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AERODYNAMIC INTERFERENCE BETWEEN TWO DARRIEUS WIND TURBINES

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Aerodynamic Interference Between Two Darrieus Wind Turbines

P. R. Schatzle, P. C. Klimas, and H. R. Spahr

Abstract

The effect of aerodynamic interference on the performance of two curved bladed Darrieus-type vertical axis wind turbines has been calculated using a vortex/lifting line aerodynamic model. The turbines have a tower-to-tower separation distance of 1.5 turbine diameters, with the line of turbine centers varying with respect to the ambient wind direction. The effects of freestream turbulence were neglected. For the cases examined, the calculations showed that the downwind turbine power decrement (1) was significant only when the line of turbine centers was coincident with the ambient wind direction, (2) increased with increasing tipspeed ratio, and (3) is due more to induced flow angularities downstream than to speed deficits near the downstream turbine.

Nomenclature

A_f	projected frontal area of turbine, m^2
c	blade chord, m
C_L	blade lift coefficient $(L/\frac{1}{2}\rho_\infty V_\infty^2 c)$
C_P	power coefficient $(Q\omega/\frac{1}{2}\rho_\infty V_\infty^3 A_f)$
D	equatorial diameter of turbine, m
F_c	chordwise blade force coefficient $(\text{force}/\frac{1}{2}\rho_\infty V_\infty^2 \ell_e c)$
H	turbine height, m
ℓ_e	blade element length, m
L	blade lift, N/m
N	number of blades
P	turbine power output $(Q\omega)$, kW
Q	turbine shaft torque, N/m
R	equatorial radius of turbine, m
Re_c	Reynolds number based on chord $(\rho_\infty V_R c/\mu_\infty)$
u	streamwise induced flow, m/sec
V	velocity, m/sec
X	tipspeed ratio $(R\omega/V_\infty)$
α	local blade angle of attack, deg
Γ	dimensionless airfoil circulation $(\frac{1}{2}C_L C_R c/V_\infty R)$
ω	angular velocity, rad/sec

Subscripts

R	relative to local
∞	freestream conditions

Introduction

Since its inception, the DOE Wind Energy Program has been largely concerned with the problems associated with individual wind turbines and systems. As the single turbine state-of-the-art has progressed, increasing attention is being given to the operation of turbines in multiple machine arrays. This attention is required because of the impact of turbine spacing on interconnect and land usage costs. Small separation distances work toward minimizing these as long as array members are not so close as to negatively interfere with each other aerodynamically. Sandia National Laboratories, with its Darrieus Wind Turbine Program, is interested in the problem of optimizing these separation distances.

Darrieus turbine aerodynamics is different from and somewhat more complicated than that of most horizontal axis wind turbines. Blades normally operate in both the linear and deep stall portions of the C_L vs α curve. Although the wake may be periodic, it is unsteady and unsymmetrical. The flowfield downstream of an advancing blade differs from that downstream of a retreating blade and the blades do not operate independently of each other. There is always some degree of mutual interaction as blades cut wakes generated by those preceding. A mathematical representation which treats all of these effects is the vortex/lifting line model developed by Strickland, Webster, and Nguyen.[1] In particular, it calculates a highly detailed wake. This wake is felt to be representative of actual turbine wakes within a few downwind diameters, i.e., before the non-included dissipative effects of atmospheric turbulence are no longer negligible. The model is viable and may be modified to simultaneously treat more than one turbine. As long as separation distances are small, the aerodynamic calculations may be considered realistic.

This report describes a study of aerodynamic interference between two Darrieus turbines using a vortex/lifting line model without the effects of freestream turbulence.

Aerodynamic Model

Strickland, Webster, and Nguyen[1] have developed a three-dimensional model for use in predicting performance and detailed blade loads on a single Darrieus turbine, in which the blades and their wakes are replaced by an equivalent system of bound and free vortices. As the names imply, the bound vortices remain attached to the blades and rotate with them while the free vortices are shed from the blades into the ambient flow. The strength of the bound vortex (circulation) at any point on the blade is determined from the local blade lift using the Kutta-Joukowsky law, while the strengths of the free vortices are given in terms of the spatial and temporal variation of the circulation by Helmholtz's and Kelvin's theorems. Once the strengths of the vortex filaments are known, the Biot-Savart law may be used to determine the velocity induced by the entire vortex system on any point. The total velocity seen by points on the blades is therefore the vector sum of the ambient, rotational, and induced velocities, while the free wake filaments experience only the ambient and induced velocities. Having obtained the velocity components on a given blade segment, the local angle of attack is computed and used to determine the aerodynamic forces acting on the segment by interpolation in the lift and drag tables for the particular airfoil section used. Finally, the velocities of the wake filaments are integrated with respect to time to yield a developing wake geometry.

An interesting feature of this model is the fact that a detailed account of the rate at which energy is extracted from the wind is communicated downstream via the free vortex system. As more energy is removed from the wind, the amount of work done on the turbine increases, which means that the integral of the chordwise blade forces along the path of rotation increases. This implies an increase in the blade lift since it is the dominant component of the chordwise force. Accordingly, there is an increase in circulation on the blades and a corresponding increase in the strength of the shed vortices, resulting in higher induced velocities. A change in power output thus manifests itself in higher induced velocities downstream.

The presence of the free vortex system downwind of the turbine thus makes this model an attractive candidate for use in studying the aerodynamic interference on turbines in proximity. The VDART3 computer code developed by Strickland, et al, has been modified by the present authors in order to predict performance of an arbitrary number of Darrieus turbines. The turbines are required to be geometrically identical and to operate in phase but may be located wherever desired. A further refinement has been to interpolate on Reynolds number as well as angle of attack when computing blade element forces from the tabulated airfoil section data. In addition, an extensive graphics capability has been added in order to speed interpretation of results. This is described in more detail in the section Computer Codes Used. The ability of the modified code (VDARTC) to accurately predict performance of a single turbine is demonstrated in Fig. 1 while the predicted wake geometry for the same turbine is given in Fig. 2.

Computer Codes Used

The mathematical model of clustered three-dimensional vertical axis wind turbines, discussed in the previous section, was implemented in computer code VDARTC. VDARTC, while based on the VDART3 computer code[2], has been modified extensively by:

1. Permitting the definition of the locations of the clustered turbines and computing the locations of each blade element for each turbine.

2. Properly allocating the array elements for computed variables to the appropriate blade elements for each wind turbine.

3. Adding a two-dimensional interpolation subroutine to include the effects of local blade element Reynolds number and the angle of attack on aerodynamic coefficients.

The program is now operational on the Sandia CDC Cyber 76 and 7600 computers using 111,216 (octal) words of small core memory and 155,030 (octal) words of large core memory in a batch mode.

The mathematical model of clustered wind turbines was also implemented in computer code WINMIL, an interactive graphics computer code being developed at Sandia to analyze two- and three-dimensional vertical axis wind turbines and giromills. The interactive feature, with human engineering, allows one to rapidly and easily make runs and the graphics output, described later, helps provide insight into the wake structure from the turbines and the variations of pertinent blade parameters with blade azimuthal position.

The graphics implementation of the clustered wind turbine model was based on the VDARTC computer code, with the simplification made to use a constant Reynolds number for all blade elements to minimize computer core requirements. To minimize core requirements, WINMIL consists of 29 overlays with 353 FORTRAN subroutines. WINMIL uses the Graphics Compatibility System (GCS) graphics language[3-6].

For short runs, WINMIL is used on a Sandia CDC 6600 computer using Network Operating System (NOS) software in an interactive mode with Texas Instrument Silent 700 series terminals, and Tektronix 4006, 4010, 4012, 4013, 4014, 4015, 4027 (color terminal), 4051, and 4081 terminals. The computer code uses 107,603 (octal) core locations.

For longer runs, the interactive WINMIL program prepares the input data and then routes it to the Sandia Cyber 76 or 7600 computers using SCOPE operating software. The batch version of the WINMIL program uses 120,102 (octal) words of small core memory and 166,100 words of large core memory.

Output of the WINMIL program consists of:

1. Plots of the aerodynamic data being used for the airfoil and Reynolds number selected.

2. Plots of the vortex wakes shed by the equatorial element of each blade of each turbine.

3. Plots of airfoil angle of attack, airfoil nondimensional circulation, airfoil nondimensional normal force, and local nondimensional total velocity for each equatorial element of each blade of each turbine as a function of azimuthal position around the rotor revolution.

4. Tabulated average rotor power coefficients for each revolution.

This graphical output is easily available in a number of forms. These include hardcopy plots from the interactive terminals and black and white and color 35 mm slides and black and white and color movies made by off-line computer output microfilm systems. Some of this graphical output has been used in the preparation of this report.

Some of the runs required to generate the results for one orientation of the turbines and one tipspeed ratio required over two hours of CDC Cyber 76 or 7600 computer time. Obviously, both Sandia National Laboratories and its contractors[7] are pursuing ways to reduce the computer time required by these computer codes.

Test Cases

The large amount of CPU time required to run VDARTC prevents an extensive compilation of interference data in this report. Presented here is the predicted interference effect between two Darrieus wind turbines (Sandia 17-m configuration) with tower-to-tower spacing equal to three equatorial radii. The Sandia 17-m turbine is a H/D = 1, troposkein approximation, blade planform machine having 2 blades of 0.61 m chord NACA 0015 profile. It develops 80 kW in a 19.7 m/sec ambient wind at 1585 m altitude. The turbine solidity, σ, is 0.146. Eight different orientations of the turbines were investigated as shown in Fig. 3, and the corresponding power coefficients obtained at a tipspeed ratio of 3 are tabulated in Table 1. This tipspeed ratio was chosen because historically, the maximum value of shaft power is obtained near $X_\infty = 3$. Of special interest is the case where the turbines are aligned in the streamwise direction (configuration A) since the largest power loss occurs there. For this orientation, a more complete power curve was generated and is shown in Fig. 4 compared to the predicted single turbine curve. The band on the downwind turbine prediction arises from the difficulty in obtaining numerical convergence at moderately high tipspeed ratios. Finally, Fig. 5 presents a typical sequence of plots which shows the development of the free vortex systems for both turbines ($X_\infty = 4$).

TABLE 1

Predicted Power Coefficients for Different Configurations, $X_\infty = 3$

Configuration	Turbine 1	Turbine 2
A	.200	.160
B	.199	.197
C	.199	.199
D	.199	.200
E	.160	.200
F	.197	.199
G	.199	.199
H	.200	.199
Single Turbine	.199	

Discussion of Results

The data summarized in Table 1 indicate that, for a tower-to-tower spacing of three equatorial radii and $X_\infty = 3$, the only orientation which produces a significant change in turbine power output is when the turbines are aligned in the streamwise direction. This is not surprising since the wake from the upwind turbine passes through the downwind turbine in this alignment, but not in the others. A more thorough investigation of the power curve (Fig. 4) for this alignment indicates that the power loss in the downwind turbine increases as the tipspeed ratio increases, at least over the range of speed presented.

The power loss at a given tipspeed ratio may be explained by considering the structure of the free vortex system associated with the upwind turbine. Figure 6 shows how the circulation on the equatorial blade element of the upwind turbine varies with angular position (Θ) of the turbine (the sign convention for Θ is shown in Fig. 7). Kelvin's theorem dictates that the strength of a shed vortex is equal in magnitude and opposite in sign to the temporal change in circulation of a blade element. It is evident that the circulation becomes increasingly negative over the left-hand side of the rotor (Θ = 90° to Θ = 270°, roughly), and positive over the right-hand side (Θ = 270° back through Θ = 0° to Θ = 90°). This means that, on the average, the vortices shed during the right-hand half of the revolution will be negative sense (clockwise viewed from above) and those shed on the left-hand side will be positive sense (counterclockwise viewed from above). This situation is illustrated in Fig. 7. It can be seen that a significant streamwise velocity is induced against the ambient flow by the free vortex system. The variation of the induced streamwise flow seen by a blade element as it rotates around the turbine is shown for both turbines in Fig. 8. (The data in Figs. 8-11 are for the equatorial blade segments, configuration A, $X_\infty = 4$. Downwind 1 and 2 refer to different blades on the downwind turbine.) It might be expected that the difference in power output of the two turbines is due to smaller total velocity (greater induced flow) seen by the downwind turbine blades. Figure 9 shows, however, that although the variation of total velocity with Θ has a different character for the two turbines, the total velocities themselves (ambient plus induced plus rotation) are not significantly different. This is because the total velocity is dominated by the rotational component of velocity, at least at moderate tipspeed ratios. The major effect of the induced streamwise flow is to modify the local blade element angle of attack as shown in Fig. 10. This results in lower chordwise blade forces (Fig. 11) and, hence, lower torque and power. Therefore, as the tipspeed ratio of the upwind turbine increases, the blade circulation increases accompanied by an increase in the strength of the shed vortices, resulting in higher induced velocities, lower angles of attack downstream, and correspondingly, lower torque and power output. The trends in Fig. 4 thus appear reasonable.

Conclusions

The mutual aerodynamic interference between two 17-m diameter Darrieus wind turbines with a tower-to-tower separation distance of 1.5 diameter has been calculated using a vortex/lifting line model neglecting the effects of freestream turbulence. The calculations showed that, for the configurations examined, downstream turbine power reductions:

1. Are significant only when the two turbines were aligned with the ambient wind direction.
2. Increase with increasing tipspeed ratio for a fixed separation distance.
3. Are due more to changes in downstream flow angularities than velocity deficits.

The calculation of downstream turbine power decrements at separation distances greater than 1.5 diameter could be calculated if a suitable velocity deficit decay model were added to the basic vortex scheme.

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FIGURE 1 Single Turbine Efficiency - Predicted vs Measured

FIGURE 2 Predicted Wake Geometry - Sandia 17-m Turbine, $X_\infty = 4$ (Wake From Equatorial Segment of One Blade Only)

FIGURE 3 Orientation of Turbines in Test Case

FIGURE 4 Predicted Turbine Efficiencies, Configuration A

FIGURE 5 Predicted Wake Geometry, Configuration A, $X_\infty = 4$ (Wake From Equatorial Segment of One Blade Only)

FIGURE 6 Azimuthal Variation of Circulation, Equatorial Segment of Upwind Turbine, $X_\infty = 4$

FIGURE 7 Streamwise Flow Induced by Vortex System

FIGURE 8 Azimuthal Variation of Induced Streamwise Flow, $X_\infty = 4$

FIGURE 9 Azimuthal Variation of Total Velocity, Equatorial Segments, $X_\infty = 4$

FIGURE 10 Azimuthal Variation Angle of Attack, Equatorial Segments, $X_\infty = 4$

FIGURE 11 Azimuthal Variation of Chordwise Blade Force, Equatorial Segments, $X_\infty = 4$

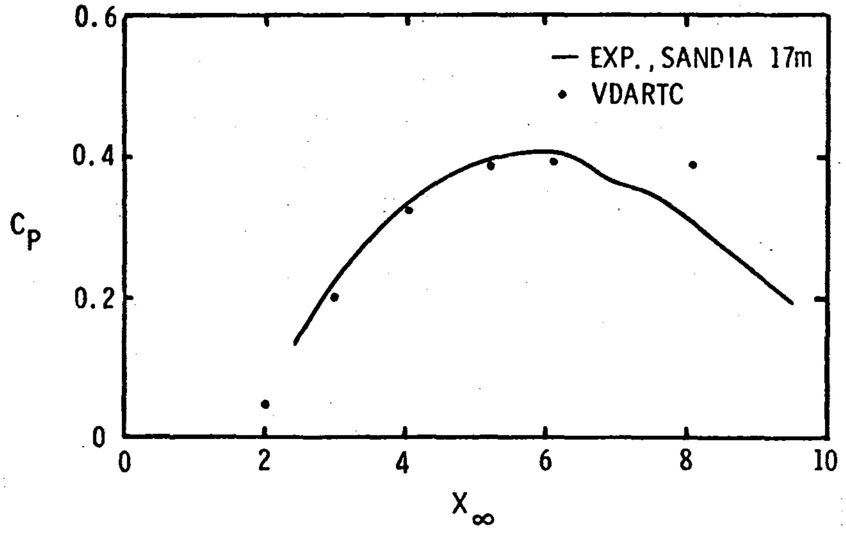
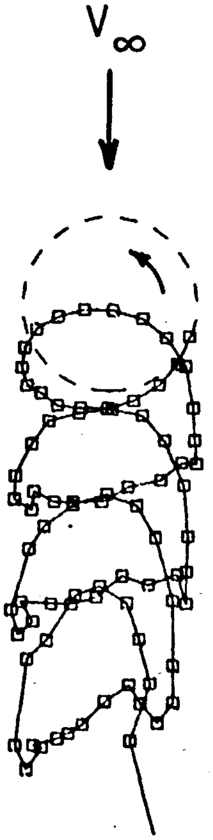


FIGURE 1



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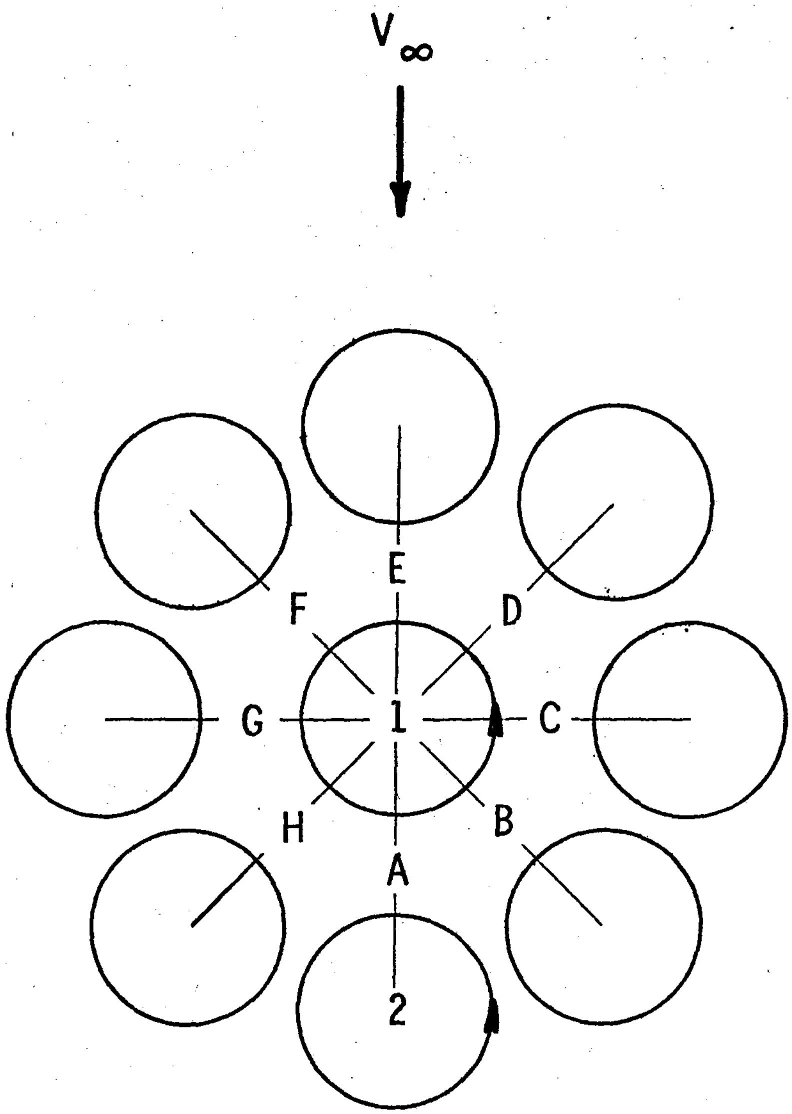

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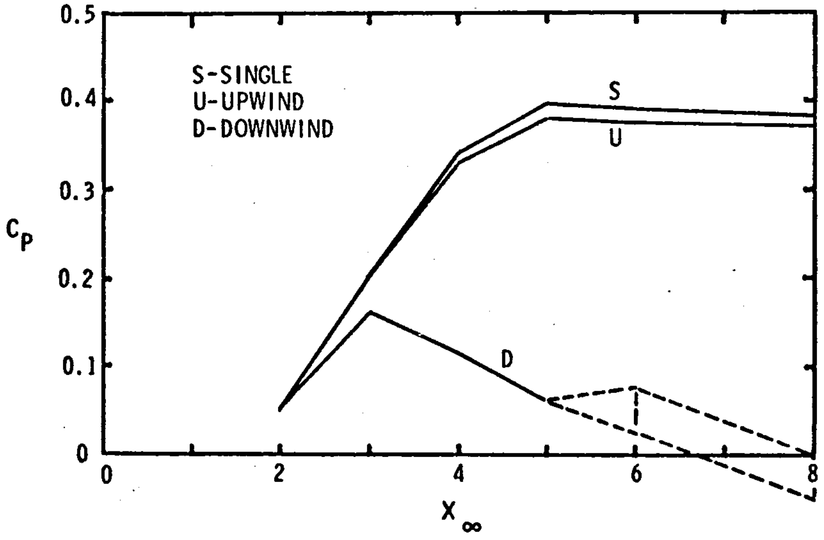

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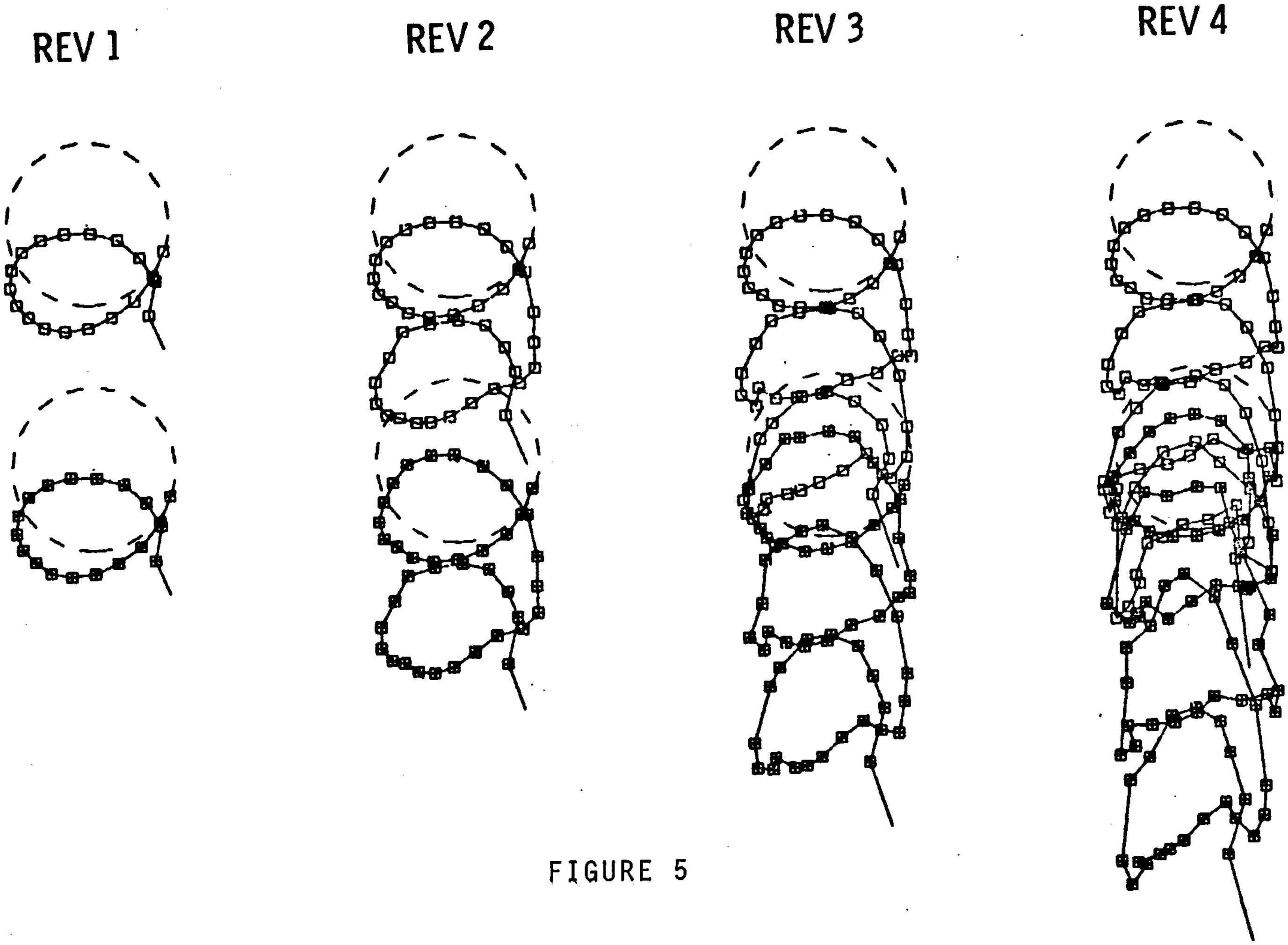

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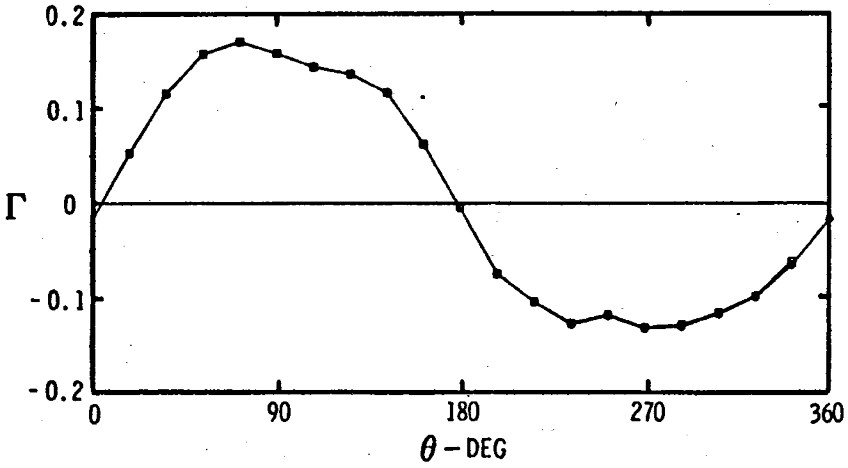
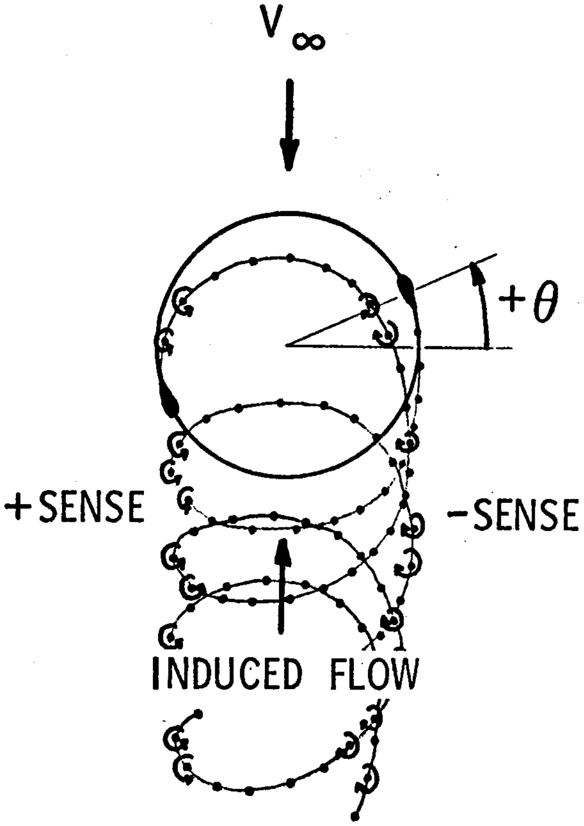


FIGURE 6



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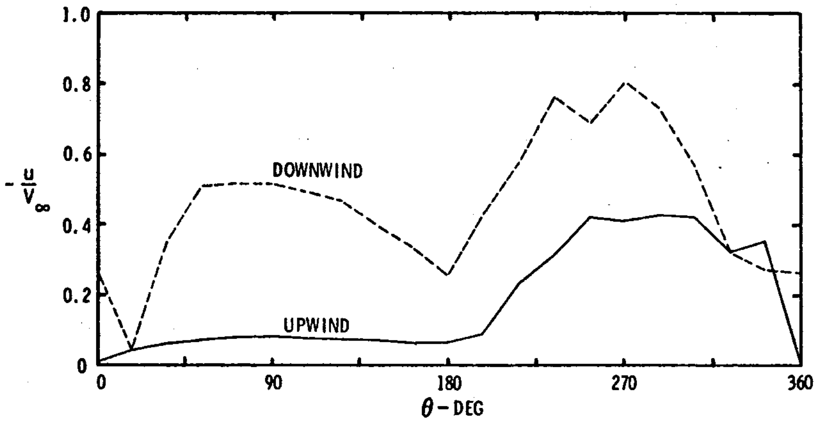

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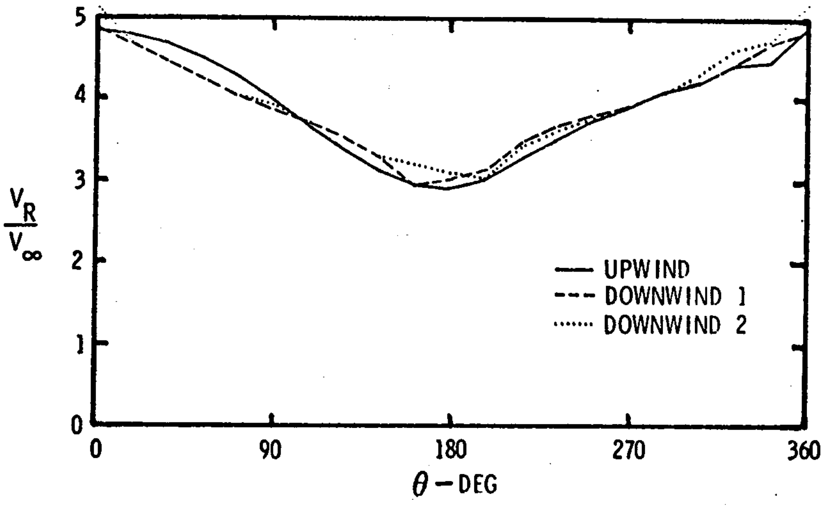

FIGURE 9

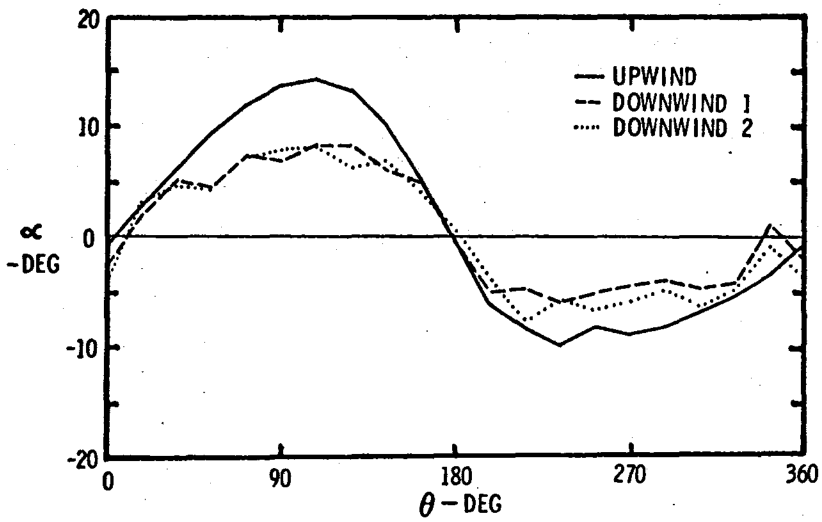

FIGURE 10

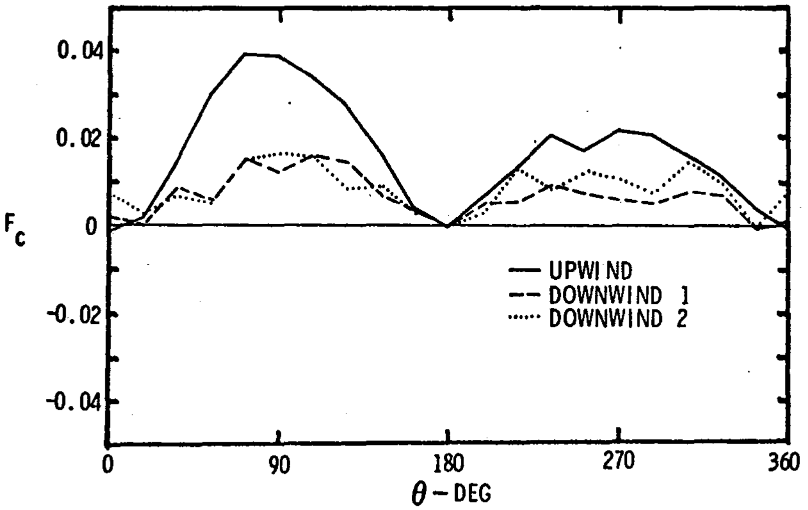

FIGURE 11

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