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Objectives

- Attempt to model yawing and furling behavior required to passively control overshoots in power and loads on a turbine at higher wind speeds.
- Focus on static equilibrium behavior depending on aerodynamic loads on the rotor and the vertical tail in its wake, and on gravity loads which influence furling.
- Examine perturbed dynamic behavior in static equilibrium operation.
- Employ YawDyn code for aerodynamic loads and power calculations.
- Compare predictions with available experimental data.

Simplifying Assumptions

- The key structural components of a small wind turbine are idealized as consisting of rigid bodies with three degrees of freedom.

- These are freedom of rotation about the yaw and furl pivot axes, and about the rotor axis of rotation. Resultant moments about the yaw and furl axes are zero in static equilibrium operation.

- Key aerodynamic loads include rotor thrust, side force and lateral or up force plus the normal force acting on the vertical tail. In addition, rotor torque and yaw and pitch couples due to the shift of the center of thrust away from the center of the rotor disk are accounted for.

- Wake flow about the vertical tail is dictated by axial induction effects on flow through the rotor disk.

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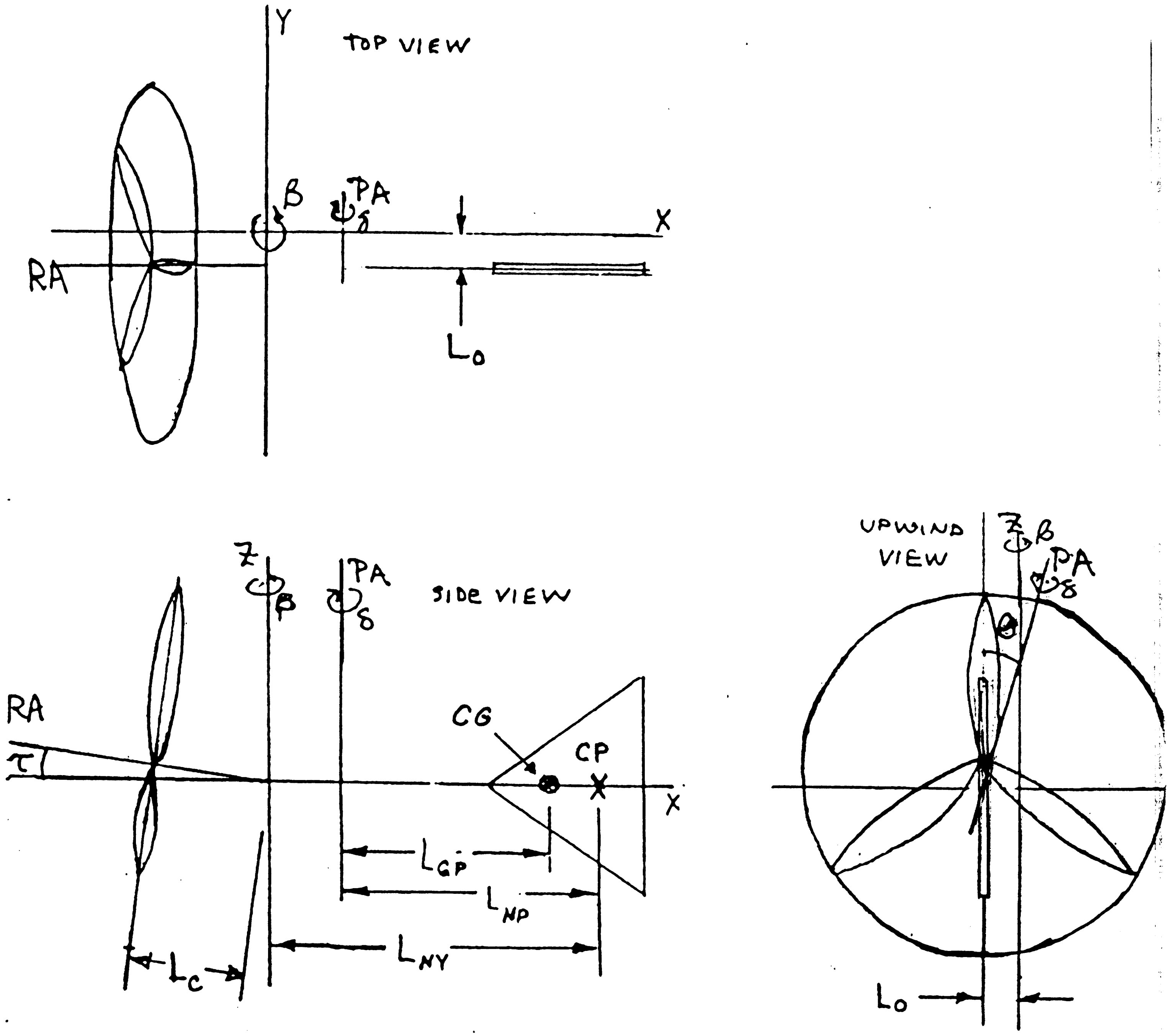
Wind Turbine in Unyawed and Unfurled Configuration



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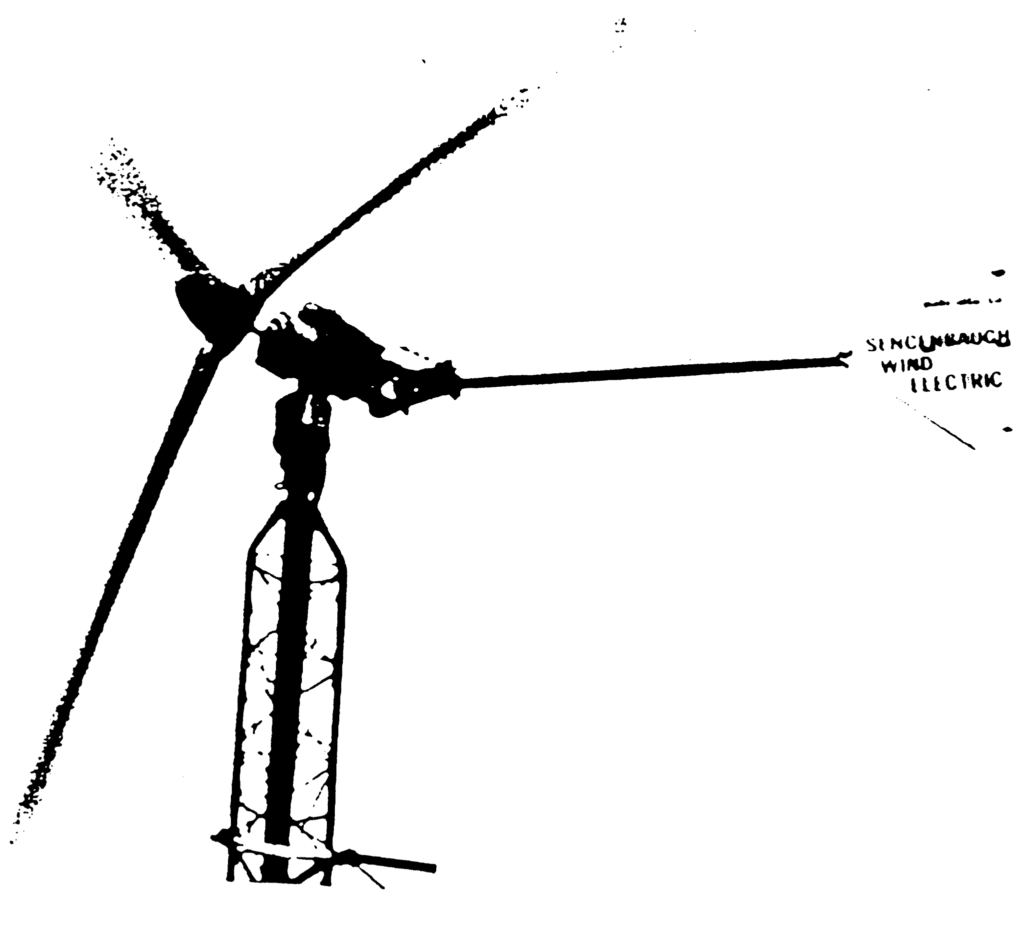
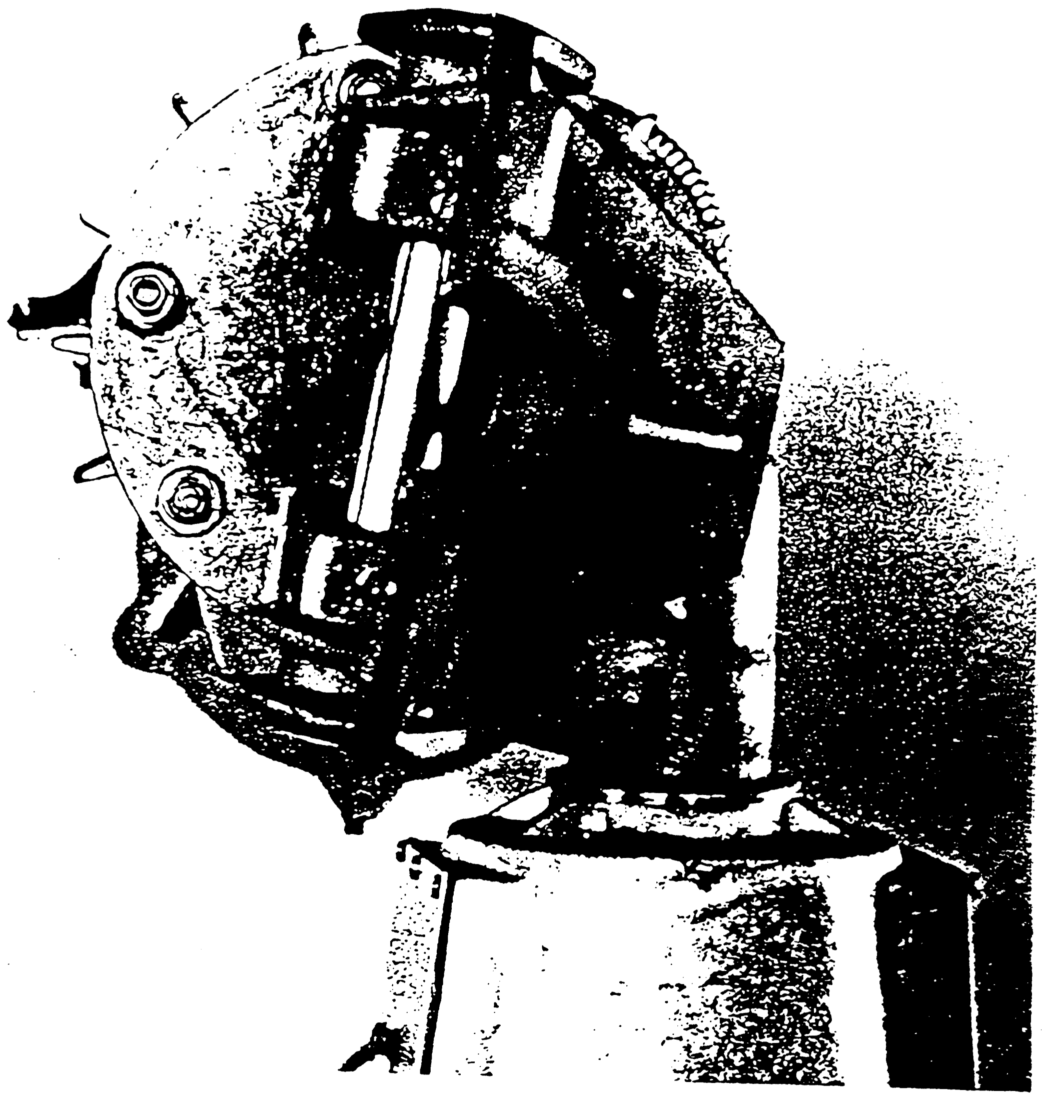
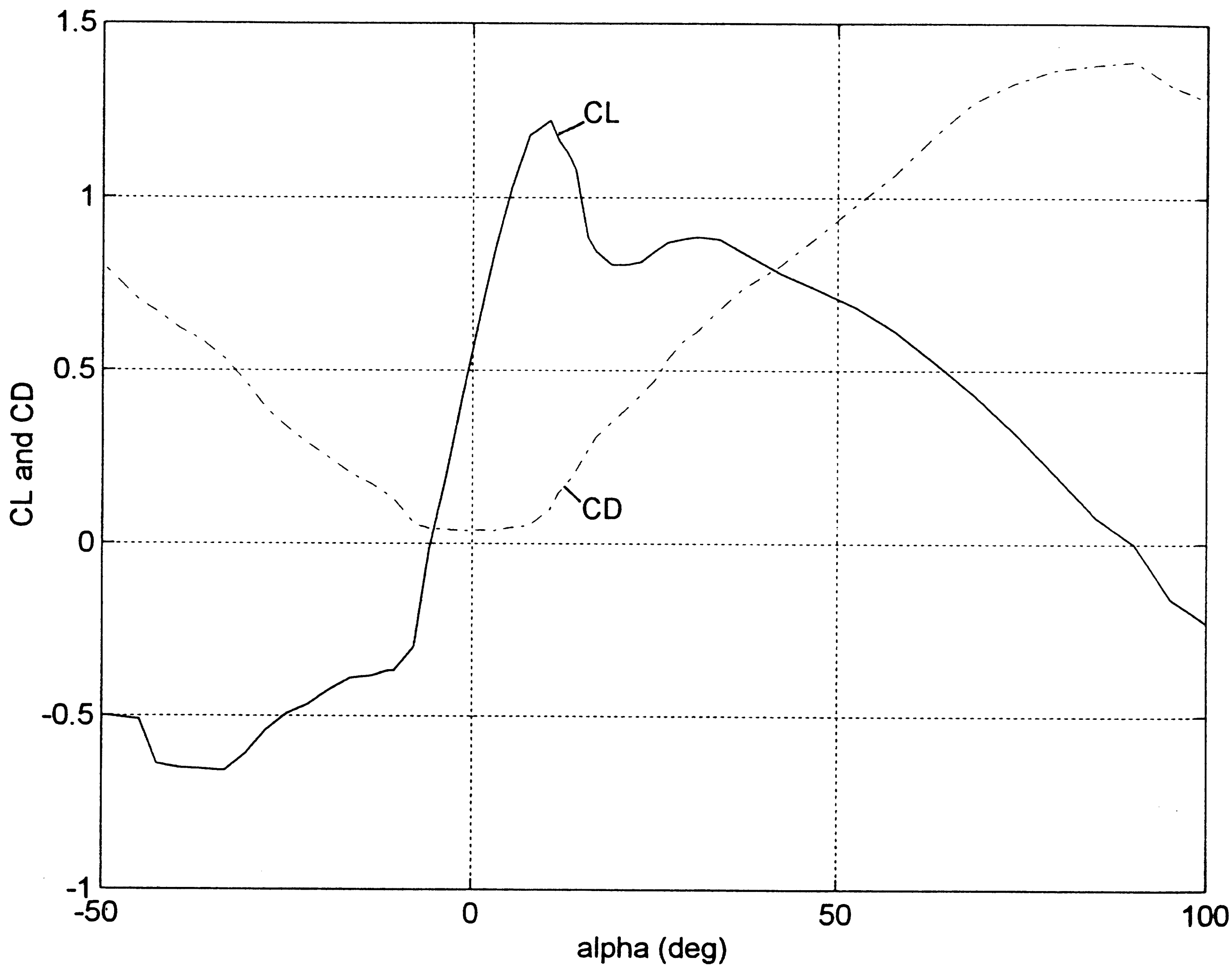
S-1000 Operating at Higher Wind Speed



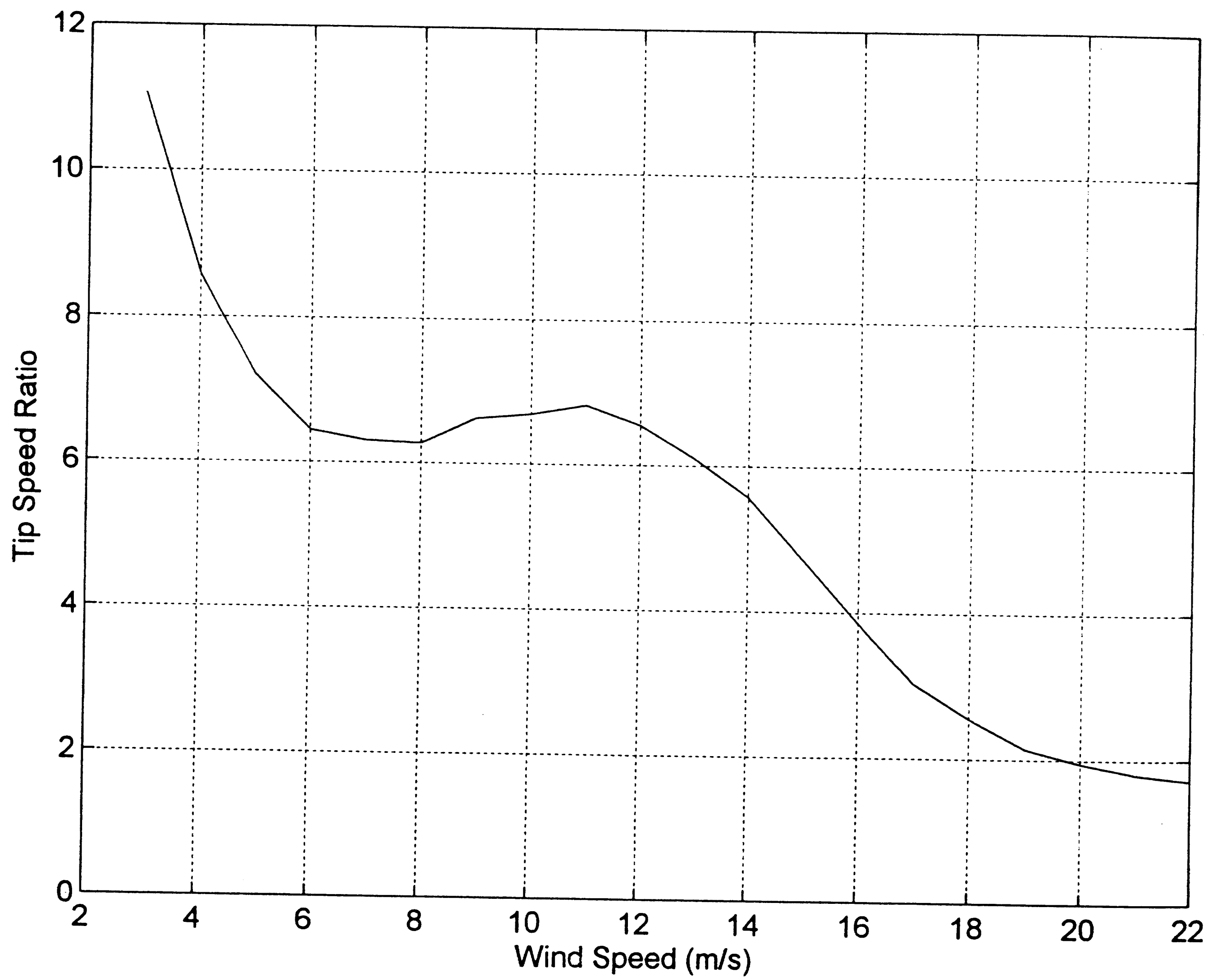
Rear View of S-1000 Tilted Furl Axis and Vertical Yaw Axis



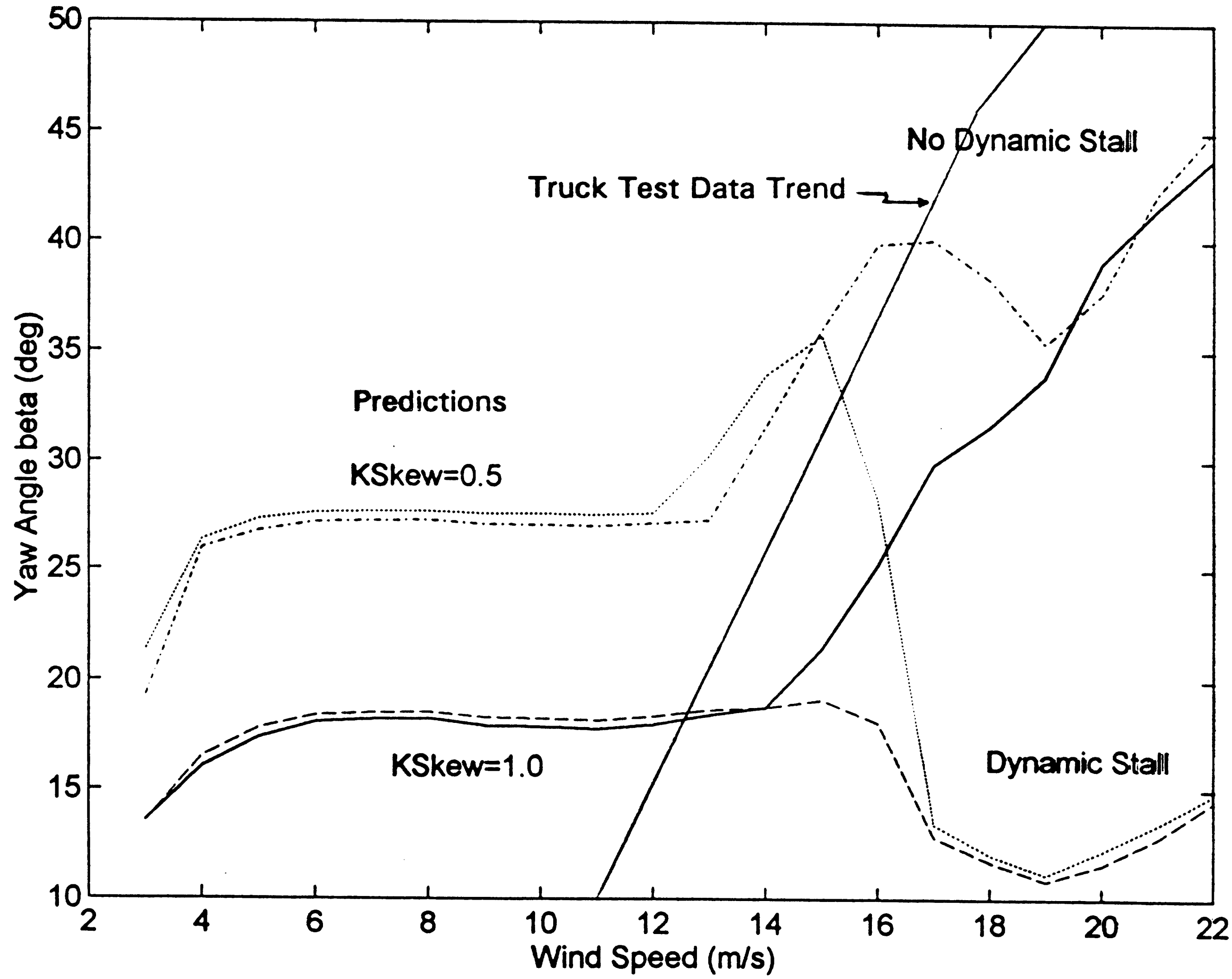
Estimated Lift and Drag Coefficients for S-1000 Blade Section



Variation of Wind Speed with Tip Speed Ratio According to S-1000 "Data"



Equilibrium Yaw for “Measured” Tail Area and Weight of S-1000



$$a = a_0\left[1+\frac{15\pi}{32}K\left(\frac{r}{R}\right)\sin\psi\tan\frac{\gamma}{2}\right]$$

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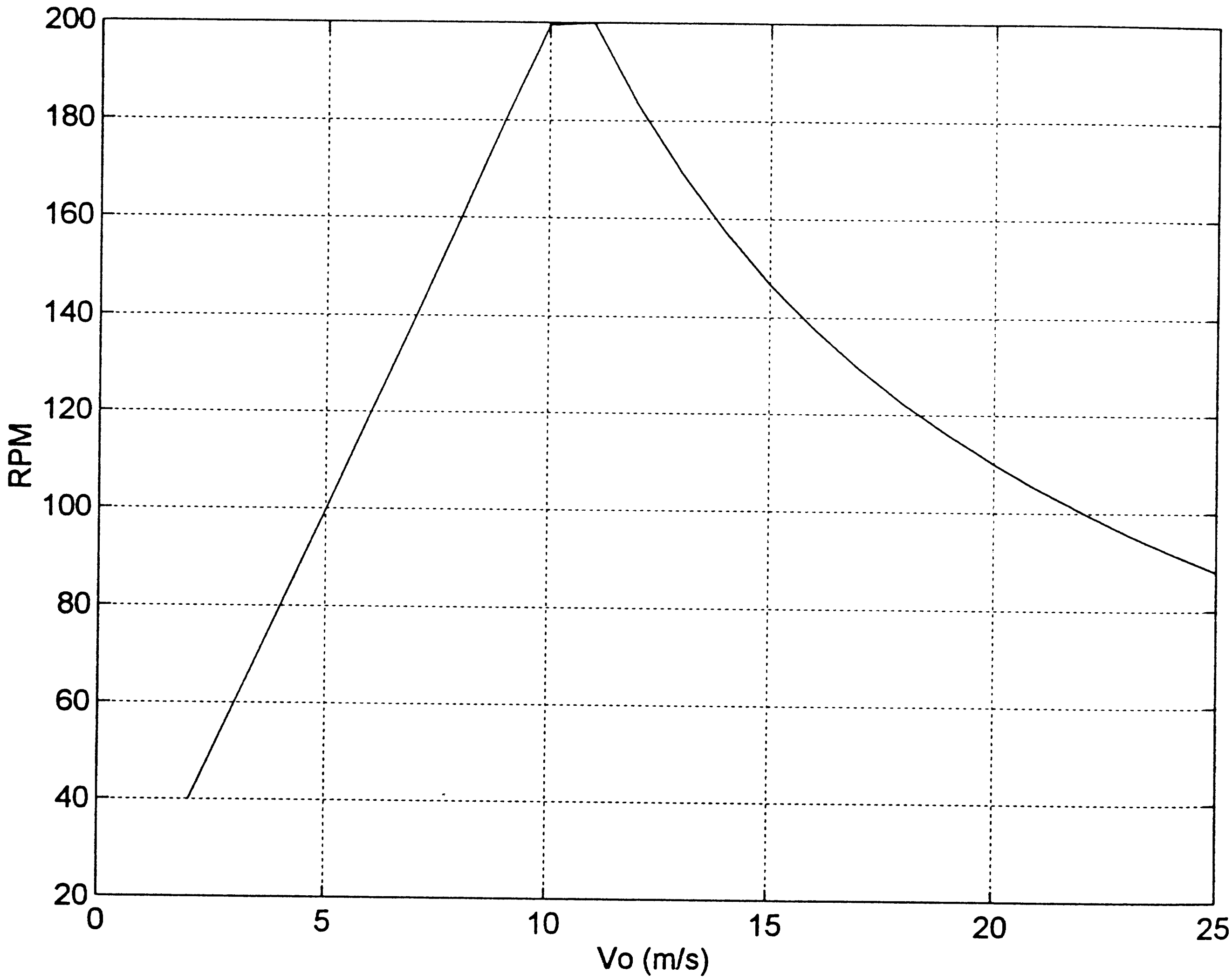
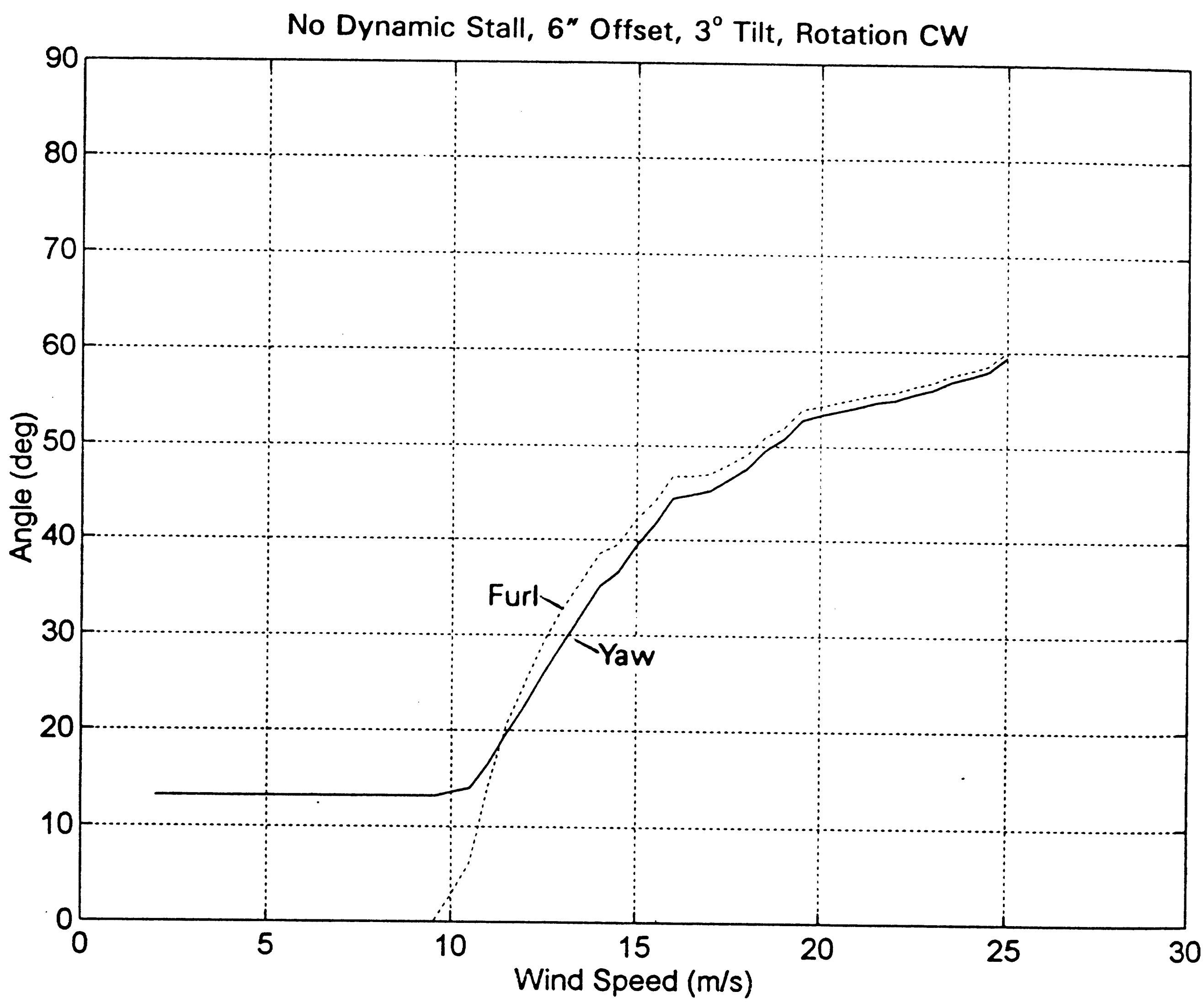
Variation of Rotor RPM with Mean Wind Speed Used in S-8000 Analysis



Predicted Equilibrium Behavior of S-8000



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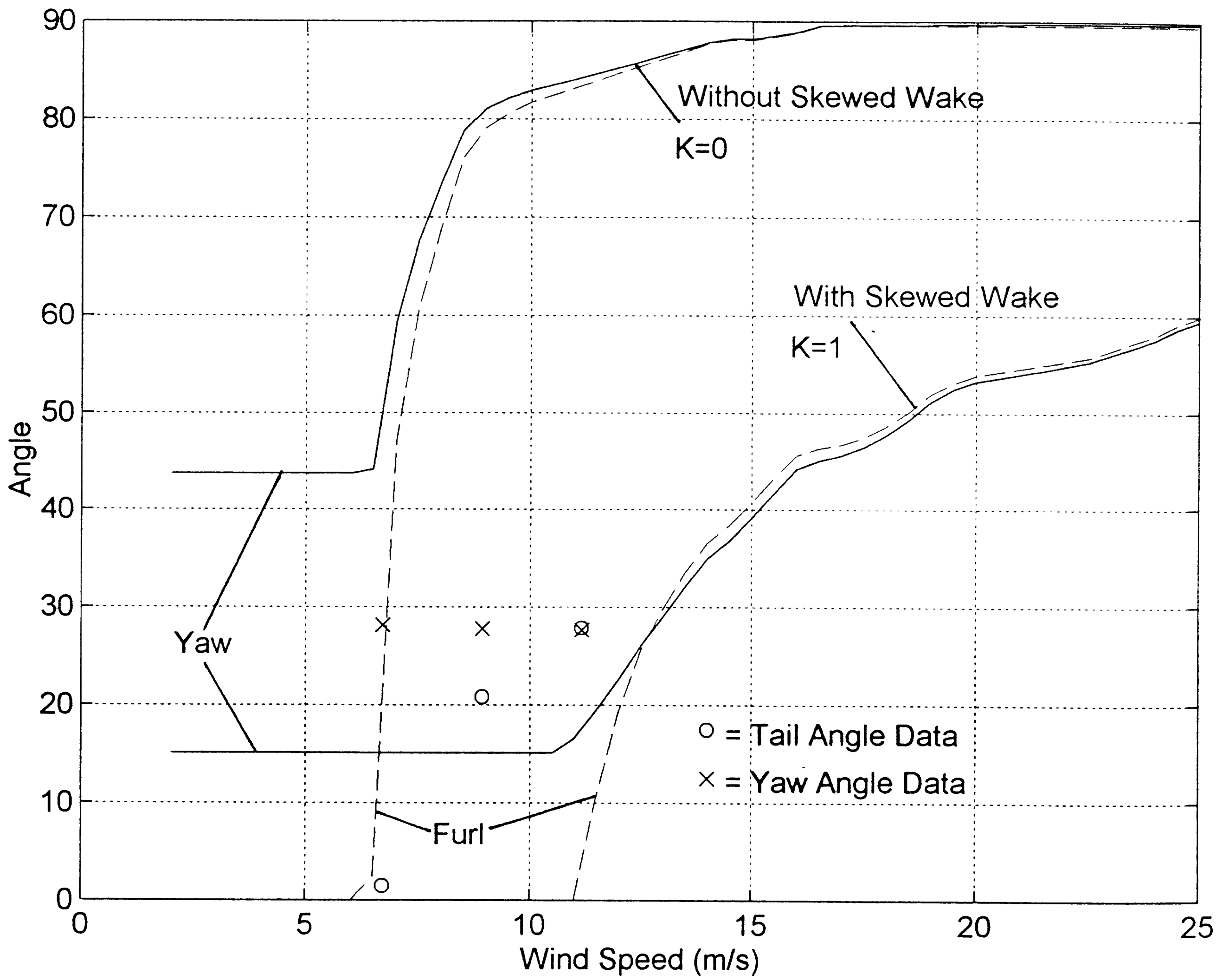
Comparison of S-8000 Truck Test Data with Predictions

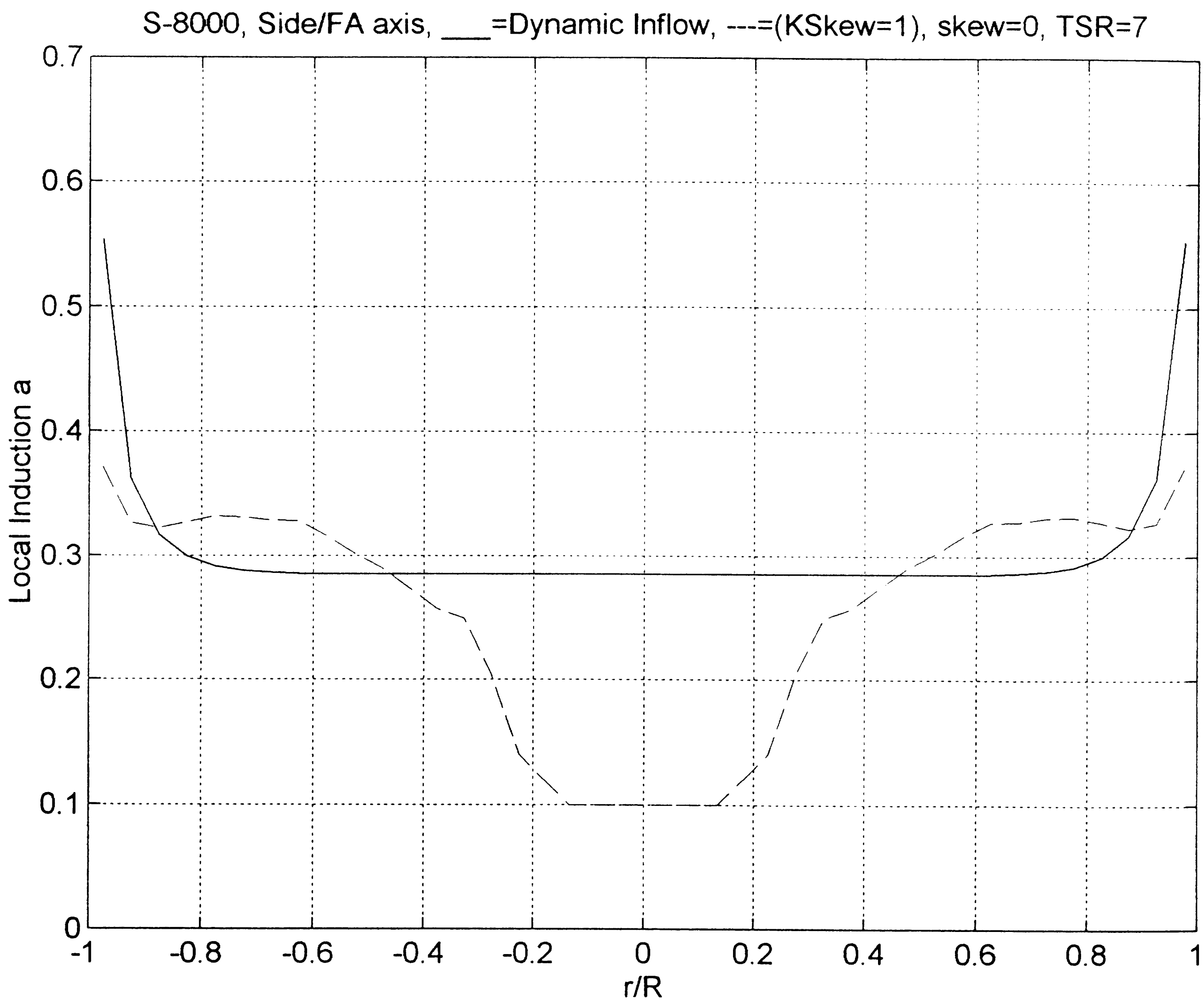


S-8000 Truck Test Results Compared to YawDyn Predictions. Lateral Tilt = 3.5°

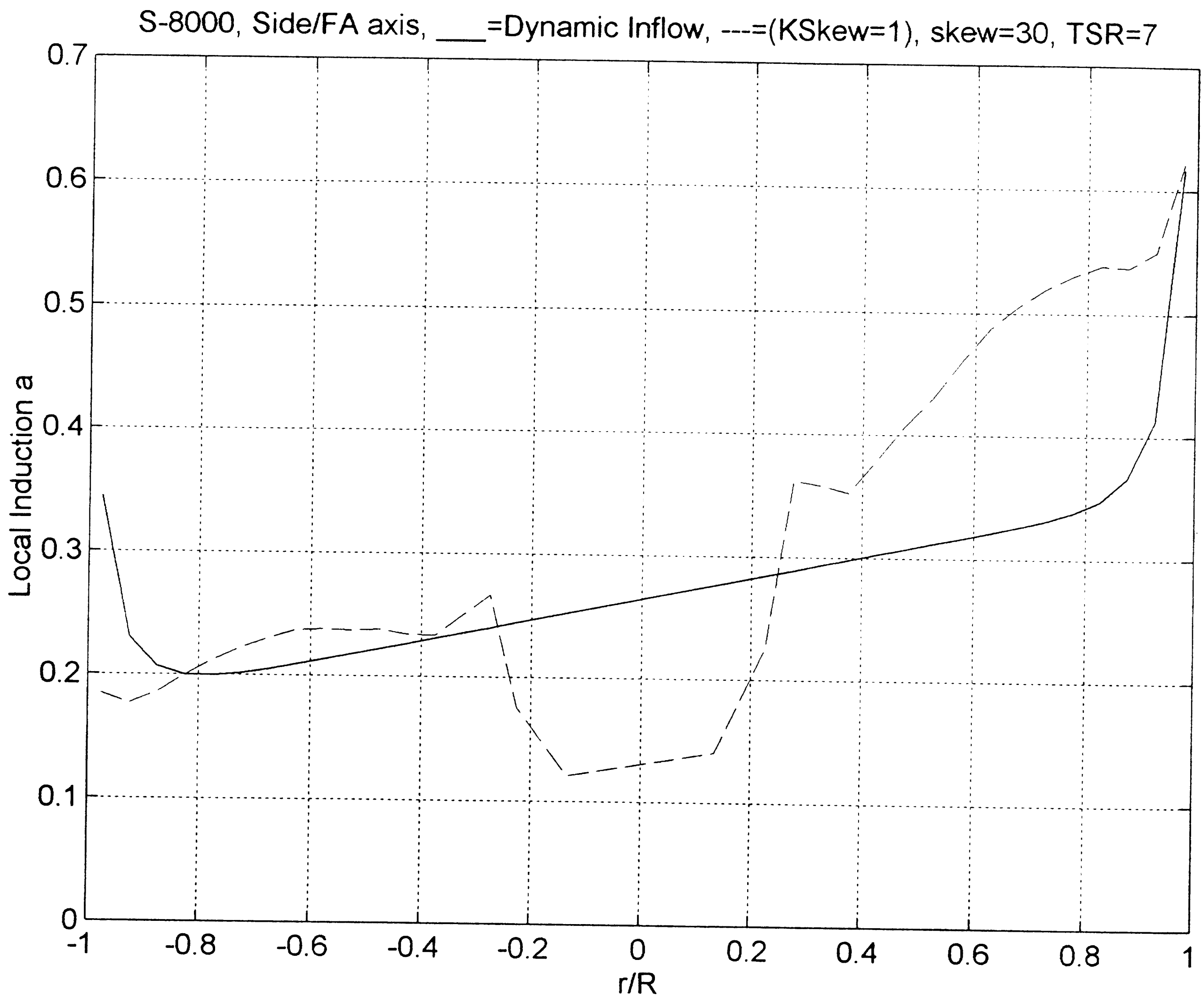
		Thrust (lb)			Center of Thrust* (m)		
Lo(m)	V_o(mph)	Truck Tests	Dyn. Inflow	Skewed Wake	Truck Tests	Dyn. Inflow	Skewed Wake
0.15	15	150	167	151	0.02	0.11	0.29
	20	300	288	263	0.09	0.10	0.25
	25	525	456	416	0.11	0.11	0.26

*Shift from center of rotor disk towards intersection with yaw axis.

Comparison of Dynamic Inflow and Skewed Wak
Model Predictions (Skew = 0°)



Comparison of Dynamic Inflow and Skewed Wake Model Predictions (Skew = 30°)



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Conclusions

- Reliable modeling of yawing and furling behavior of small wind turbines is in doubt because of uncertainties in the predictions of aerodynamic loads on the rotor and the vertical tail in its wake.
- The dominant factor in these uncertainties is skewed wake effects on flow through the rotor.
- These effects should include those due to vorticity shed into the wake from inboard locations on the rotor.
- There is a burning need for more reliable data on rotor loads and wake flow about the downwind tail.
- The planned tests of a small wind turbine in the NASA Ames 80 x 120 foot wind tunnel will hopefully provide such data.

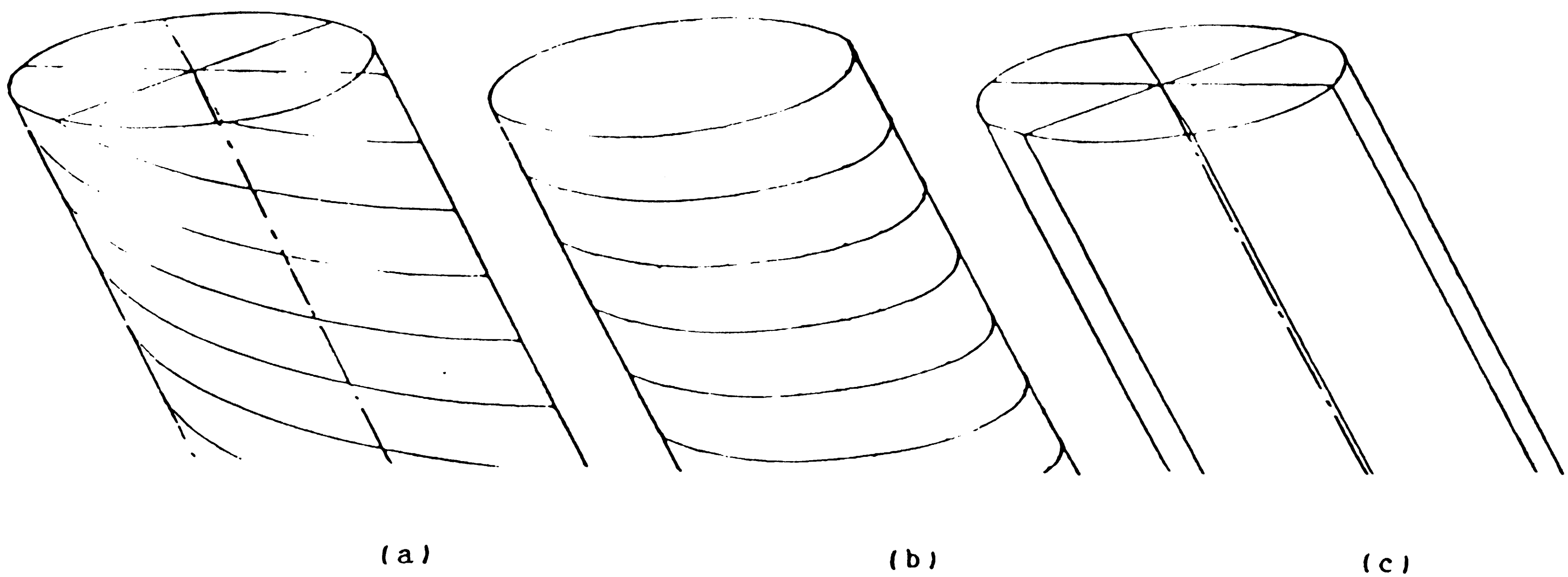

Figure 1. Representation of Skewed Helical Vortex Wake by Circular and Linear Vortex Wakes

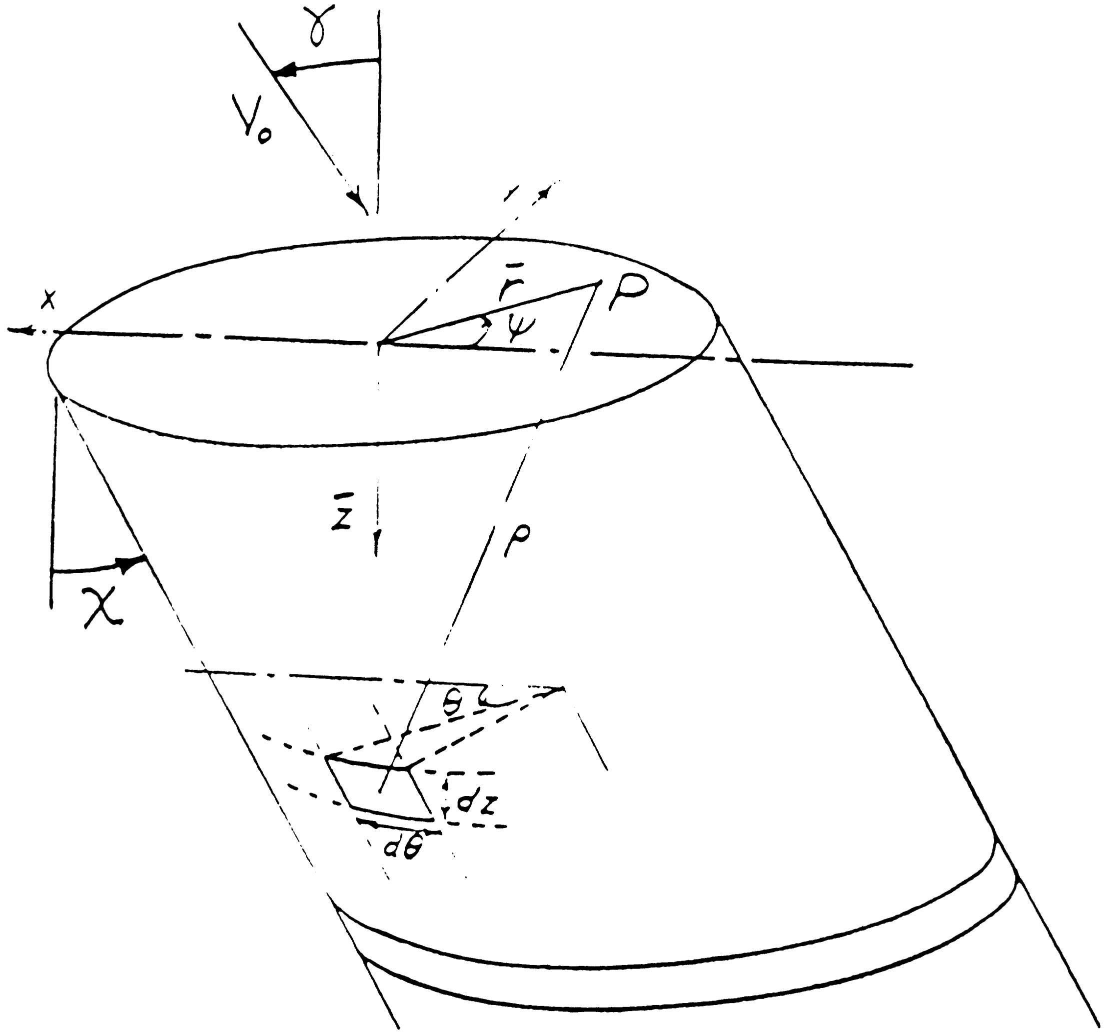

Figure 2. Coordinate System for Obtaining Induced Velocities at Rotor Disk

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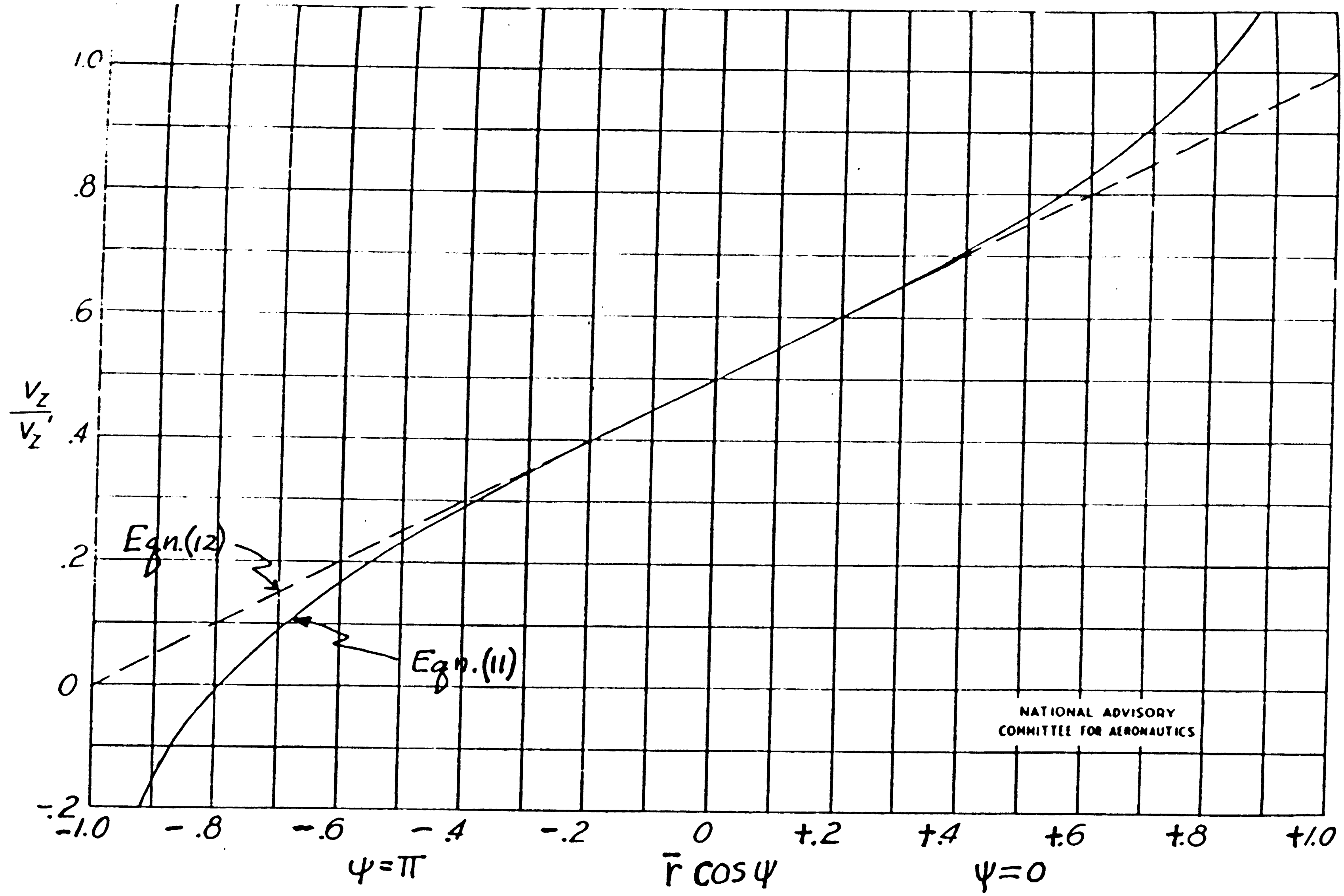
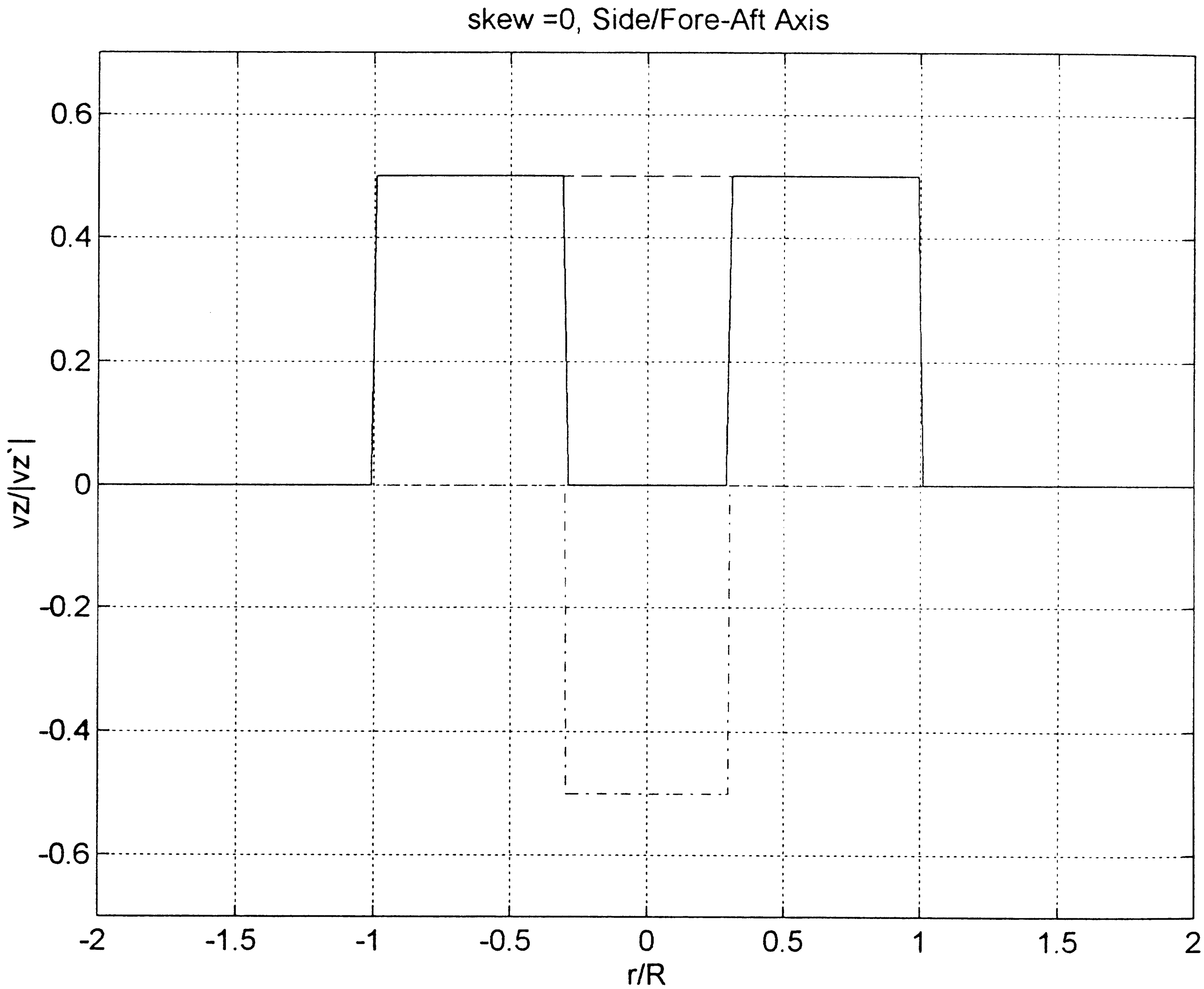
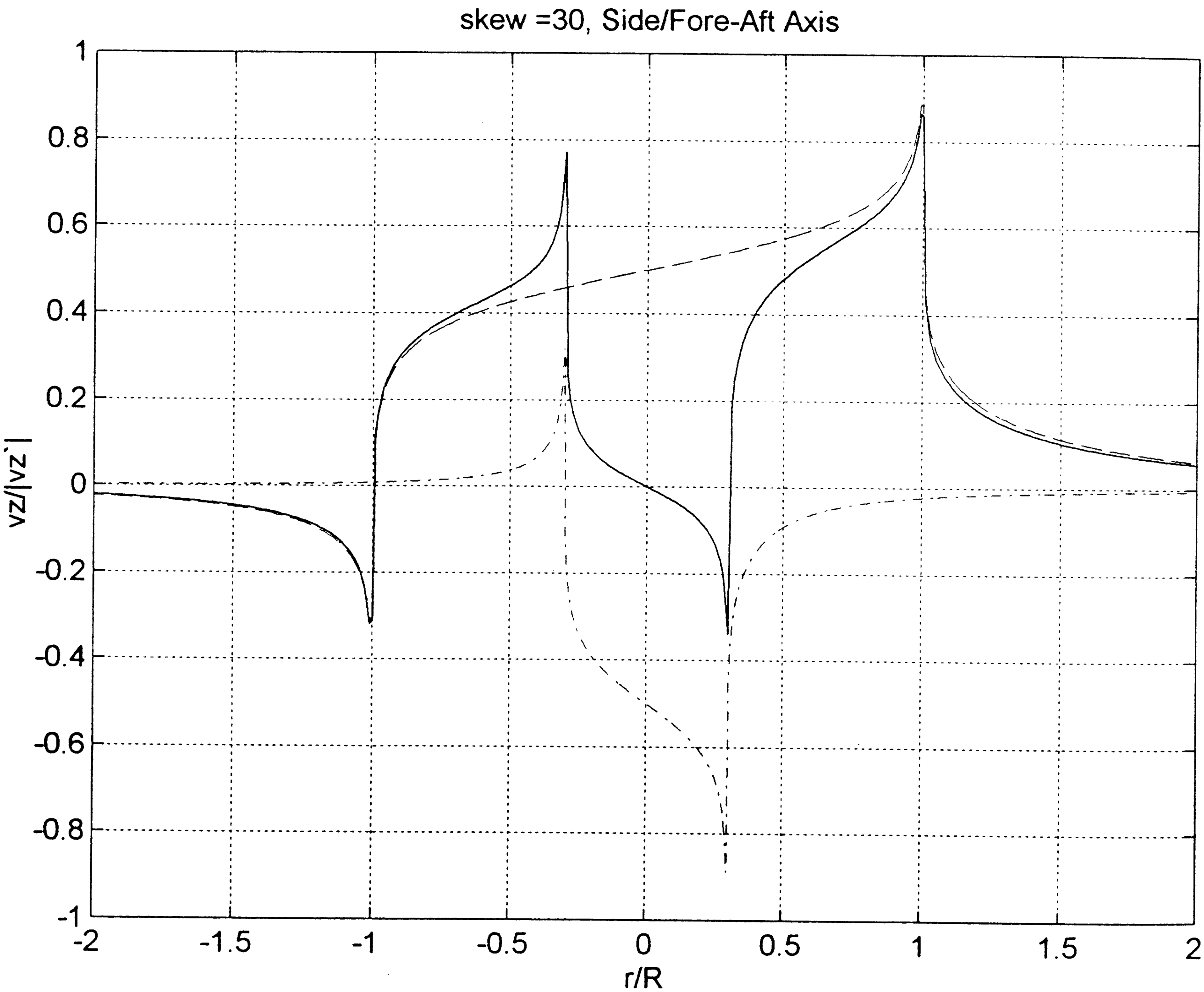


Figure 3. Vertical Induced-Velocity Distribution Along the Fore-and-Aft Diameter of Rotor Disk for $x = \pi/2$.

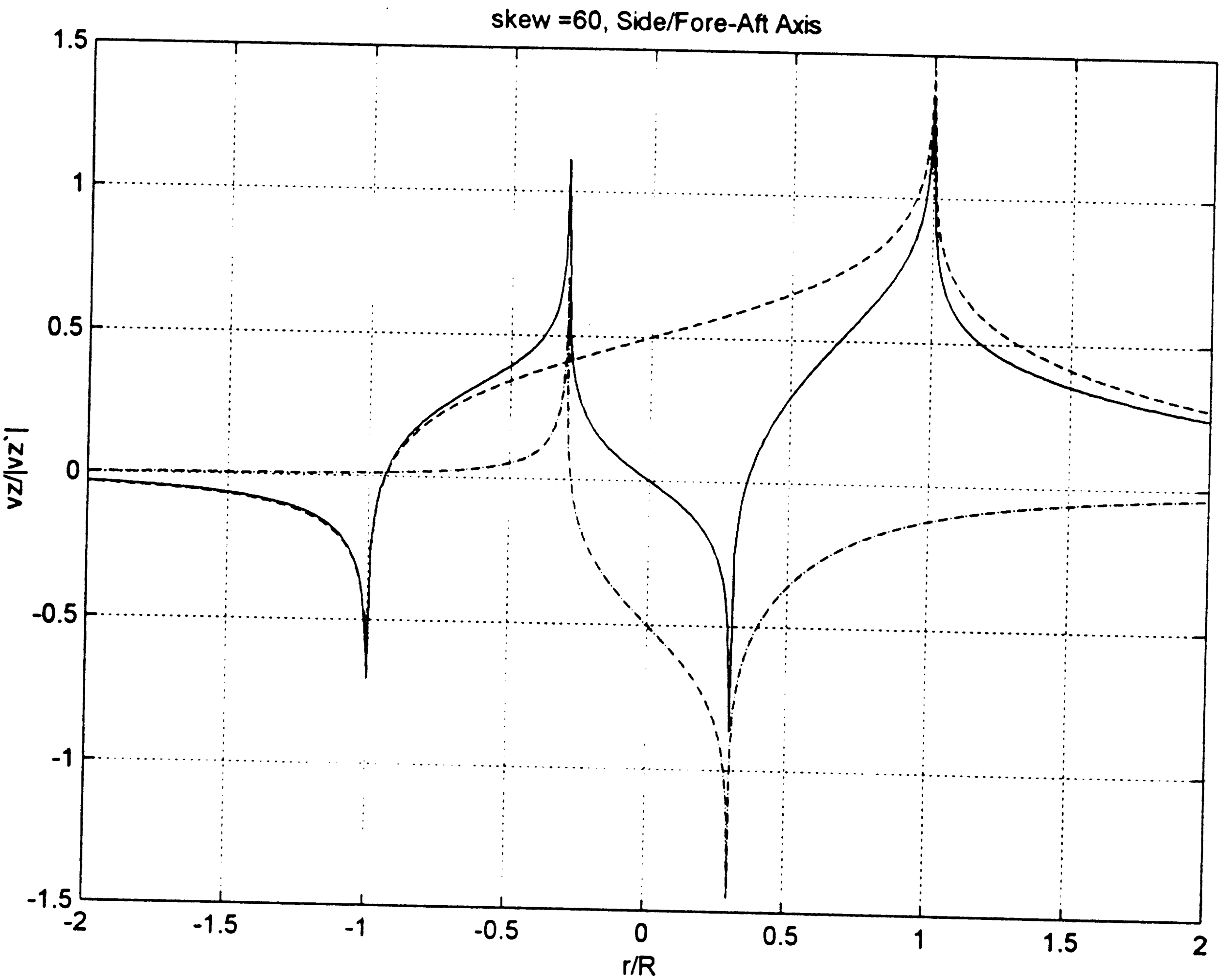
Generalized Coleman Model Predictions (Skew = 0°)



Generalized Coleman Model Predictions (Skew = 30°)



Generalized Coleman Model Predictions (Skew = 60°)



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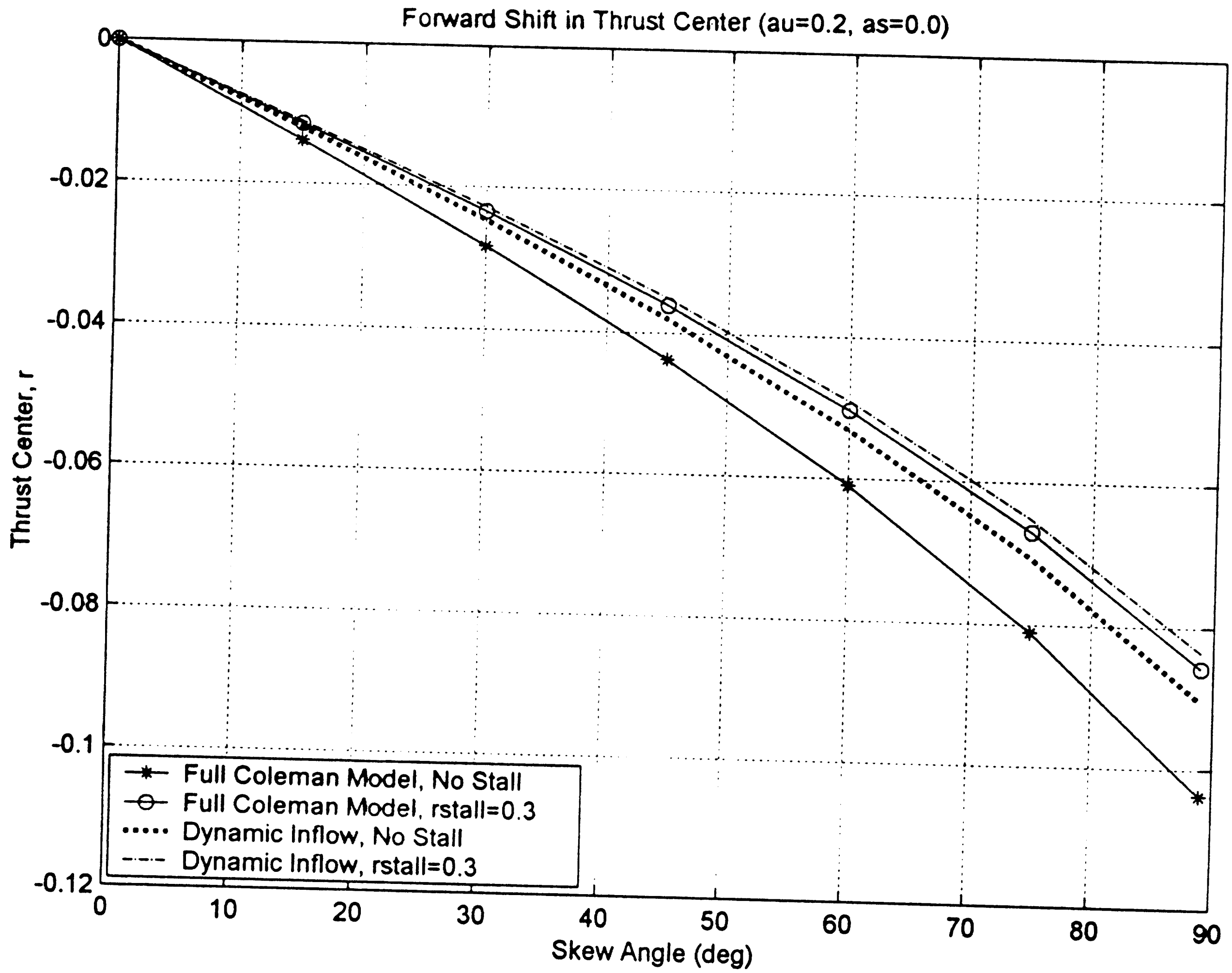
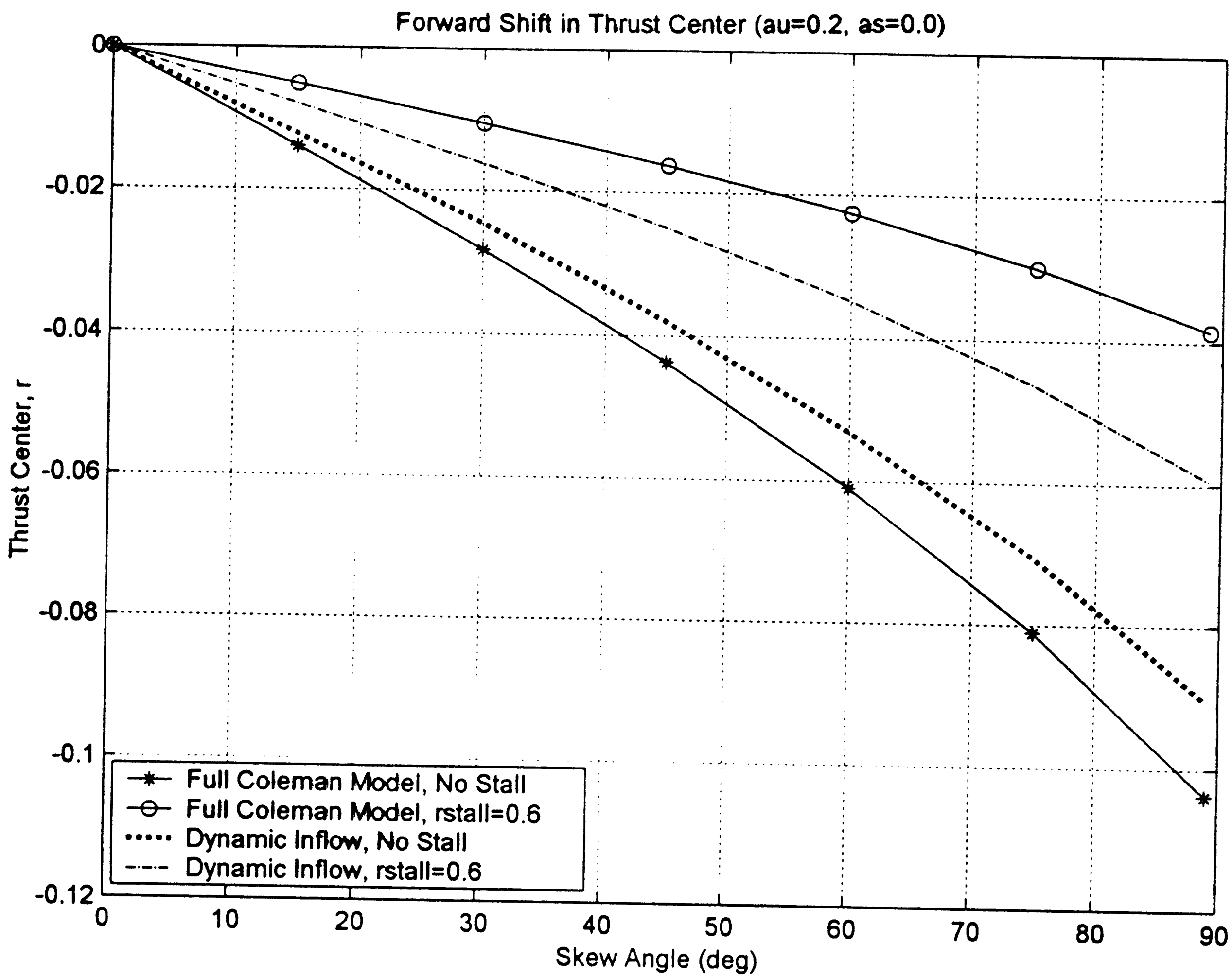
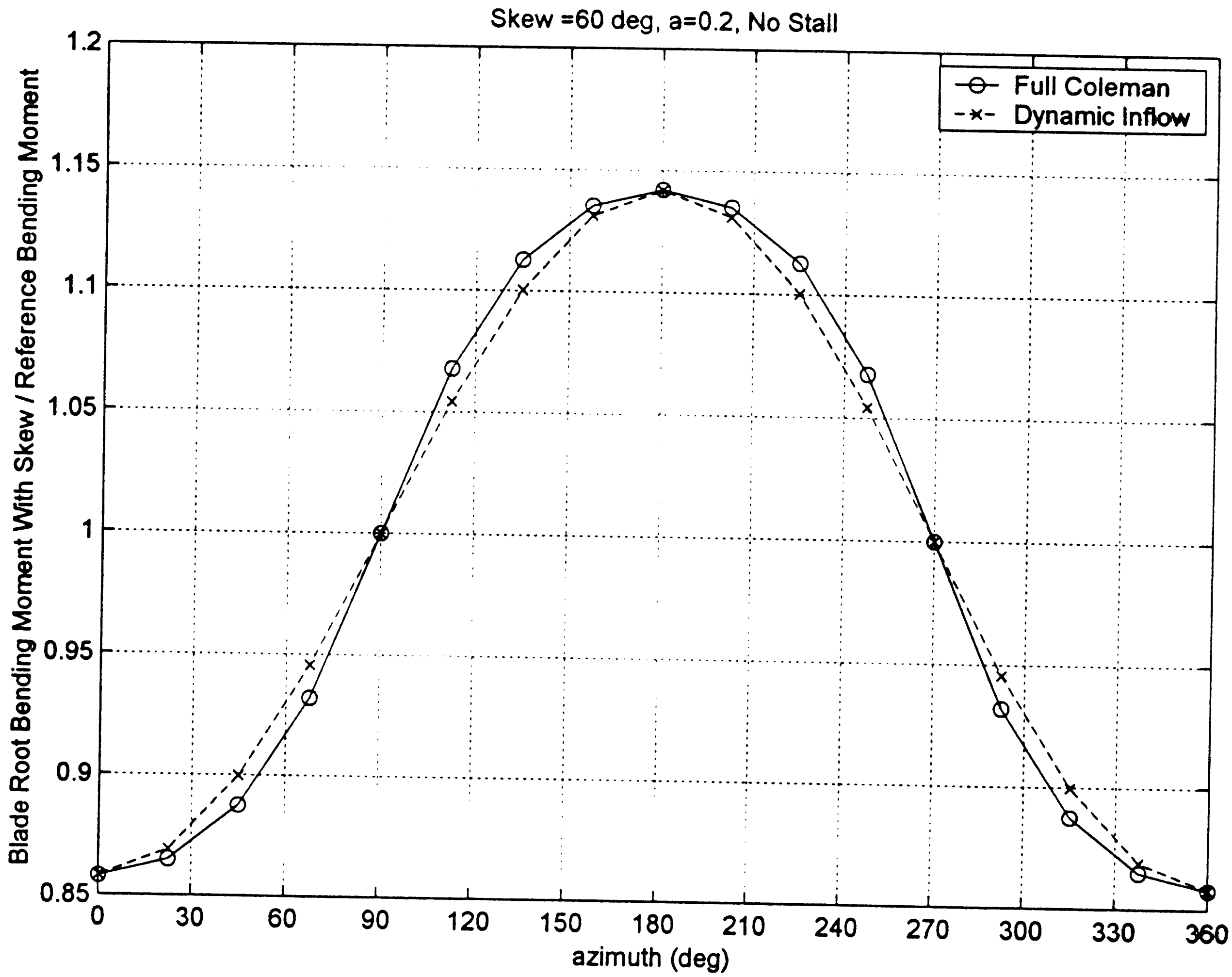
Center of Thrust
($Stall/r_s = 0.3$)



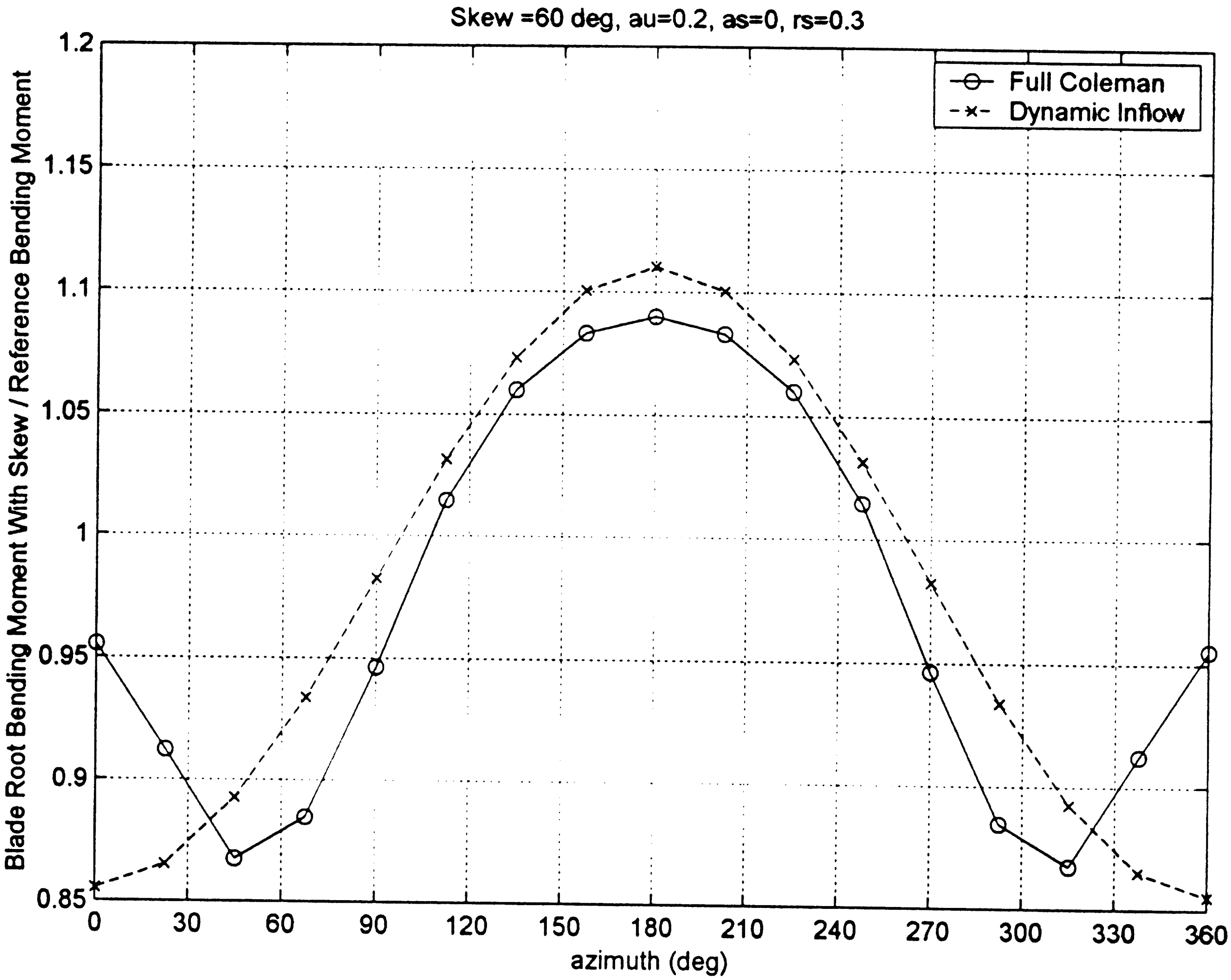
Center of Thrust
(Stall/r_s = 0.6)



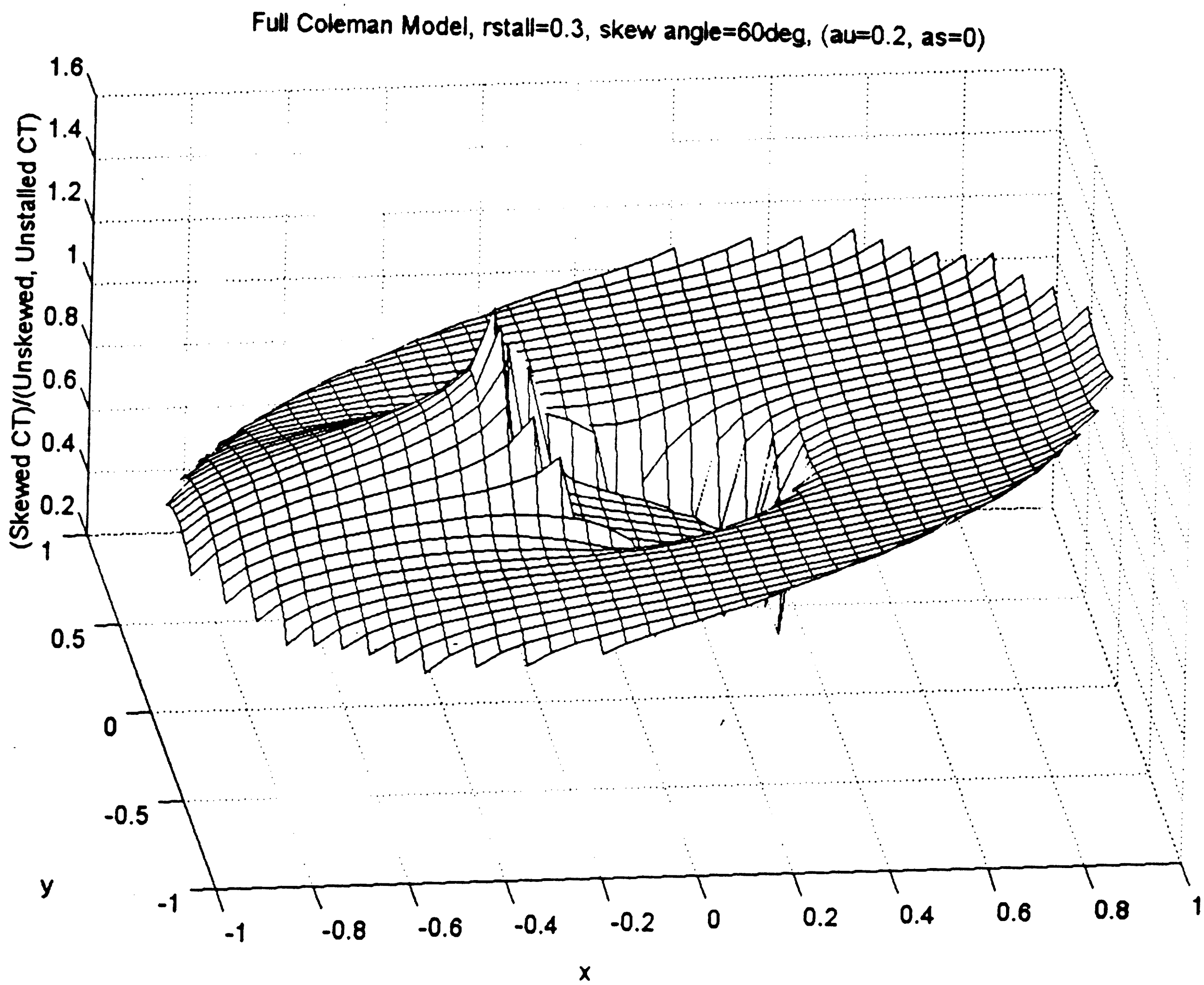
Blade Root Bending Moments
(No Stall)



Blade Root Bending Moments
(Stall/r_s = 0.3)



Local Thrust Coefficients
(Stall/r_s = 0.3)



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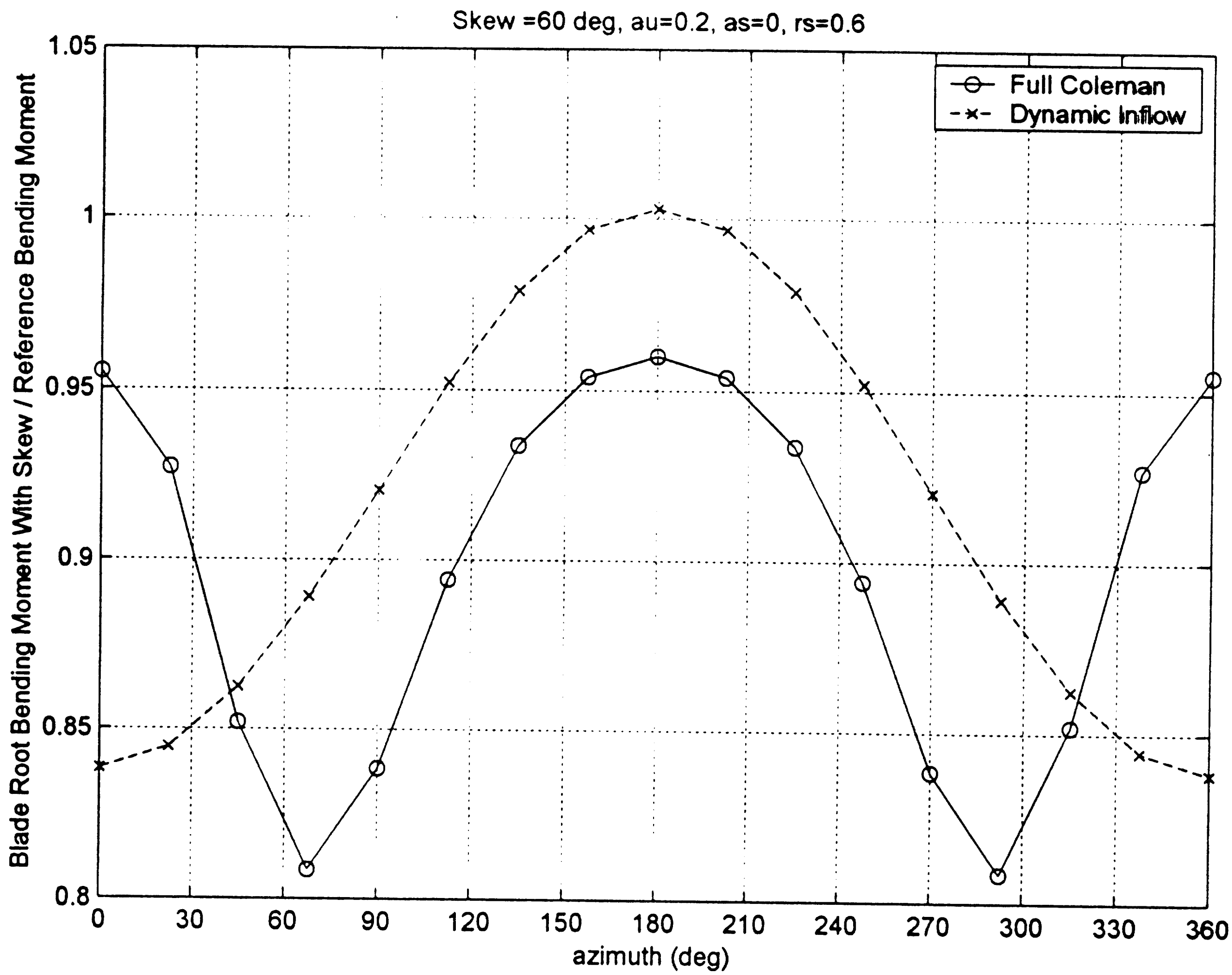
Blade Root Bending Moments
(Stall/r_s = 0.6)



Perturbed Coleman Model
Conservation of Mass Effect