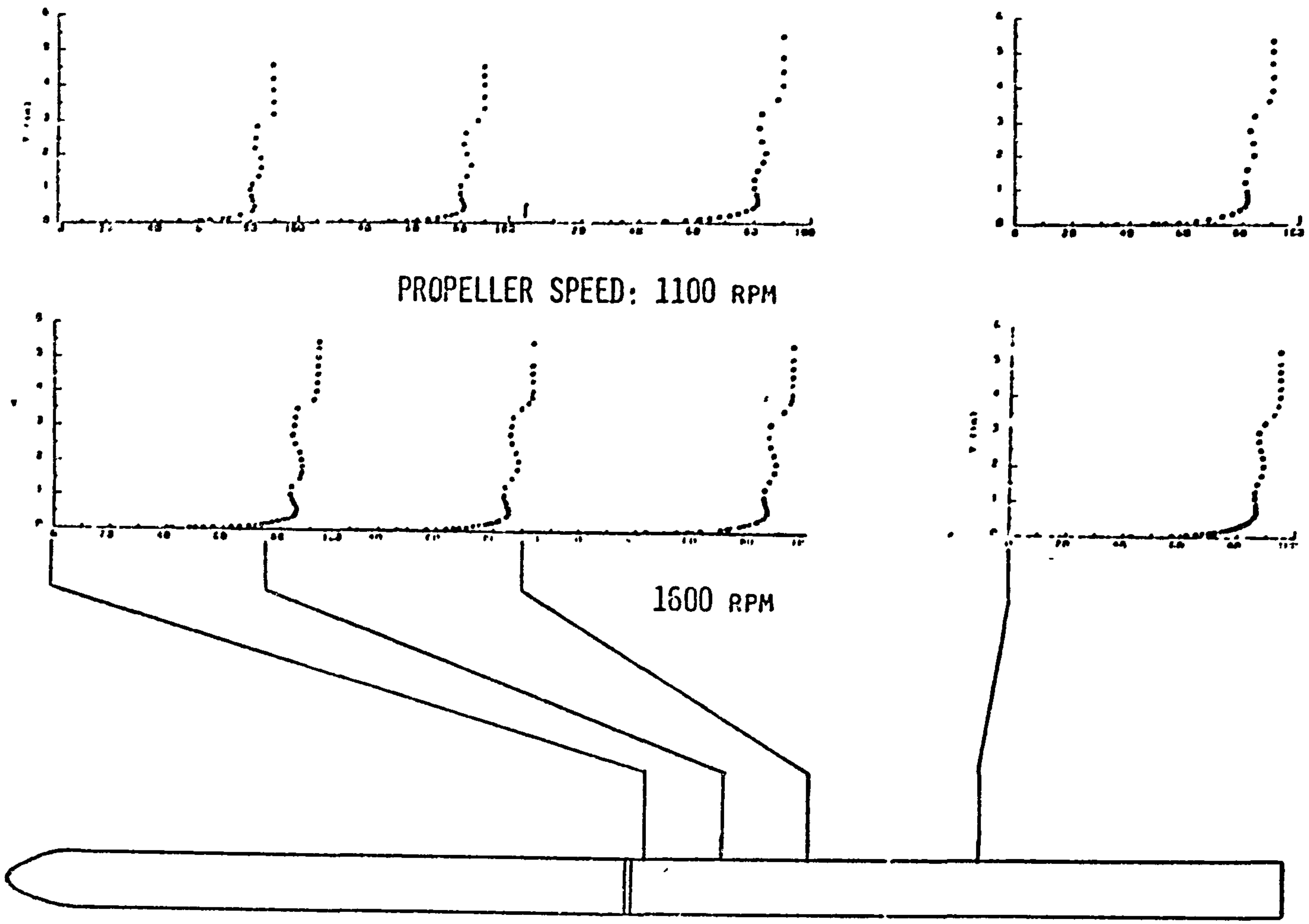


Figure 7. Influence of windmill loading on velocity profiles at 88 ft/sec (26.8 m/s).

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