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TECHNIQUES FOR THE DETERMINATION OF LOCAL DYNAMIC PRESSURE AND ANGLE OF ATTACK ON A HORIZONTAL AXIS WIND TURBINE

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ABSTRACT

Data from the National Renewable Energy Laboratory's "Combined Experiment" has been utilized to develop techniques for indirectly calculating the instantaneous local dynamic pressure and angle of attack on a horizontal axis wind turbine. First, an analytic model based upon inflow geometry relative to the wind turbine was developed for both parameters. Second, dynamic pressure and angle of attack were inferred from the pressure required to normalize the blade stagnation point to $C_p = 1.0$. Third, rotor blade pressure profiles were compared to those from wind tunnel tests to determine angle of attack. Test results are shown over a variety of typical inflow conditions and are corroborated by measured data. Differences between the calculated and measured values are also discussed.

NOMENCLATURE

a	total axial induction factor
a_o	axial induction factor from PROP
C_p	measured surface pressure coefficient
p	pressure measured at blade surface (psi)
p_{stag}	pressure measured on the blade surface at the stagnation point (psi)
p_∞	reference pressure measured at the hub (psi)
q	dynamic pressure (psi)
r	radial distance from hub (m)
R	radial distance to blade tip (m)
sw	skewed wake factor
V_c	cross-flow velocity component (m/s)
V_n	velocity component normal to rotor disc (m/s)
V_s	spanwise velocity component (m/s)
V_t	velocity component tangent to rotor rotation (m/s)
V_w	wind velocity measured at Vertical Plane Array (m/s)
$\overline{V}_w$	calculated wind velocity (m/s)
V_∞	local freestream velocity (m/s)
α	angle of attack (deg)
β	geometric blade pitch angle (deg)
γ	measured yaw (deg)
ψ	azimuth angle of instrumented blade (deg)
ψ_o	half angle of tower shadow sector (deg)
ρ	air density measured at the far meteorological tower (kg/m^3)
ω	rotational frequency (2.4π rad/sec)

INTRODUCTION

Two of the most important parameters for quantifying the aerodynamic response of a wind turbine blade are the local dynamic pressure, q, and angle of attack, α. Normalization of surface pressure data by the local dynamic pressure enables pressure distributions to be compared across the span and to wind tunnel tests. Local angle of attack is the primary indicator of aerodynamic performance. Knowledge of the angle of attack permits direct comparison of blade lift, drag, and pressure histories to those seen in wind tunnel tests and allows performance indices to be established.

Horizontal axis wind turbines (HAWTs) operate in an extremely complicated flow environment. Consequently, the determination of local dynamic pressure and angle of attack is not a simple task. Direct measurement is difficult due to complex and highly variable inflow, upwind flowfield disturbances, and unknown dynamic effects. Moreover, measurement devices can alter the very flowfield that they are trying to measure and can be susceptible to the same unsteady phenomena as a rotor blade. In addition, placement of the devices to minimize flow disturbance introduces a magnitude and/or phase difference into the measurements.

The current study focuses on the development of techniques to estimate instantaneous local dynamic pressure and angle of attack on a HAWT blade that do not suffer from these limitations. Data from the National Renewable Energy Laboratory's (NREL's) "Combined Experiment" was utilized to develop and validate two methods for determining instantaneous local dynamic pressure and three methods for angle of attack. These techniques provide an indirect estimation of the local inflow parameters based upon data collected by other instruments. The FORTRAN code developed to implement these techniques is included in the appendix.

EXPERIMENTAL TEST SETUP

NREL's Combined Experiment horizontal axis wind turbine (Figure 1) is a 10.1 meter diameter, three-bladed downwind machine that rotates at a constant 72 RPM and is capable of producing 20 kW of power. The turbine is supported on a 0.4 meter cylindrical tower at a height of 17 meters from the ground to the center of the hub. The blades used were rectangular, untwisted NREL S809 airfoil sections with a 0.457 meter chord. One of the three blades was instrumented with pressure transducers (Figure 2) at four different span locations (30%, 47%, 63%, and 80% span). The blade surface pressures were referenced to the static pressure measured at the hub and recorded as pressure coefficients, C_p. Dynamic pressure, q, and angle of attack, α, were also measured at or near these four span locations through instrumentation that will be discussed in later sections. The data sample rate (521 Hz) was sufficient to capture the dynamic and transient pressure events elicited from time variant inlet flow conditions. The inlet flow magnitude, V_w, and direction were measured by anemometers mounted on the Vertical Plane Array (VPA) located 12 meters upwind of the turbine. Yaw was calculated as the angle between the direction that the turbine was facing and the wind direction measured at the VPA. For a complete description of the Combined Experiment test setup and instrumentation see Butterfield et al. (1992).

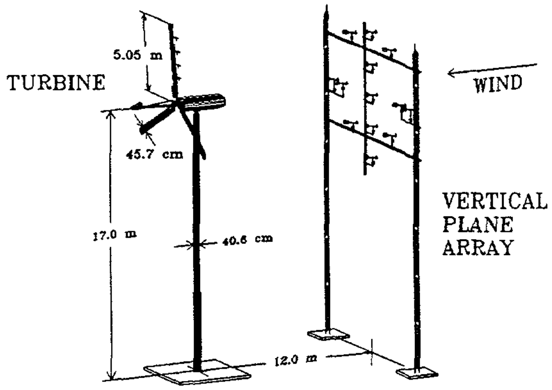

FIGURE 1: VIEW OF THE COMBINED EXPERIMENT TEST SITE INCLUDING THE GRUMMAN WIND STREAM 33 HORIZONTAL AXIS WIND TURBINE AND THE VERTICAL PLANE ARRAY.

DETERMINATION OF LOCAL DYNAMIC PRESSURE

Dynamic pressure is measured on the Combined Experiment rotor by four pressure probes that protrude 0.62 meters from the leading edge at 34%, 50.3%, 67.3%, and 80% span (Figure 3). The probes were tested in the wind tunnel to have less than 10% error for angles of attack between ±40° (Huyer, 1993).

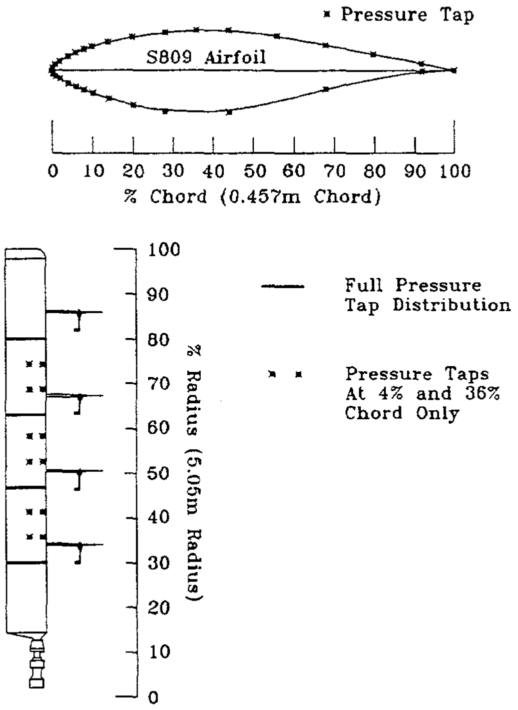

FIGURE 2: ROTOR BLADE CROSS SECTION AND LONGITUDINAL VIEWS SHOWING CHORDWISE PRESSURE TAP DISTRIBUTION AT EACH OF FOUR PRIMARY LOCATIONS (30%, 47%, 63%, AND 80% SPAN). DYNAMIC PRESSURE PROBES AND ANGLE OF ATTACK FLAGS ARE LOCATED JUST OUTBOARD OF SURFACE PRESSURE TAPS.

The utility of these probes for the normalization of surface pressures is limited due to their position outboard and upstream of the pressure taps. The higher rotational velocity of the probes relative to the surface pressure taps results in an added effect in dynamic pressure. The extension of the probes 1.35 chord lengths ahead of the blade creates a phase difference between the dynamic pressure and surface pressure measurements from 8.2° azimuth at 86% span to 20.7° azimuth at 34% span. In addition, the inboard span locations of 30% and 47% often operate at angles of attack greater than 40° where the data from the probes is not reliable. Therefore, two additional approaches were undertaken to determine the instantaneous local dynamic pressure. First, an analytic model was developed based upon the turbine geometry relative to the inflow. Second, the dynamic pressure was inferred from the magnitude of the stagnation point on the blade's lower surface.

Analytic Model

The analytic model used was adapted from Huyer (1993). The local velocity components, and hence dynamic pressure, were estimated from the geometry of the inflow relative to the turbine. Huyer's code was adapted to include instantaneous values for blade position, velocity, and yaw; use axial induced velocities predicted by PROP (Wilson et al, 1976); and evaluate the dynamic pressure at different span locations.

A cosine function was used to model the profile of the tower shadow velocity deficit. According to Hansen et al.(1989) with a maximum velocity deficit of 30% of freestream:

$$V_W = V_W\left\{1-\frac{0.30}{2}\left[1+\cos\left(\frac{2\pi}{2\psi_o}\psi\right)\right]\right\} \qquad (1)$$

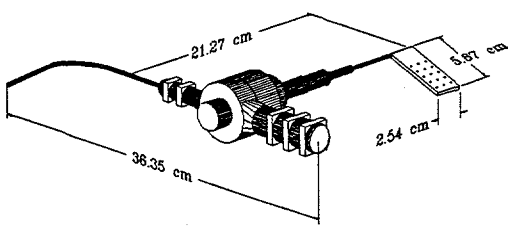

FIGURE 3: INSTRUMENTATION USED TO MEASURE THE LOCAL DYNAMIC PRESSURE AND ANGLE OF ATTACK ON THE COMBINED EXPERIMENT ROTOR.

This portion of the model is limited due to the inability to predict vortex shedding from the tower. A study based upon Combined Experiment measured angle of attack indicates that the maximum velocity deficit can range from 10% - 90% freestream with a mean value of approximately 25% to 30%. Therefore, on average the deficit should be modeled relatively closely, but instantaneous predictions may vary.

PROP was utilized to predict the axial induction factors, a_o, at each span from blade element/momentum theory. A second order hyperbolic regression was performed on the 30% span data with fourth order hyperbolic regressions used for the three outboard span locations (Figure 4).

A skewed wake correction was used according to Hansen et al.(1989) to adjust the induction factors to account for wake deformation under yawed conditions:

$$sw = 1+\frac{15\pi}{32}\sqrt{\left(\frac{1-\cos\gamma}{1+\cos\gamma}\right)}\frac{r}{R}\sin\psi \qquad (2)$$

then: $a = a_o * sw$

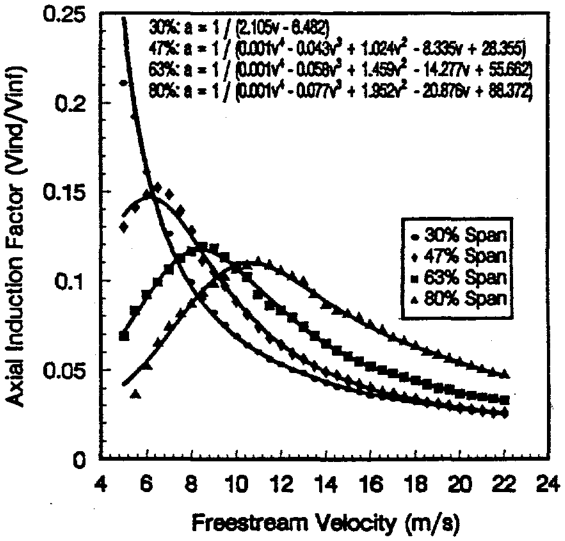

FIGURE 4: AXIAL INDUCTION FACTORS PREDICTED BY PROP FOR THE FOUR PRIMARY PRESSURE TAP LOCATIONS. A SECOND ORDER HYPERBOLIC REGRESSION IS FIT THROUGH THE 30% SPAN DATA AND FOURTH ORDER HYPERBOLIC REGRESSIONS USED FOR THE OUTBOARD THREE SPAN LOCATIONS.

From Figure 5, the inflow velocity can be broken down into components that are normal to and across the plane of disk rotation:

$$V_n = V_w(1-a)\cos\gamma \qquad (3)$$
$$V_c = -V_w\sin\gamma \qquad (4)$$

The crossflow velocity vector can be further decomposed into components that are tangent to the rotor rotation and along the span of the blade:

$$V_t = r\omega + V_c\cos\psi \qquad (5)$$
$$V_s = V_c\sin\psi \qquad (6)$$

Then, the total inflow velocity at a given position in the rotor disc can be found from the vector sum of the three orthogonal velocity components, V_n, V_t, and V_s:

$$V_\infty = \sqrt{V_n^2 + V_t^2 + V_s^2} \qquad (7)$$

Finally, the dynamic pressure is defined as:

$$q = \frac{1}{2}\rho V_\infty^2 \qquad (8)$$

The wind velocities and directions used in the model are those measured at the Vertical Plane Array located 12 meters upstream from the turbine. Blade azimuth angle and turbine yaw angle were measured on the turbine itself..

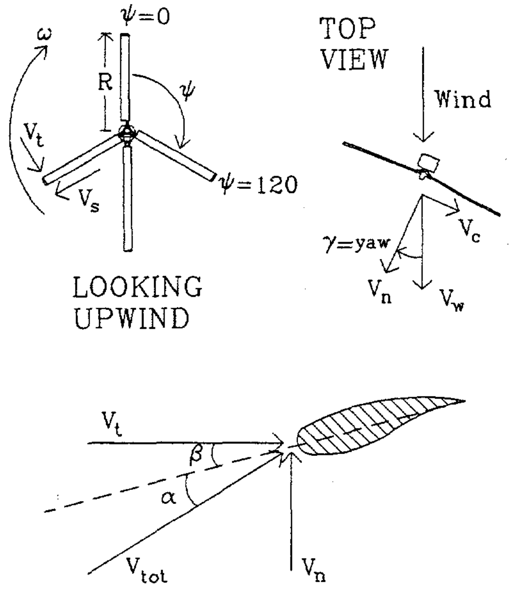

FIGURE 5: GEOMETRIC RELATIONSHIP BETWEEN INFLOW VARIABLES AND A DOWNWIND HORIZONTAL AXIS WIND TURBINE.

Stagnation Pressure Normalization

The analytic model was based upon a number of assumptions regarding induced velocities, tower shadow profile and size, and inflow magnitude and velocity. In addition, the limited frequency response of the anemometers used to measure inflow magnitude and direction makes high resolution data impossible to attain. Therefore, a technique independent of these assumptions and limitations was developed based upon the surface pressure measured at the blade stagnation point.

The stagnation point is the location on the blade where the local velocity equals zero. For incompressible and irrotational flow, a stagnation point exists on the airfoil where $C_p = 1.0$ where:

$$C_p = \frac{p - p_\infty}{q_\infty} \qquad (9)$$

The dynamic pressure at the stagnation point is equal to the differential pressure measured on the blade surface:

$$q_\infty = p_{stag} - p_\infty \qquad (10)$$

Therefore, to determine the local freestream dynamic pressure, only the differential surface pressure measured at the stagnation point ($p_{stag} - p_\infty$) was required. The stagnation point can be located simply by finding the maximum positive surface pressure. For positive angles of attack, this point will always be on the blade lower surface. The pressure tap resolution on the lower surface of the Combined Experiment blade was sufficient to provide a reasonable estimate of the maximum pressure. This was true particularly at low angles of attack where the stagnation point was near the leading edge. For users of this technique with a lower pressure tap resolution, accuracy could be improved by curve fitting the pressures on either side of an observed maximum.

Comparison of Dynamic Pressure Results

The two techniques were compared using data collected from nine single rotational cycles spanning the most typical operational conditions for the Combined Experiment turbine. Dynamic pressures

TABLE 1: INFLOW CONDITIONS OF THE TEST MATRIX USED IN THE EVALUATION AND VALIDATION OF THE DYNAMIC PRESSURE AND ANGLE OF ATTACK TECHNIQUES.

Tape	Cycle	Velocity (m/s)	Yaw (deg)
d072042	72	6.93 ± 0.02	-10.36 ± 0.30
d075011	349	7.20 ± 0.05	0.10 ± 0.20
d075012	194	7.09 ± 0.11	10.41 ± 0.44
d066021	269	10.48 ± 0.01	-10.08 ± 0.43
d067012	111	10.10 ± 0.05	0.48 ± 0.46
d072042	277	9.72 ± 0.08	9.88 ± 1.03
d068011	115	15.18 ± 0.12	-10.36 ± 0.61
d072011	28	15.59 ± 0.04	0.26 ± 0.60
d068022	111	15.82 ± 0.08	9.72 ± 0.79

obtained from the models were evaluated at three different yaws (-10°, 0°, and 10°) and wind velocities (7 m/s, 10 m/s, and 15 m/s). The mean and standard deviation for velocity and yaw of the assessed cycles are given in Table 1.

Dynamic pressure given by the analytic model and stagnation point normalization technique were co-plotted with the corresponding measured data for each of the test cases (Figures 6-14).

Overall, a relatively high level of agreement between all methods is seen, especially inboard. The stagnation point normalization technique and the measured data tend to exhibit an extremely high correlation. Often, nearly identical fluctuations can be seen in both traces. However, these fluctuations tend to occur earlier in the rotational cycle in the measured data. Additionally, the stagnation pressure normalization technique underpredicts the measured q in all cases. These effects can be explained by the location of the dynamic pressure probe outboard of the surface pressure taps and in front of the blade. Correcting for these differences yields even closer comparisons.

In Figure 15, the measured dynamic pressure for the 15 m/s, -10 degree case is shifted both in azimuth and magnitude to account for the probe's position outboard and upstream. Equations (3)-(8) were used to calculate the local inflow velocity at 34%, 51%, 67%, and 86% span assuming a constant rotational velocity. Given this inflow velocity, the dynamic pressure was re-calculated at 30%, 47%, 63%, and 80% span from (3)-(8) using an azimuth angle shifted to compensate for the phase difference between measurements. The results were co-plotted with the dynamic pressure calculated from the stagnation pressure normalization technique.

The measured dynamic pressure when adjusted for probe location correlates extremely well with the stagnation pressure difference ($p_{stag} - p_\infty$) obtained from the blade lower surface. There is some discrepancy in the tower shadow region, however. At the outboard three span locations, the shifted measured dynamic pressure remains constant for approximately twenty azimuthal degrees in the tower shadow region while the stagnation point dynamic pressure estimate fluctuates widely. This discrepancy is discussed later in the paper during comparison of angle of attack determination techniques.

For the majority of the test cases, the dynamic pressure predicted by the analytic model tracks the other two methods closely. However, in the 7 m/s and -10° yaw case (Figure 6), neither of the other methods show the cyclic variation in dynamic pressure with azimuth demonstrated in the analytic model. This might indicate one of two possibilities. Either the local wind direction and magnitude are different from that measured upstream or other important factors, such as variations in velocity across the rotor disc due to wind shear are not properly accounted for. These types of effects could, for example, completely negate the effects of yaw.

Another important difference is the dynamic pressure values obtained in the tower shadow region. The location and magnitude of the velocity deficit can differ dramatically between the three methods. It is expected that the analytic model would differ from the other methods since a constant value for the maximum velocity deficit was assumed. Coherent vortex shedding within the tower may also explain the difference between the measured and calculated values.

DETERMINATION OF LOCAL ANGLE OF ATTACK

Angle of attack on a wind turbine blade is not solely a function of the blade geometric angle. The angle of attack varies with wind speed and direction as well as rotational velocity. Hence, each blade span location simultaneously operates at a different angle of attack.

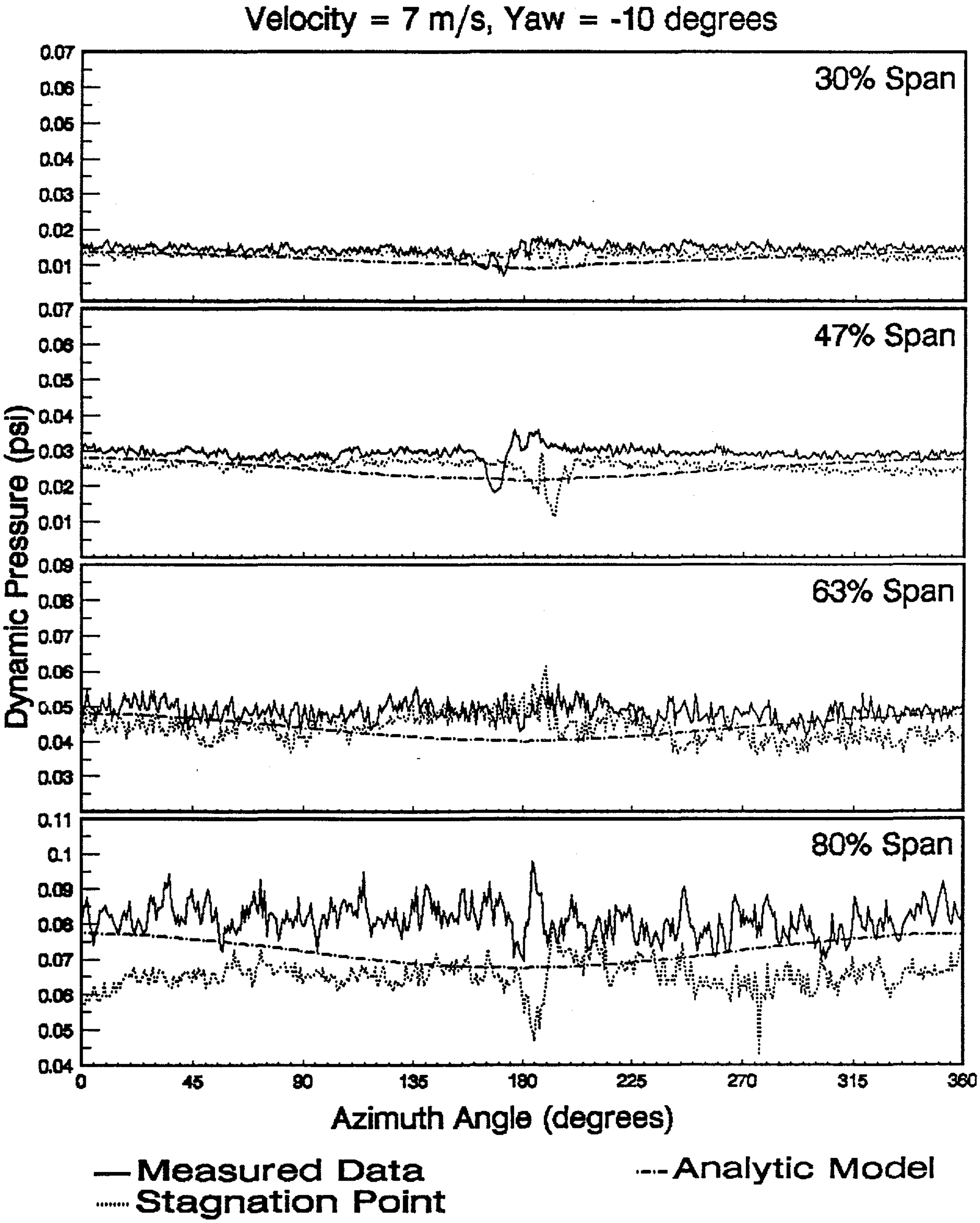

FIGURE 6: COMPARISON OF DYNAMIC PRESSURE CALCULATED USING THE ANALYTIC MODEL AND THE STAGNATION POINT NORMALIZATION TECHNIQUE TO MEASURED DATA AT A VELOCITY OF 7 M/S AND A YAW OF -10°.

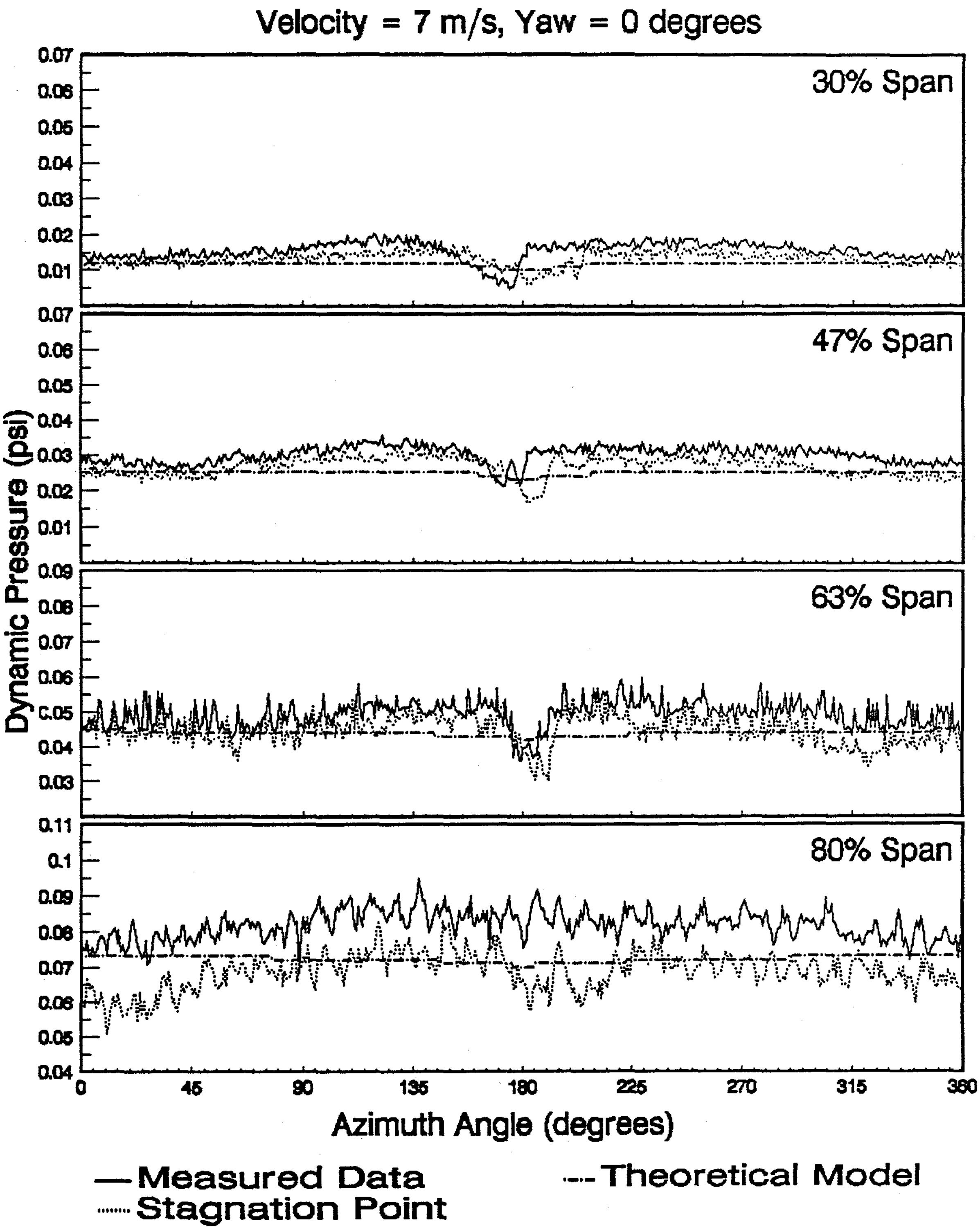

FIGURE 7: COMPARISON OF DYNAMIC PRESSURE CALCULATED USING THE ANALYTIC MODEL AND THE STAGNATION POINT NORMALIZATION TECHNIQUE TO MEASURED DATA AT A VELOCITY OF 7 M/S AND A YAW OF 0°.

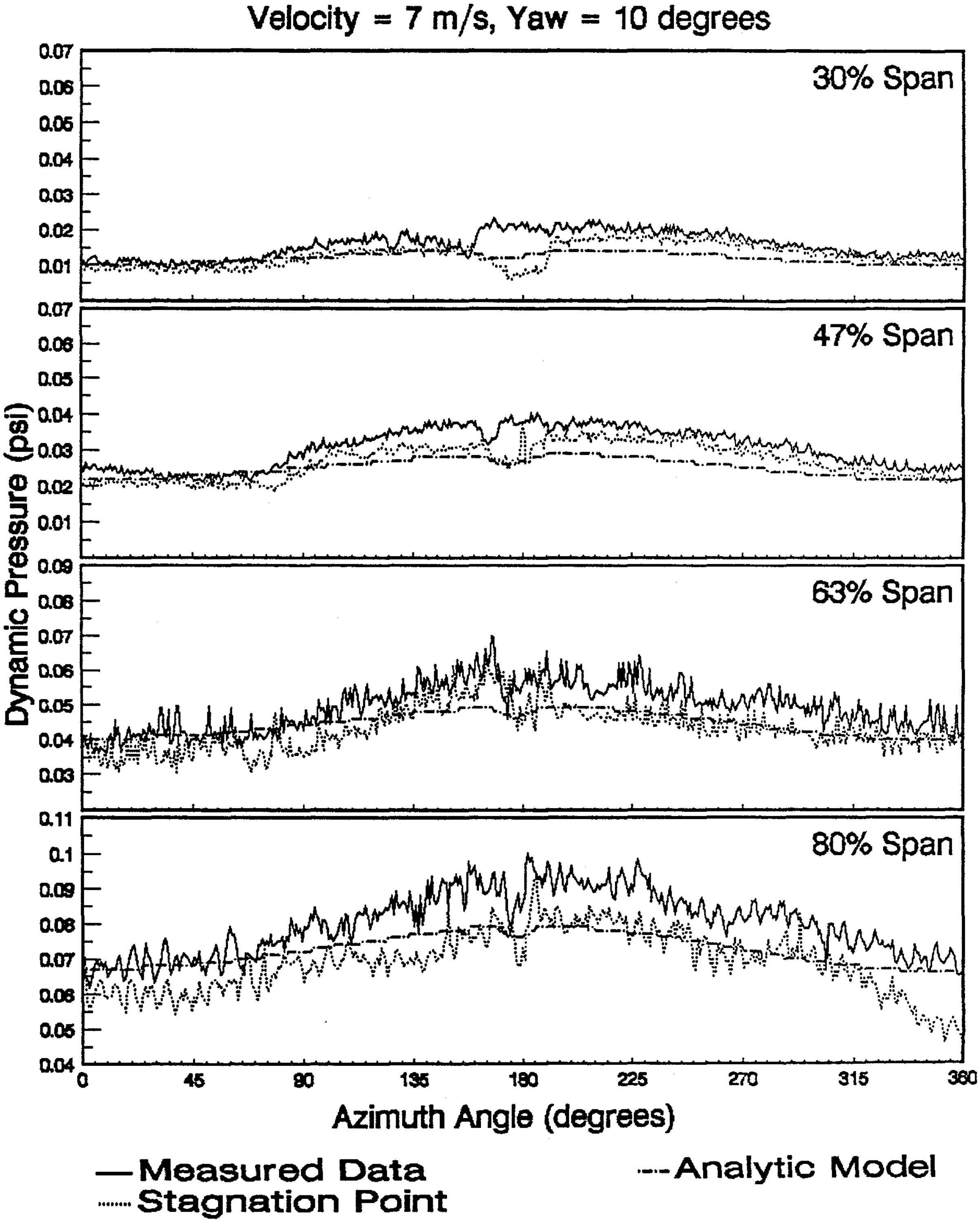

FIGURE 8: COMPARISON OF DYNAMIC PRESSURE CALCULATED USING THE ANALYTIC MODEL AND THE STAGNATION POINT NORMALIZATION TECHNIQUE TO MEASURED DATA AT A VELOCITY OF 7 M/S AND A YAW OF 10°.

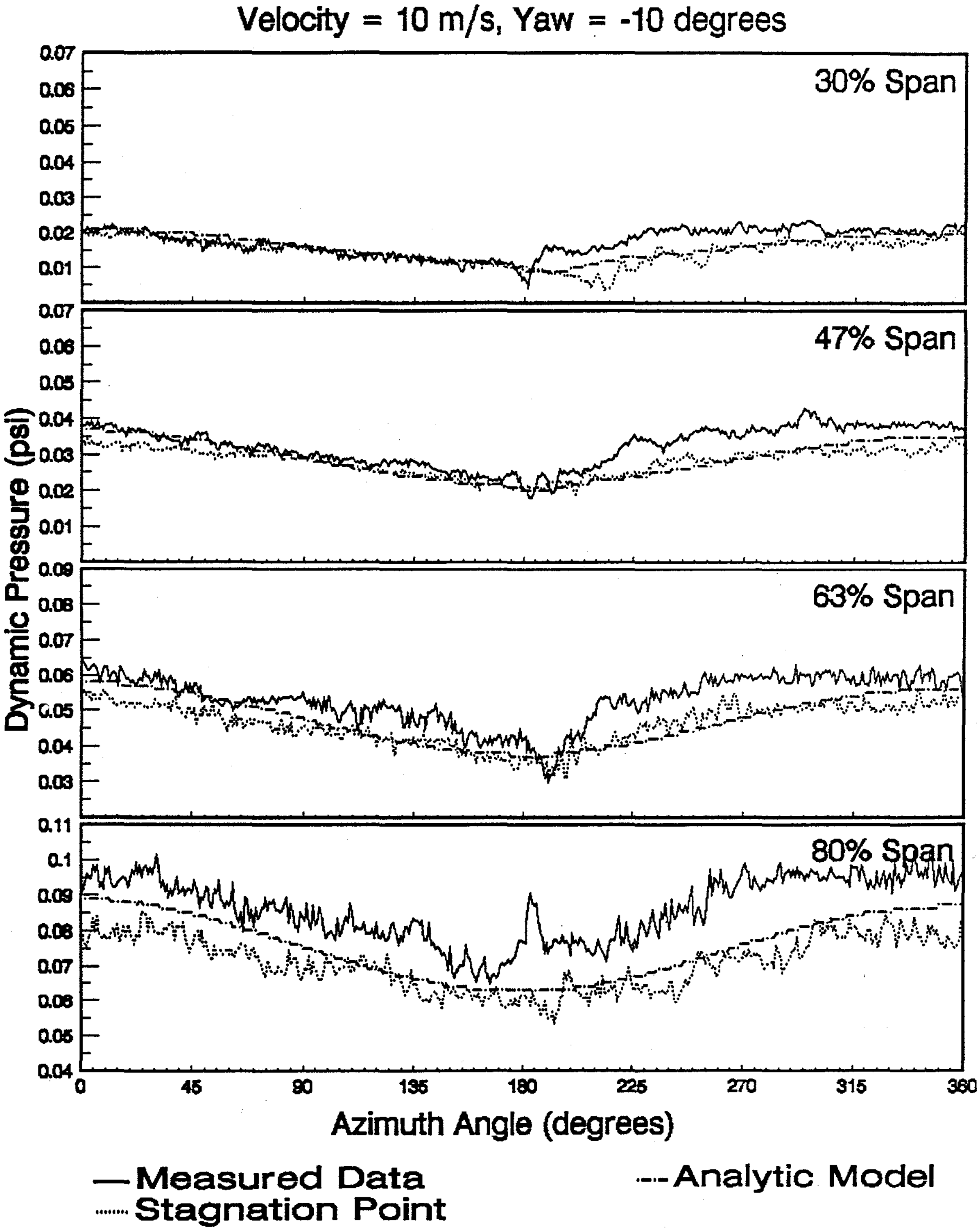

FIGURE 9: COMPARISON OF DYNAMIC PRESSURE CALCULATED USING THE ANALYTIC MODEL AND THE STAGNATION POINT NORMALIZATION TECHNIQUE TO MEASURED DATA AT A VELOCITY OF 10 M/S AND A YAW OF -10°.

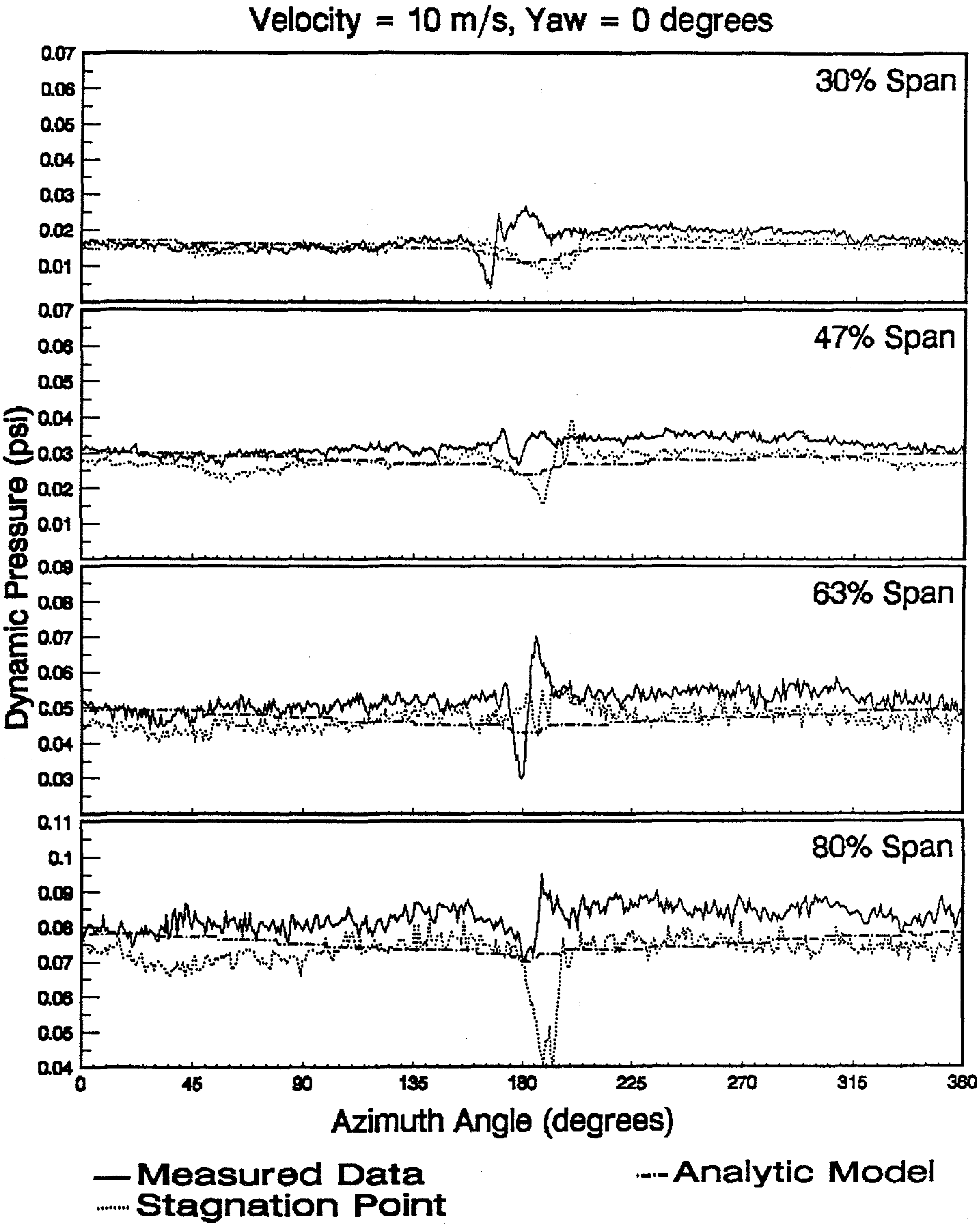

FIGURE 10: COMPARISON OF DYNAMIC PRESSURE CALCULATED USING THE ANALYTIC MODEL AND THE STAGNATION POINT NORMALIZATION TECHNIQUE TO MEASURED DATA AT A VELOCITY OF 10 M/S AND A YAW OF 0°.

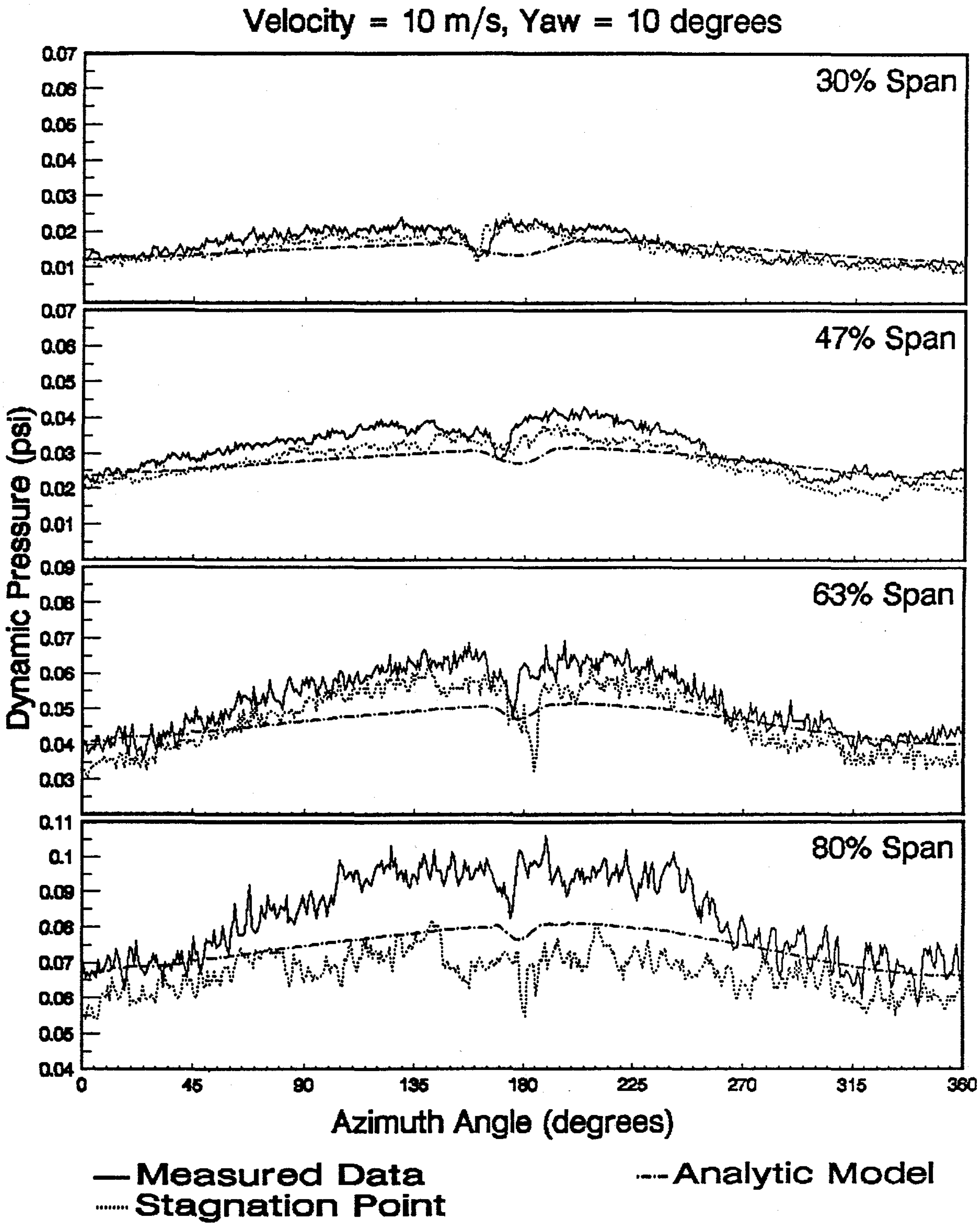

FIGURE 11: COMPARISON OF DYNAMIC PRESSURE CALCULATED USING THE ANALYTIC MODEL AND THE STAGNATION POINT NORMALIZATION TECHNIQUE TO MEASURED DATA AT A VELOCITY OF 10 M/S AND A YAW OF 10°.

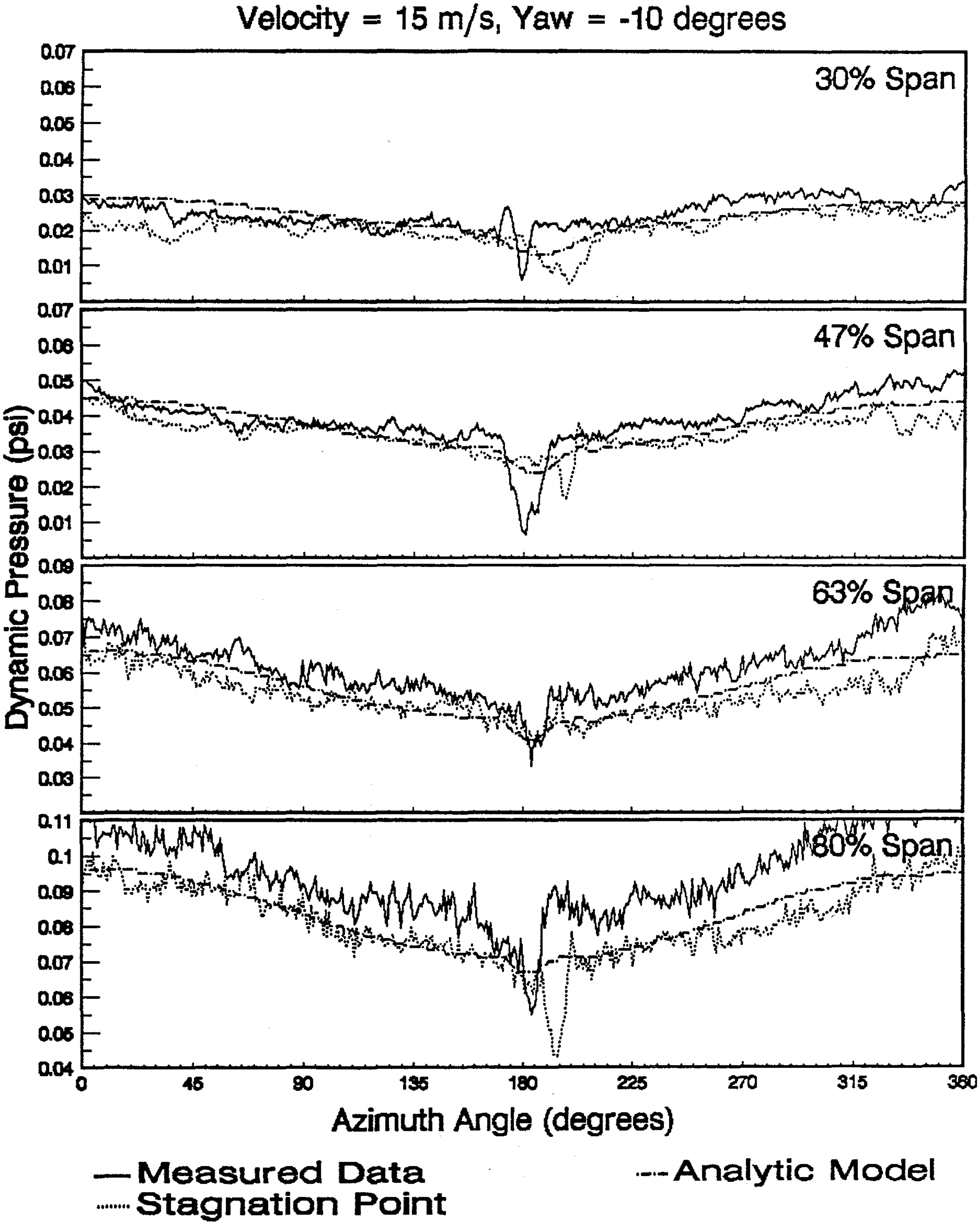

FIGURE 12: COMPARISON OF DYNAMIC PRESSURE CALCULATED USING THE ANALYTIC MODEL AND THE STAGNATION POINT NORMALIZATION TECHNIQUE TO MEASURED DATA AT A VELOCITY OF 15 M/S AND A YAW OF -10°.

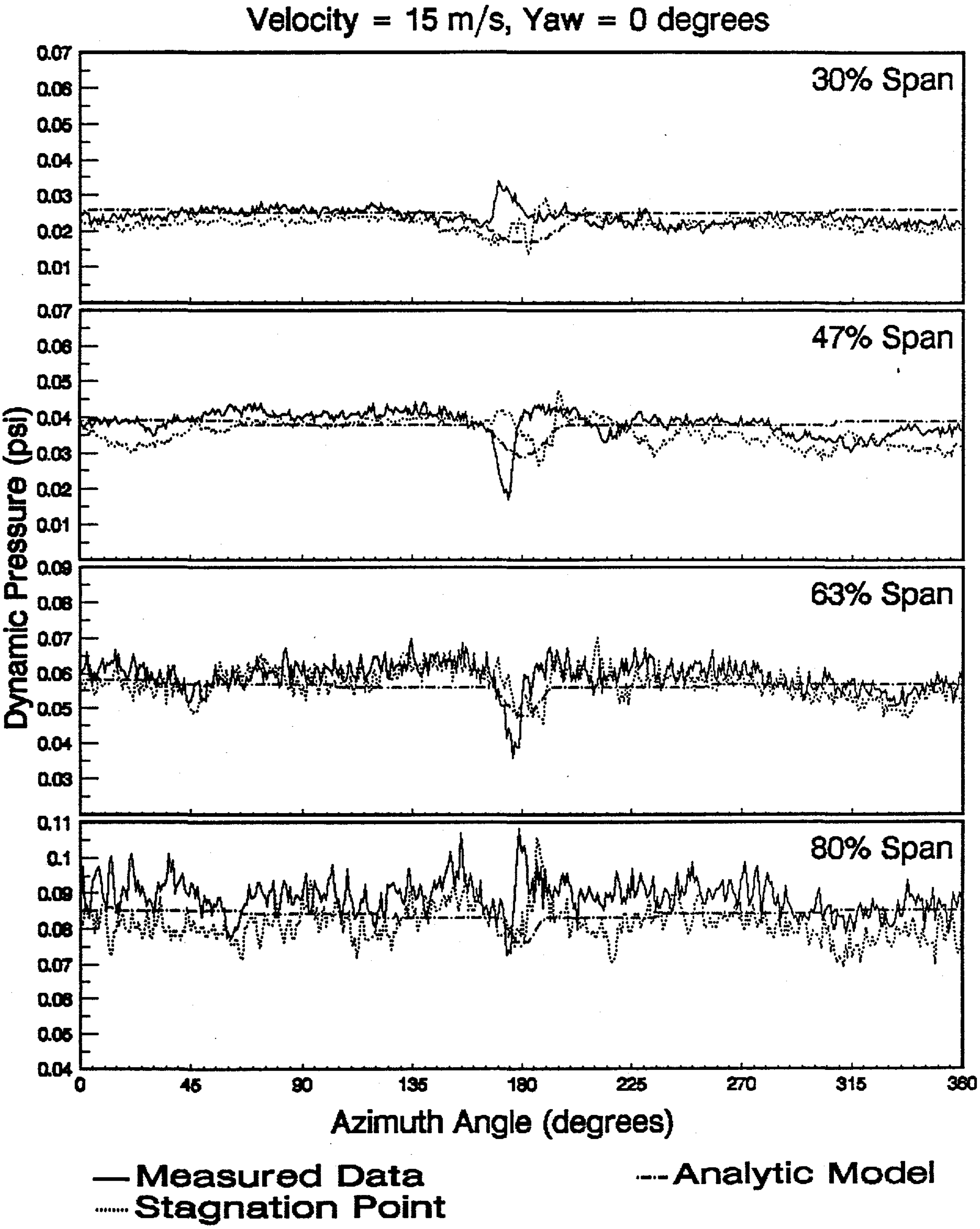

FIGURE 13: COMPARISON OF DYNAMIC PRESSURE CALCULATED USING THE ANALYTIC MODEL AND THE STAGNATION POINT NORMALIZATION TECHNIQUE TO MEASURED DATA AT A VELOCITY OF 15 M/S AND A YAW OF 0°.

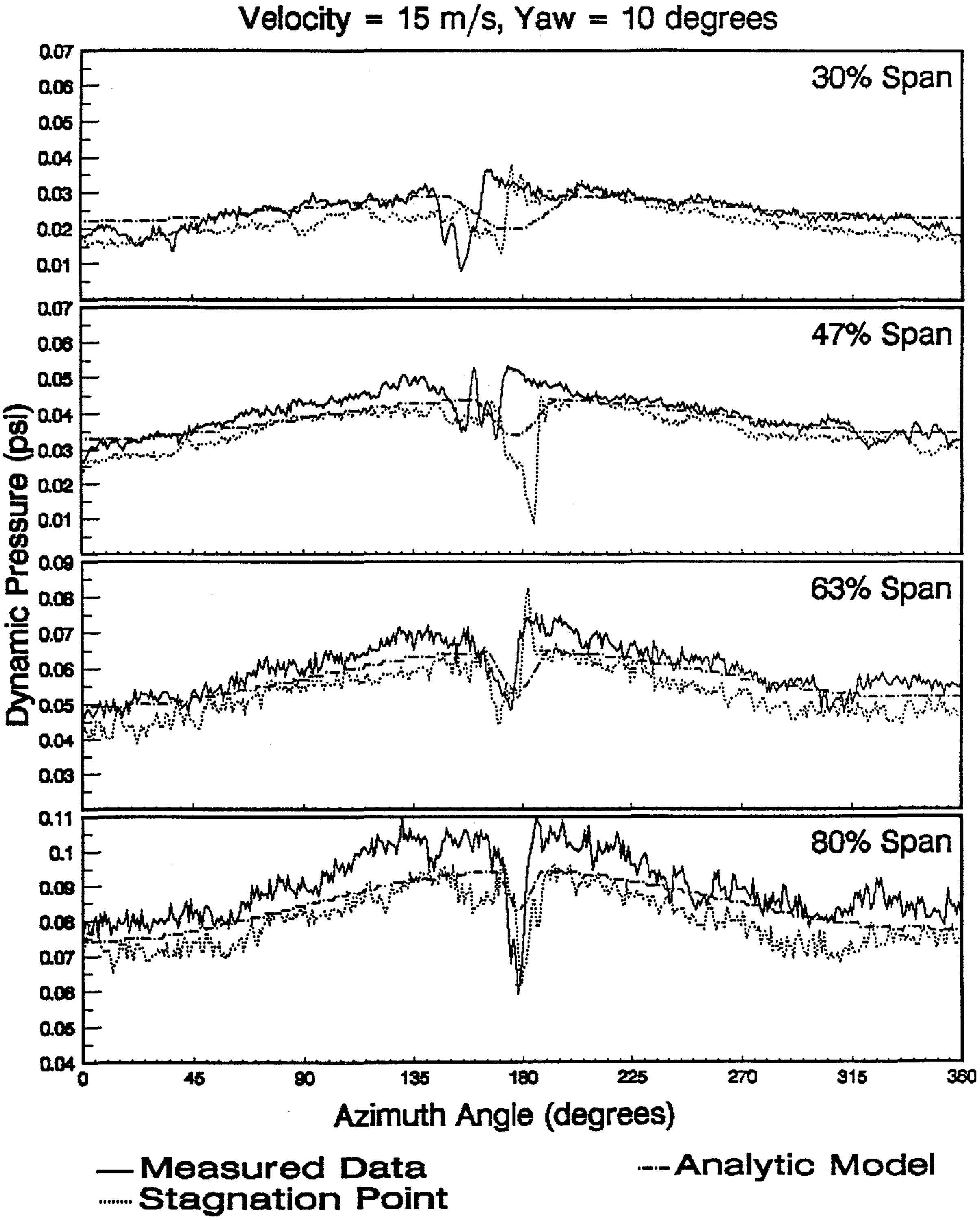

FIGURE 14: COMPARISON OF DYNAMIC PRESSURE CALCULATED USING THE ANALYTIC MODEL AND THE STAGNATION POINT NORMALIZATION TECHNIQUE TO MEASURED DATA AT A VELOCITY OF 15 M/S AND A YAW OF 10°.

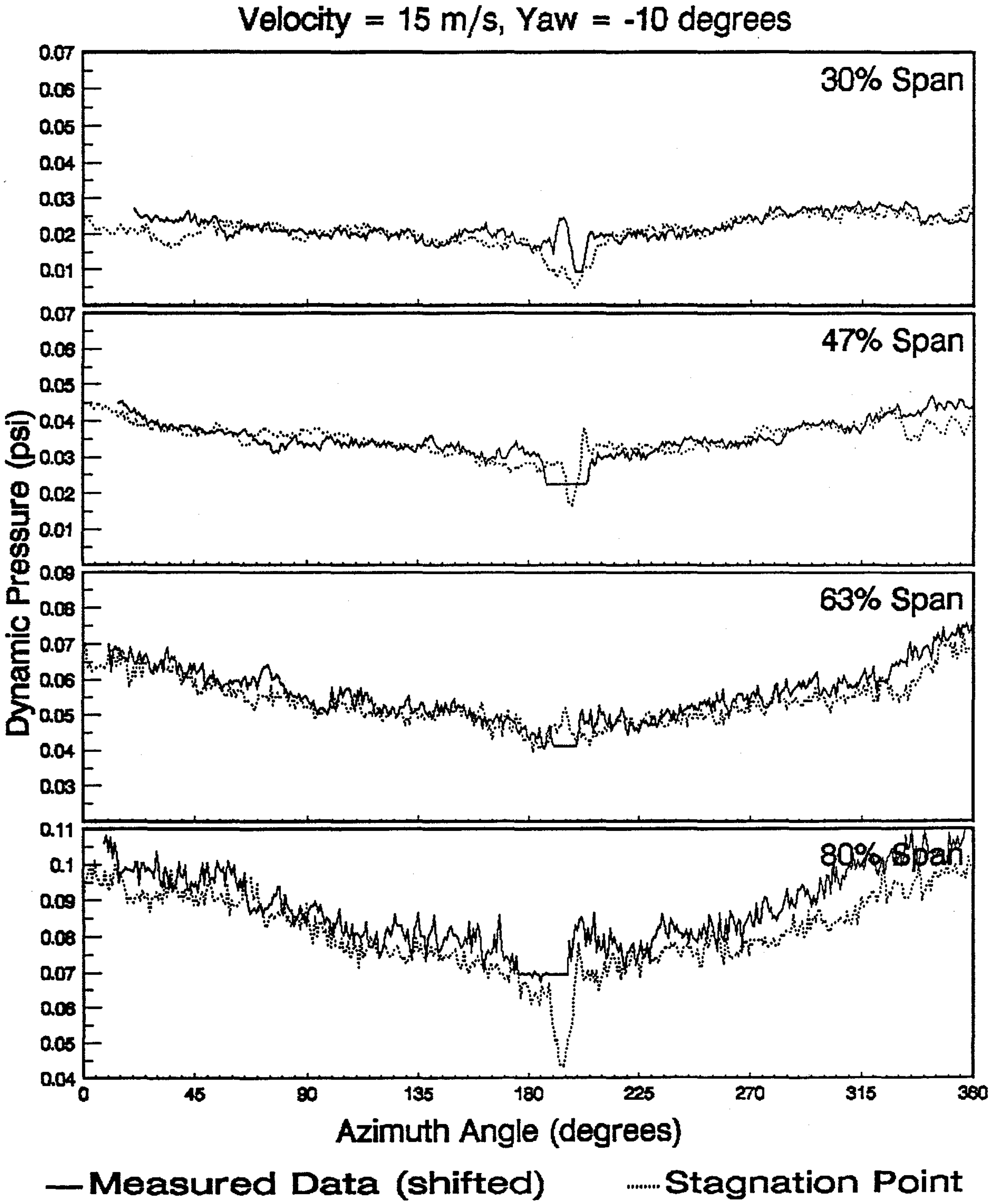

FIGURE 15: COMPARISON OF DYNAMIC PRESSURE CALCULATED USING THE STAGNATION POINT NORMALIZATION TECHNIQUE TO MEASURED DATA CORRECTED FOR THE PROBE'S POSITION OUTBOARD AND UPSTREAM FROM THE SURFACE PRESSURE TAPS.

Measurement of angle of attack on the Combined Experiment rotor was accomplished using flow angle sensors located inboard from the dynamic pressure probes (Figure 3). These small, lightweight, rigid flags rotate freely to align themselves with the local flow velocity within a limited angle range. Rotary position sensors measured the flag angles.

There are three significant impediments to using these particular flow angle sensors to provide instantaneous angle of attack data. First, due to transducer limitations, the sensors are only capable of measuring angles in the range of $-20° < \alpha < 40°$. As previously mentioned, the inboard span locations often operate at angles much greater than 40°, especially when the machine is yawed. Second, the sensor had a limited frequency response of ≤ 10 Hz. Since many flowfield perturbations occur at higher frequencies, rapid angle of attack changes could not be accurately measured. Lastly, the flags were mounted approximately 0.34 meters in front of the leading edge creating a temporal phase between the α measurements and surface pressure data.

Three alternative methods for determining angle of attack were developed that were not subject to the limitations of the flow angle sensors. The first two methods were similar to the approaches used to estimate local dynamic pressure. First, the analytic model based on turbine and inflow geometry was extended to produce angle of attack estimates. Second, the dynamic pressure calculated from the blade stagnation point pressure was used to estimate the local angle of attack. The third method infers the angle of attack by comparing upper and lower surface pressure distributions to those measured in the Colorado State University wind tunnel on a stationary blade.

Analytic Model

The analytic model used for the determination of local angle of attack was an extension of that used for predicting dynamic pressure. The tower shadow model, axial induction factors, and the formulation of the local velocity components is identical to that of (2)-(6). The local angle of attack is determined by the velocity component normal to the rotor disk, V_n, the component tangent to rotor rotation, V_t, and the geometric blade pitch angle, β:

$$\alpha = \tan^{-1}\left(\frac{V_n}{V_t}\right) - \beta \qquad (11)$$

Stagnation Point Normalization

This method combines the geometric model developed earlier with the dynamic pressure calculated at the blade stagnation point. The instantaneous dynamic pressure is determined from the stagnation point using (10). The local inflow velocity, V_W, can then be calculated from this value for q through the following relationship:

$$q = \tfrac{1}{2}\rho\left(V_n^2 + V_t^2 + V_s^2\right) \qquad (12)$$

where:

$$V_n = V_w \cos\gamma$$
$$V_t = r\omega - V_w \sin\gamma \cos\psi$$
$$V_s = -V_w \sin\gamma \sin\psi$$

The values for dynamic pressure, air density, rotational velocity, azimuth angle, and yaw are all known.

Equation (12) was iteritively solved for V_W using a root finder. Once the local inflow velocity was known, the angle of attack was calculated in a manner identical to that of the analytic model:

$$\alpha = \tan^{-1}\left(\frac{V_n}{V_t}\right) - \beta \qquad (13$$

where:

$$V_n = V_w \cos\gamma$$
$$V_t = r\omega - V_w \sin\gamma \cos\psi$$

Since V_W was found directly, no induced velocity estimates, skewed wake effects, or tower shadow models were introduced into the calculations.

Pressure Profile Comparison

The final method involved comparing static, wind tunnel pressure profiles at various angles of attack to profiles obtained from the rotating blade. The implicit assumptions were that an airfoil operating in a particular flow environment at a given angle of attack would display a single, repeatable pressure distribution and that the rotating blades behaved as two-dimensional airfoil sections.

During the development of the S809 airfoil used on the Combined Experiment turbine, extensive wind tunnel tests were performed to characterize airfoil performance. An identical airfoil to the blades used in the field was tested in Colorado State University's Environmental Wind Tunnel at 35 different angles of attack ranging from -2.23° to 90°. Angle of attack was incremented by roughly 2° from -2.23° to 8°, 1° from 8° to 18°, 2° from 18° to 30°, and 5° from 30° to 90° (Butterfield et al., 1992). At each angle the surface pressure was measured by 32 pressure taps distributed over both the upper and lower surface of the airfoil at the same points used for the Combined Experiment. Composite plots of the upper and lower surface pressure distributions from these tests are shown in Figures 16 and 17.

To determine angle of attack, an instantaneous pressure distribution from the rotating data was then compared to the wind tunnel profiles using Pearson's correlation method. The angle of attack corresponding to the wind tunnel profile correlating most highly with the rotating profile was assigned to the rotating data at that point in time. Using this approach, the instantaneous angle of attack was established through the blade rotational cycle at each instant in time. Correlations were typically on the order of $r \geq 0.9$.

Comparison of Angle of Attack Results

Using the test data from Table 1, angle of attack results obtained from these methods are co-plotted with the corresponding measured flag sensor data in Figures 18-26. The resonance in the measured angle of attack from the flag sensor is clearly evident, especially during episodes involving rapid α changes.

Measured angle of attack data at 47% span is not shown for a majority of the cases due to instrumentation error in the original test. Only a limited number of data tapes contain angle of attack measured correctly at all span locations. Erroneous measurements were eliminated from Figures 18, 21-26 to avoid confusion.

Larger variations exist between the different techniques than in the dynamic pressure comparisons, especially at lower wind velocities. The analytic model appears to more closely approximate the measured α than does the stagnation pressure normalization technique for the 7 m/s and 10 m/s cases. As with the dynamic pressure data, the major difference between the various techniques is the failure to adequately predict α during the tower shadow.

The 7 m/s, -10° case shown in Figure 18 illustrates a problem with the stagnation pressure normalization technique. At 80% span the angle of attack calculated from this technique remains constant at -12° from approximately 0°-20° azimuth. There is no inflow velocity that can satisfy the required relationship since the dynamic pressure due to rotational velocity is greater than the calculated dynamic pressure. When this occurs, the computational routine defaults to using the wind velocity at the previous point. This problem most often occurs in the tower shadow where the dynamic pressure drops suddenly. However, it can occur in

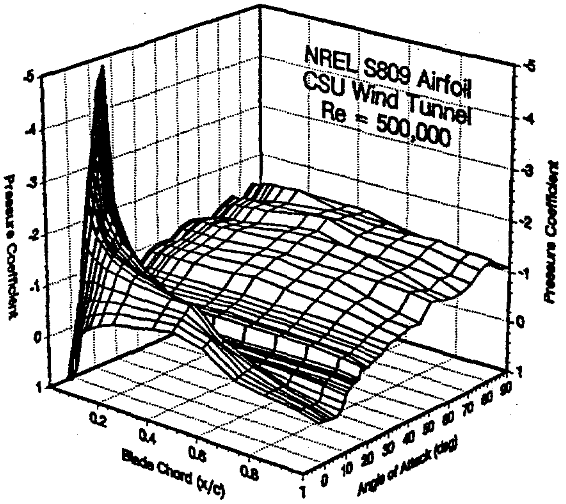

FIGURE 16: COMPOSITE GRAPH OF THE NREL S809 UPPER SURFACE PRESSURE DISTRIBUTIONS MEASURED FROM -2° - 90° ANGLE OF ATTACK IN THE COLORADO STATE UNIVERSITY ENVIRONMENTAL WIND TUNNEL.

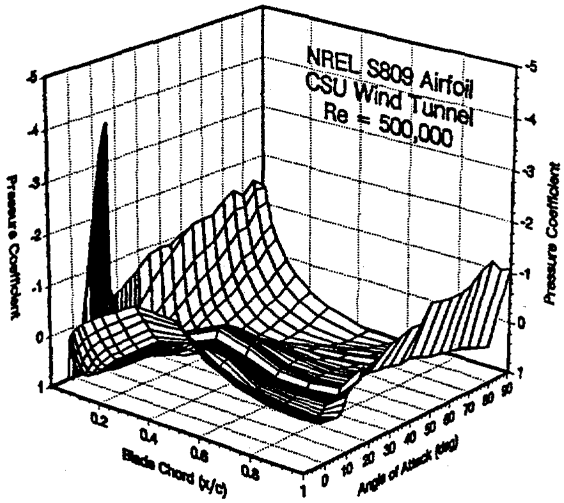

FIGURE 17: COMPOSITE GRAPH OF THE NREL S809 LOWER SURFACE PRESSURE DISTRIBUTIONS MEASURED FROM -2° - 90° ANGLE OF ATTACK IN THE COLORADO STATE UNIVERSITY ENVIRONMENTAL WIND TUNNEL.

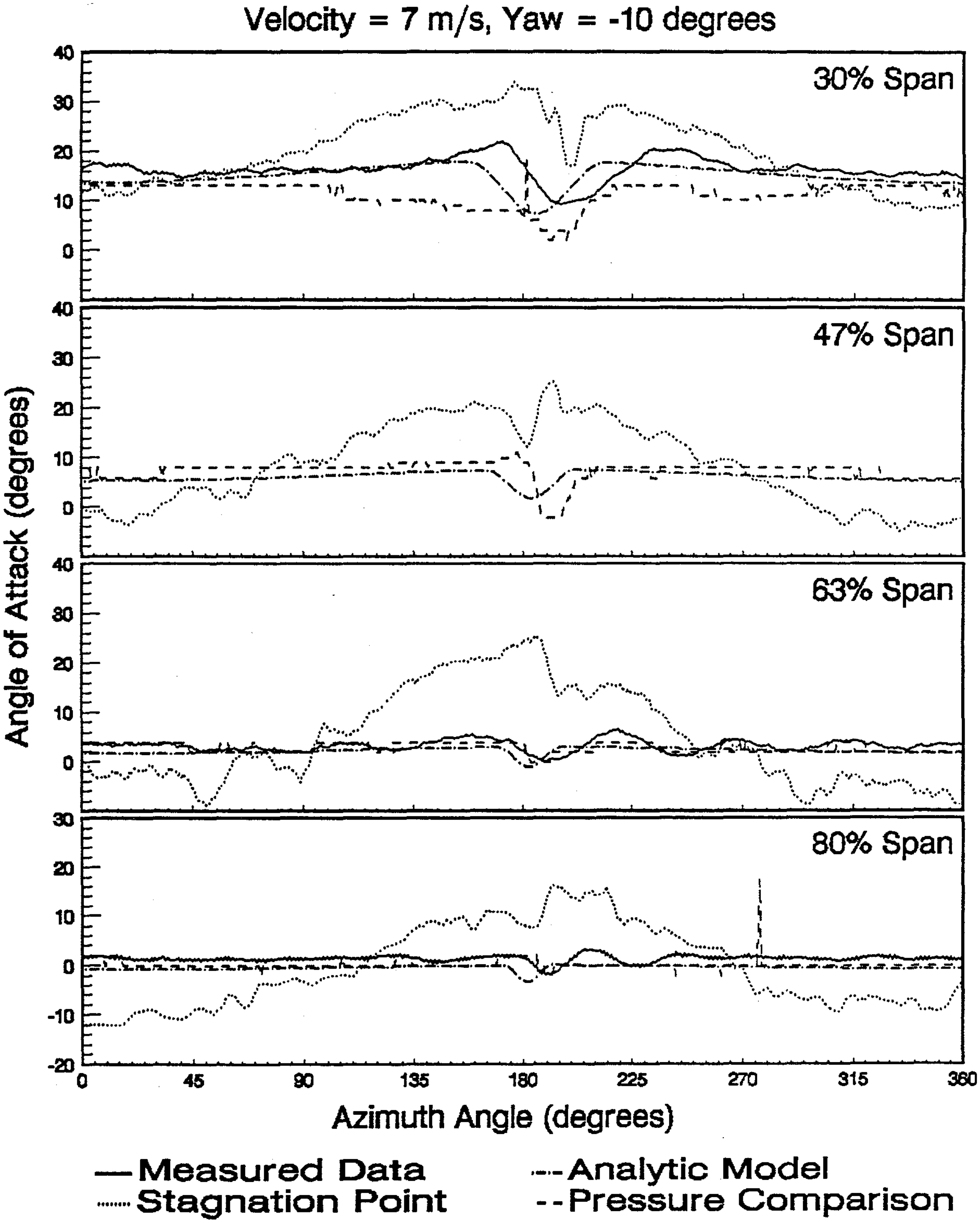

FIGURE 18: COMPARISON OF ANGLE OF ATTACK CALCULATED USING THE ANALYTIC MODEL, THE STAGNATION POINT NORMALIZATION TECHNIQUE, AND THE PRESSURE PROFILE COMPARISON METHOD TO MEASURED DATA AT A VELOCITY OF 7 M/S AND A YAW OF -10°.

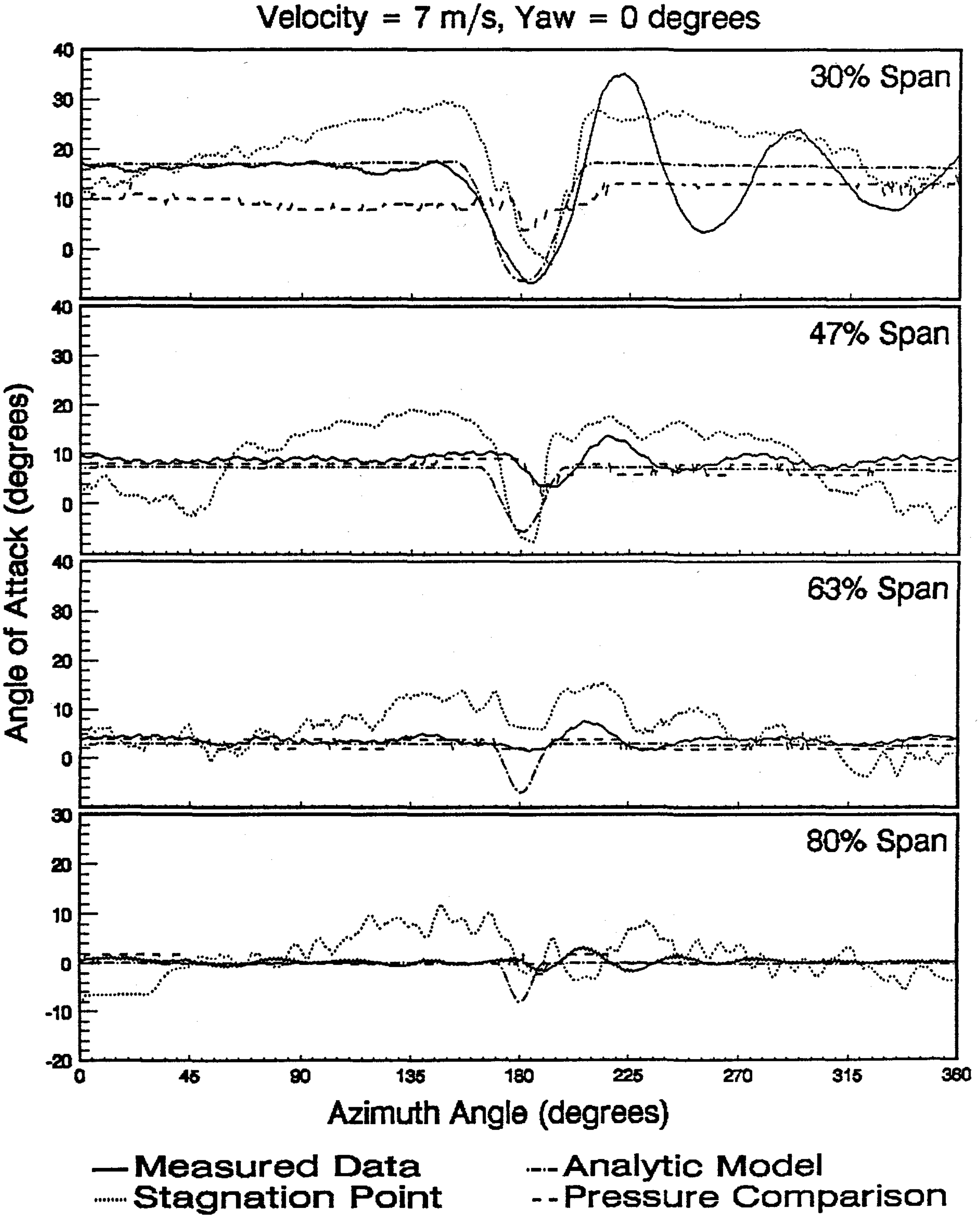

FIGURE 19: COMPARISON OF ANGLE OF ATTACK CALCULATED USING THE ANALYTIC MODEL, THE STAGNATION POINT NORMALIZATION TECHNIQUE, AND THE PRESSURE PROFILE COMPARISON METHOD TO MEASURED DATA AT A VELOCITY OF 7 M/S AND A YAW OF 0°.

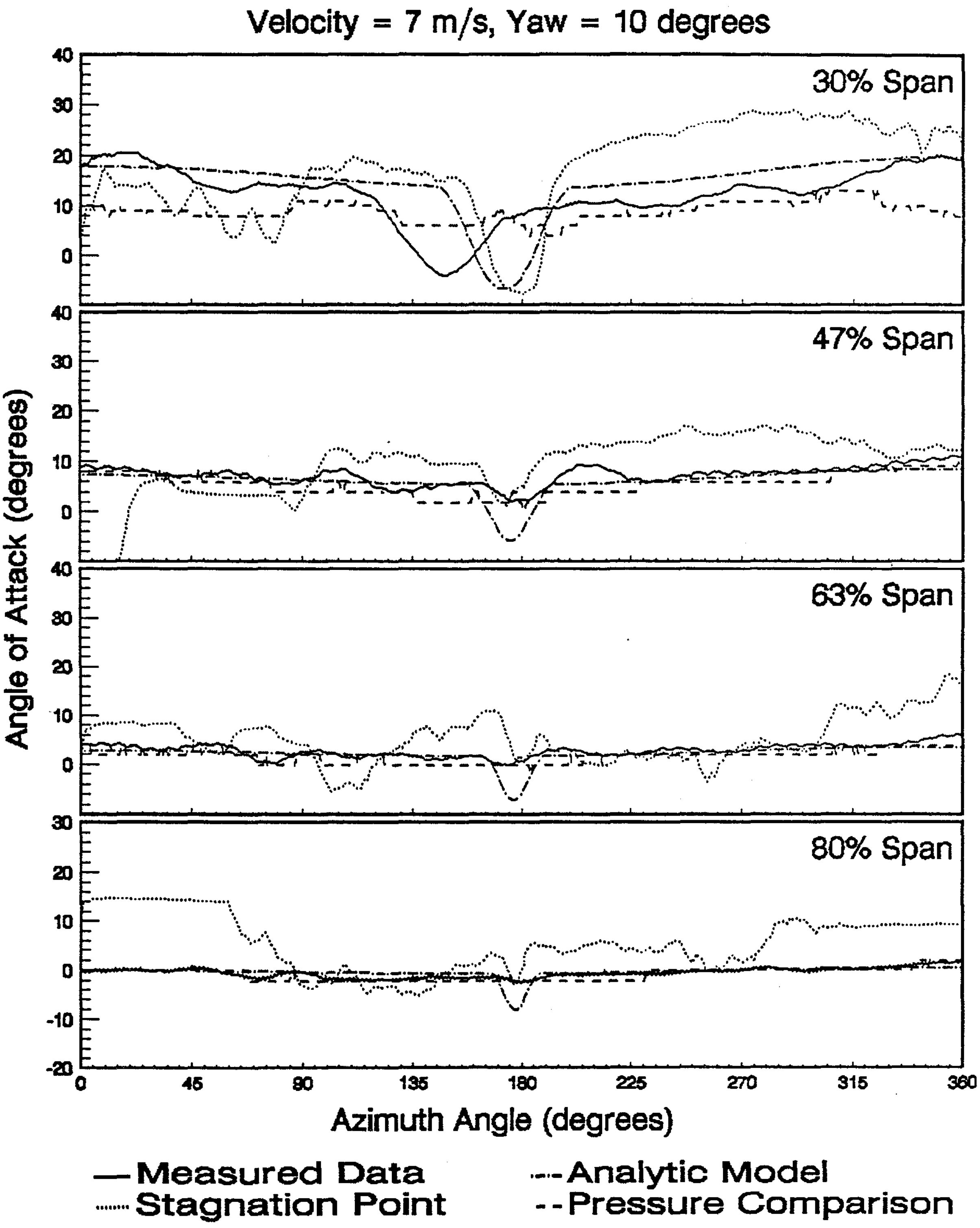

FIGURE 20: COMPARISON OF ANGLE OF ATTACK CALCULATED USING THE ANALYTIC MODEL, THE STAGNATION POINT NORMALIZATION TECHNIQUE, AND THE PRESSURE PROFILE COMPARISON METHOD TO MEASURED DATA AT A VELOCITY OF 7 M/S AND A YAW OF 10°.

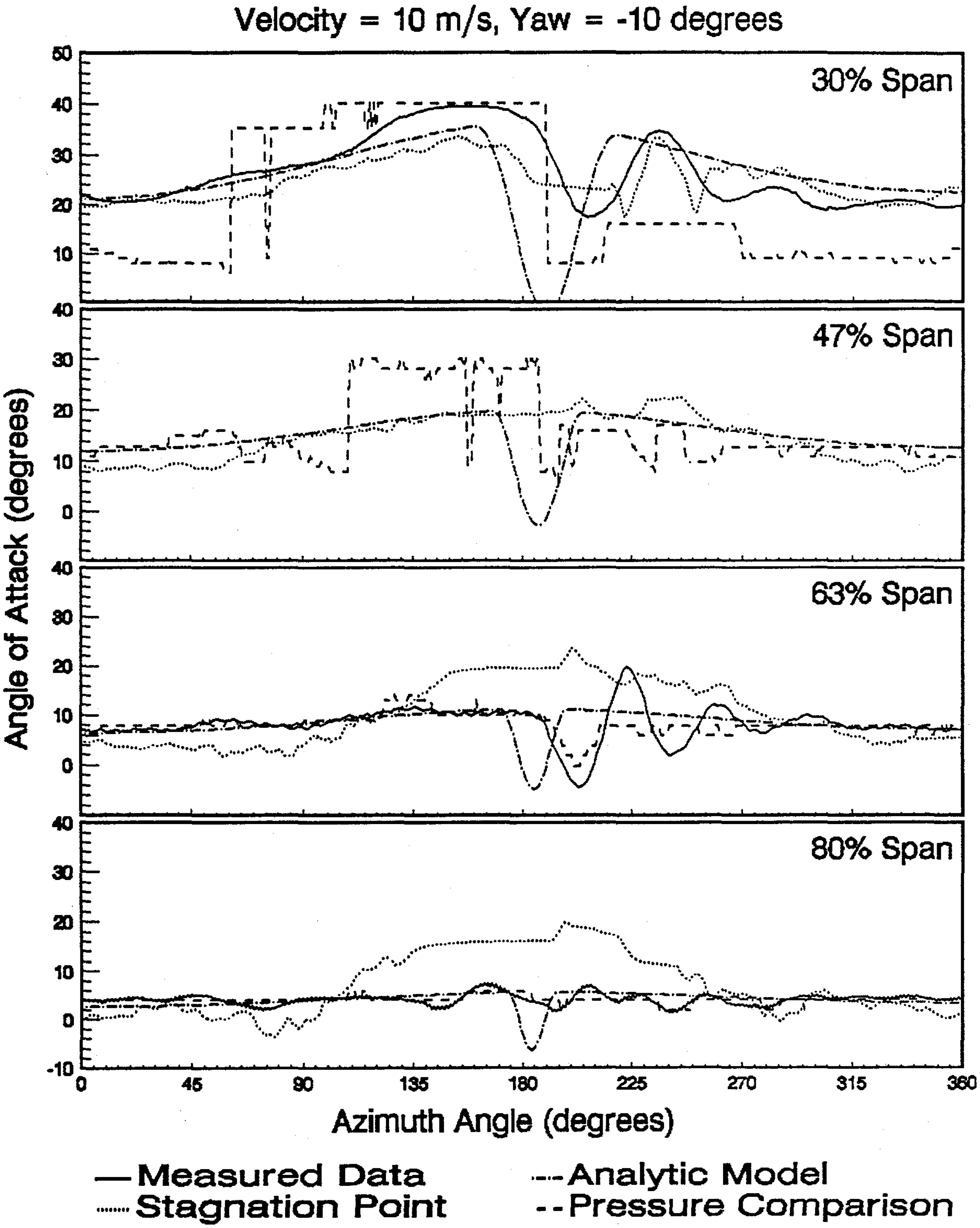

FIGURE 21: COMPARISON OF ANGLE OF ATTACK CALCULATED USING THE ANALYTIC MODEL, THE STAGNATION POINT NORMALIZATION TECHNIQUE, AND THE PRESSURE PROFILE COMPARISON METHOD TO MEASURED DATA AT A VELOCITY OF 10 M/S AND A YAW OF -10°.

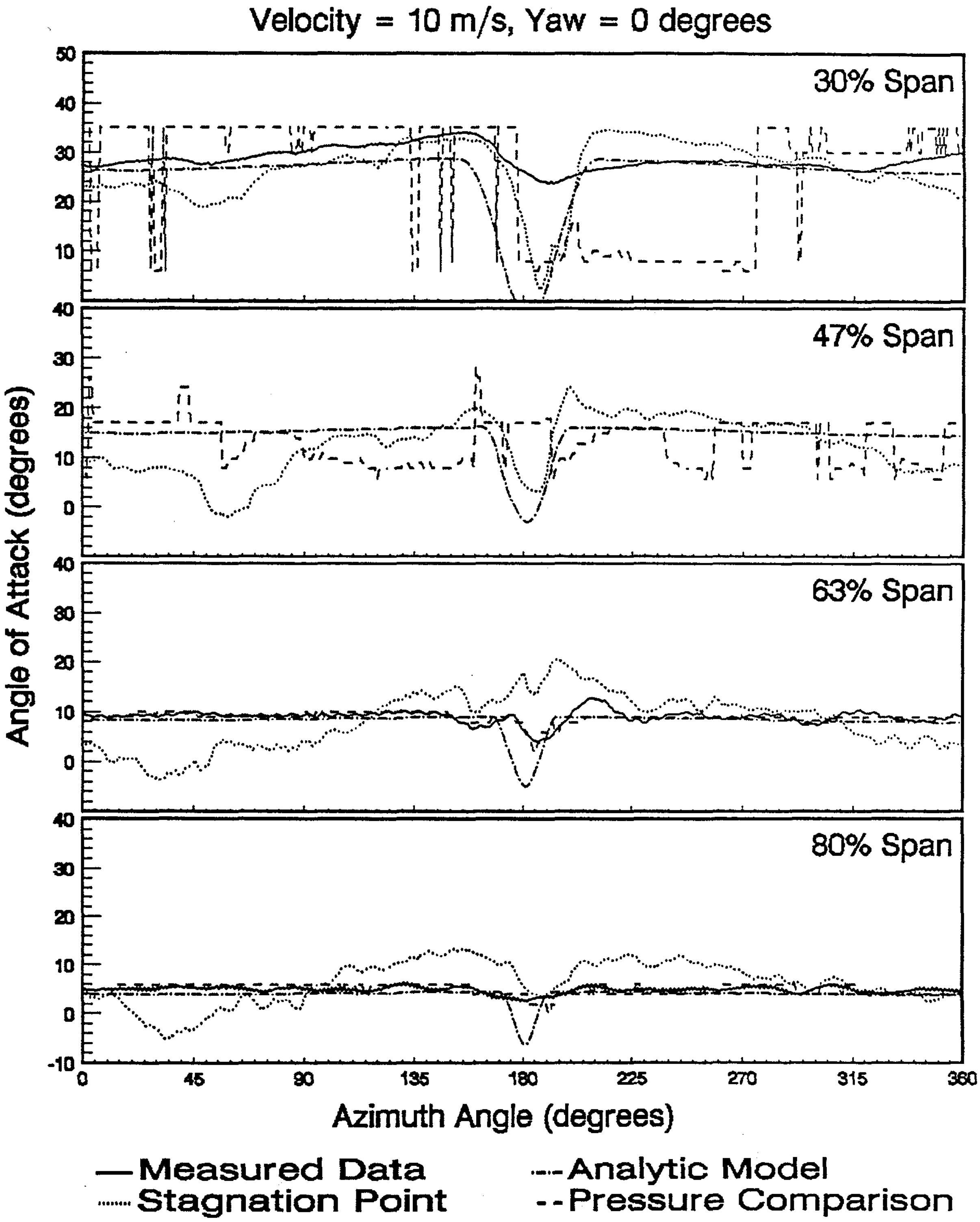

FIGURE 22: COMPARISON OF ANGLE OF ATTACK CALCULATED USING THE ANALYTIC MODEL, THE STAGNATION POINT NORMALIZATION TECHNIQUE, AND THE PRESSURE PROFILE COMPARISON METHOD TO MEASURED DATA AT A VELOCITY OF 10 M/S AND A YAW OF 0°.

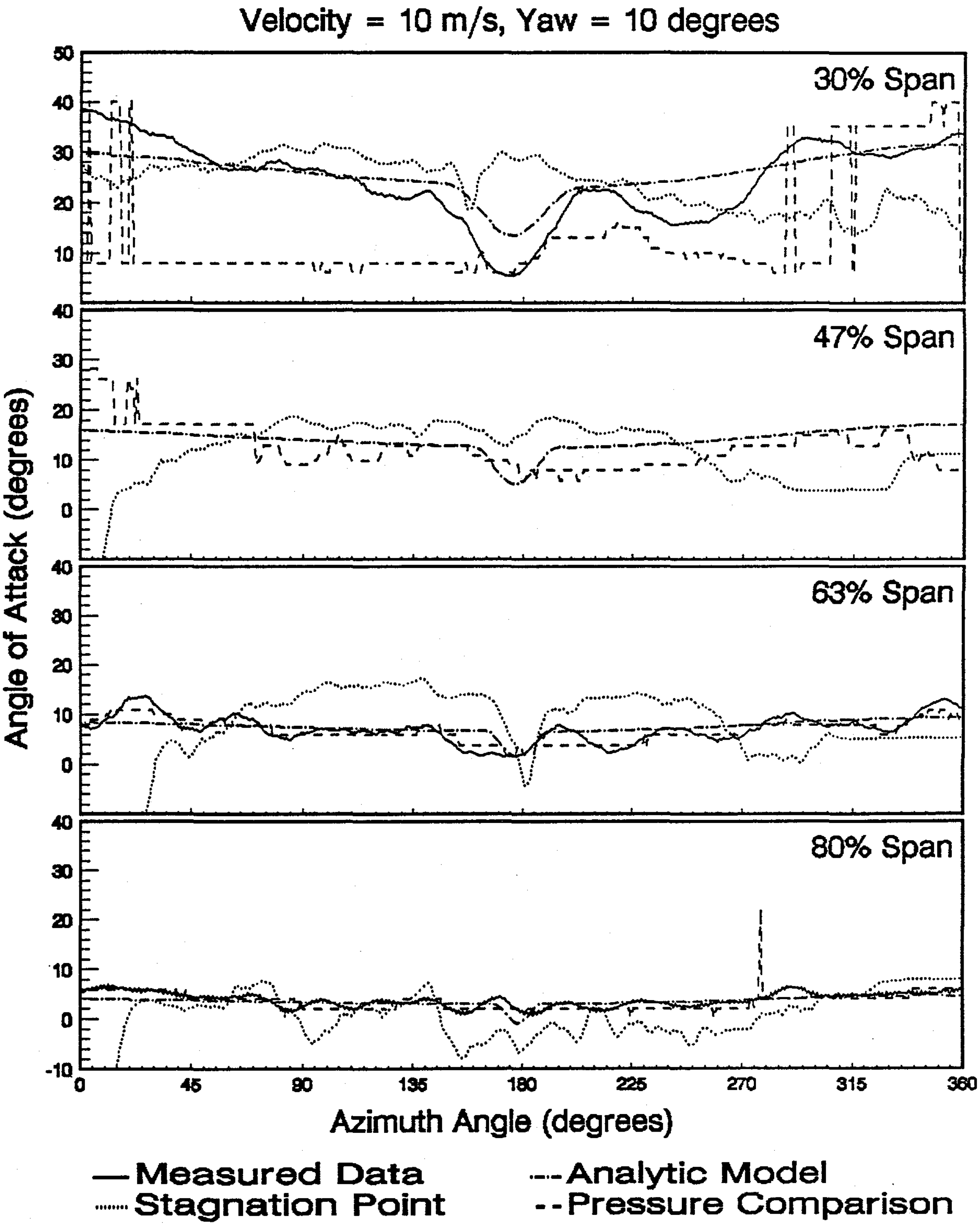

FIGURE 23: COMPARISON OF ANGLE OF ATTACK CALCULATED USING THE ANALYTIC MODEL, THE STAGNATION POINT NORMALIZATION TECHNIQUE, AND THE PRESSURE PROFILE COMPARISON METHOD TO MEASURED DATA AT A VELOCITY OF 10 M/S AND A YAW OF 10°.

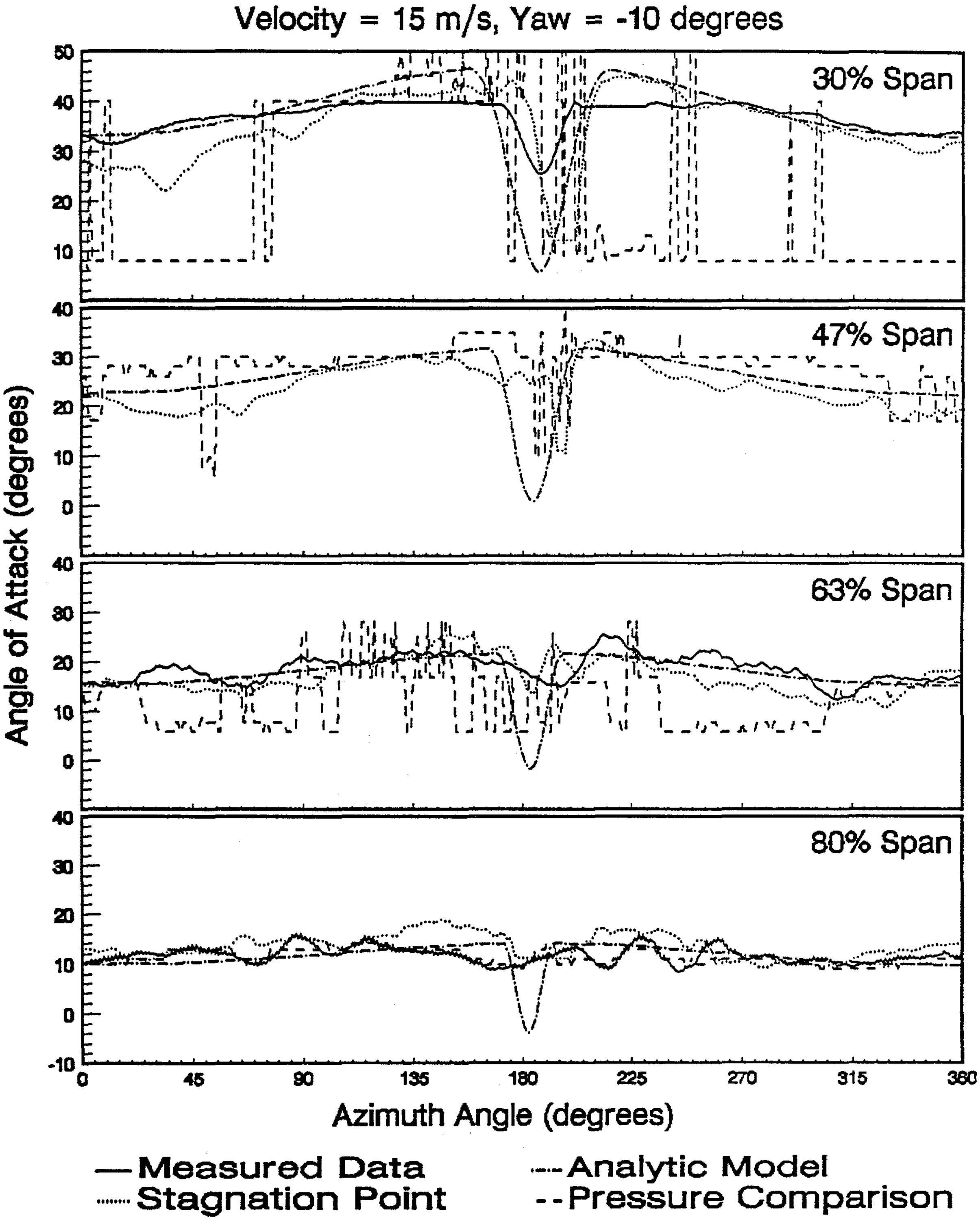

FIGURE 24: COMPARISON OF ANGLE OF ATTACK CALCULATED USING THE ANALYTIC MODEL, THE STAGNATION POINT NORMALIZATION TECHNIQUE, AND THE PRESSURE PROFILE COMPARISON METHOD TO MEASURED DATA AT A VELOCITY OF 15 M/S AND A YAW OF -10°.

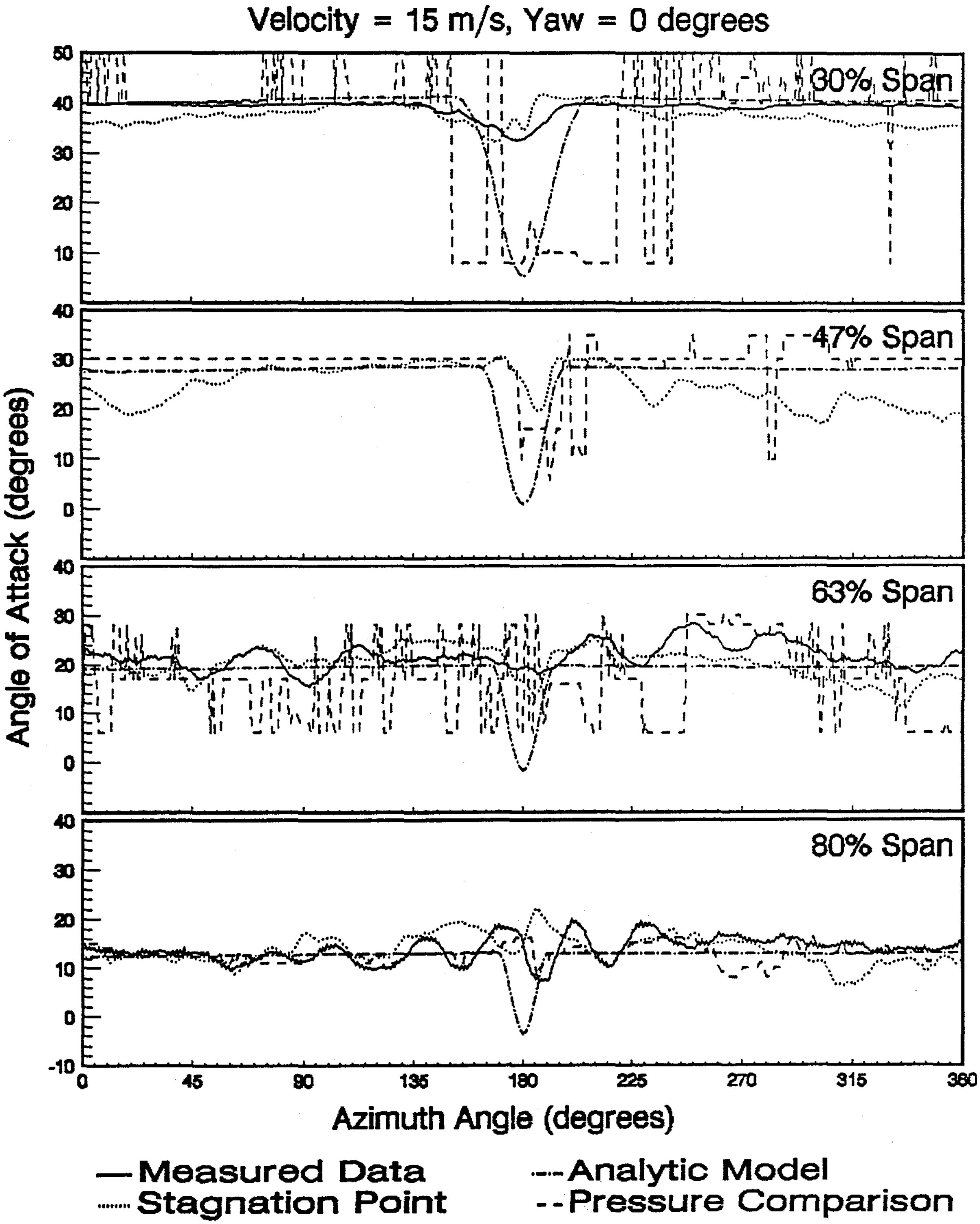

FIGURE 25: COMPARISON OF ANGLE OF ATTACK CALCULATED USING THE ANALYTIC MODEL, THE STAGNATION POINT NORMALIZATION TECHNIQUE, AND THE PRESSURE PROFILE COMPARISON METHOD TO MEASURED DATA AT A VELOCITY OF 15 M/S AND A YAW OF 0°.

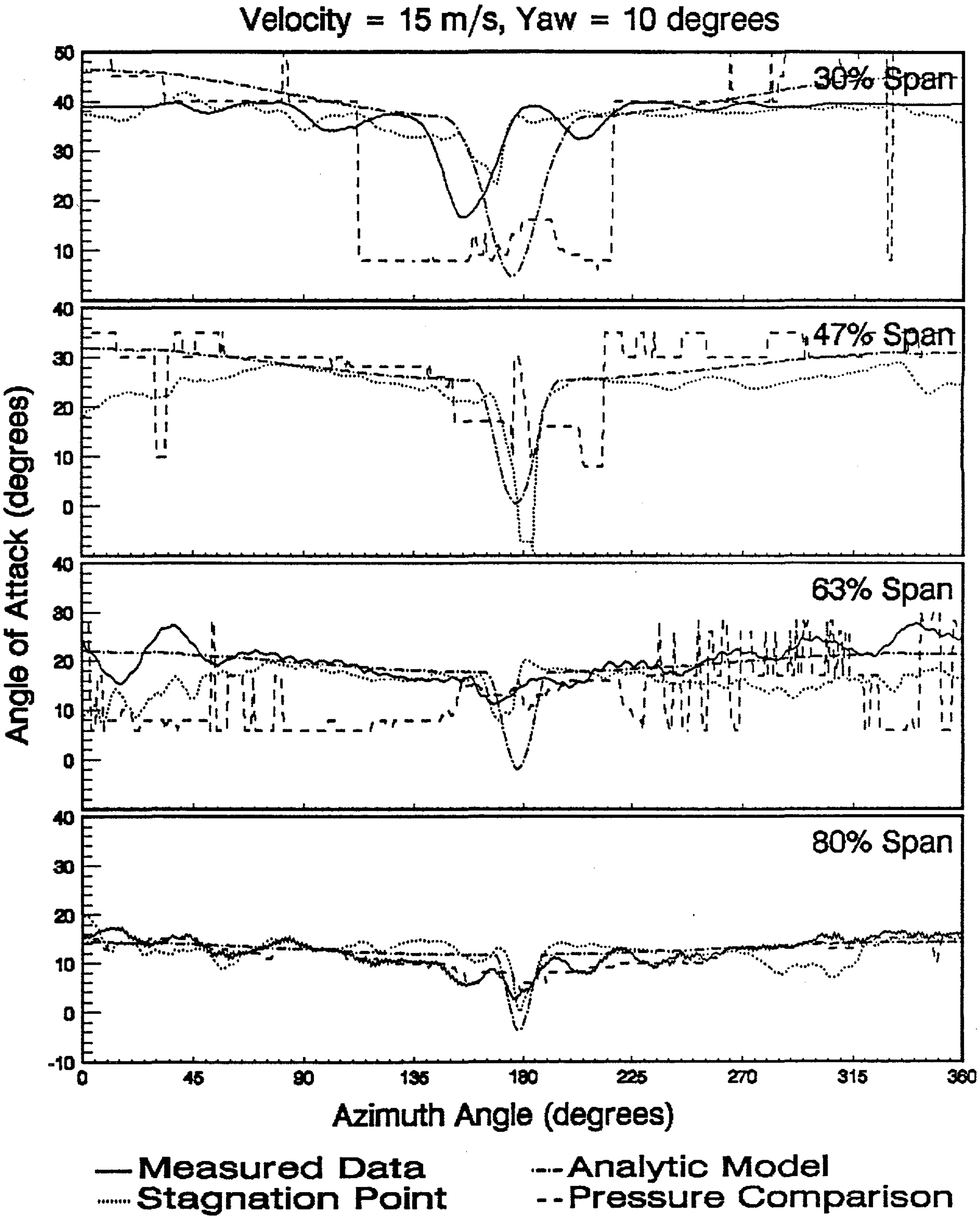

FIGURE 26: COMPARISON OF ANGLE OF ATTACK CALCULATED USING THE ANALYTIC MODEL, THE STAGNATION POINT NORMALIZATION TECHNIQUE, AND THE PRESSURE PROFILE COMPARISON METHOD TO MEASURED DATA AT A VELOCITY OF 15 M/S AND A YAW OF 10°.

other azimuthal regions, as shown in this example. One possible explanation for this effect is that the static pressure field in these regions is less than that measured by the reference static pressure transducer located at the hub.

The pressure profile comparison technique suffers from two problems. First, abrupt changes in angle of attack are evident in the pressure profile comparison data. This is due to the coarse angle of attack resolution of the wind tunnel tests. Second, the technique breaks down at angles of attack greater than the static stall angle (~ 18 degrees). Evidence of this breakdown is seen in Figures 21-26 at inboard stations where the angle calculated from this technique rapidly shifts between values of approximately 8° to 35° or 40°.

Figure 27 shows a representative pressure distribution from the 30% station at an azimuth angle of 90° for the 10 m/s - 0 degree case. Co-plotted with this data is a pressure distribution from the CSU wind tunnel tests at approximately the angle of attack indicated by the other methods (α = 30°). Comparing the two distributions and the wind tunnel pressure data from Figures 16 and 17, it is clear that the profile from the rotating turbine is unlike any measured in the wind tunnel. Thus, the founding assumption of two-dimensional behavior is not valid.

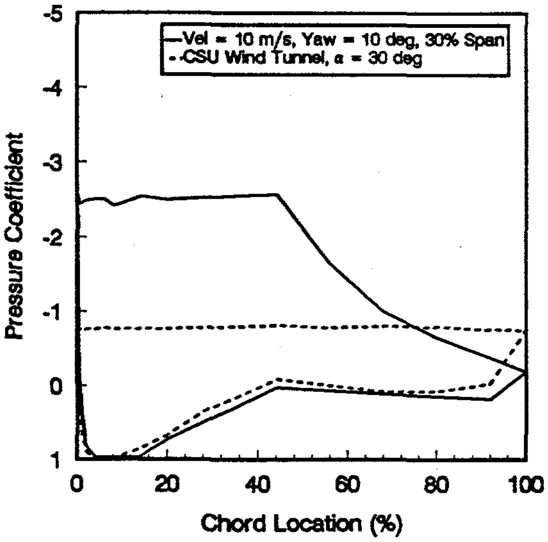

FIGURE 27: COMPARISON BETWEEN A PRESSURE DISTRIBUTION MEASURED AT 30% SPAN AT AN ANGLE OF ATTACK OF 35° TO ONE MEASURED IN THE WIND TUNNEL AT THE SAME ANGLE OF ATTACK.

Under field conditions at the 30% span location, a high suction plateau is often observed on the upper surface. This plateau persists until angles of approximately α = 35° are reached. At still higher angles the pressure distributions again closely resemble those measured in the wind tunnel. This indicates the flow environment inboard is likely much different than that of the wind tunnel, possibly containing a strong three dimensional component.

CONCLUSIONS

Utilizing independent approaches, two techniques have been developed for the indirect determination of local dynamic pressure along with three techniques for local angle of attack. These different approaches yield similar results over a majority of the test cases and are corroborated by measured data.

The stagnation pressure normalization technique provides an excellent estimation of dynamic pressure. It consistently predicts the local q without introducing a phase lag or magnitude difference into the data. It is also simpler and requires fewer assumptions than the analytic model. This technique is best suited for research wind turbines that are typically instrumented to provide surface pressure data. However, the analytic model is much more adaptable for design purposes where geometry and inflow are assumed.

The predictive capability of the stagnation pressure normalization technique is less certain for angle of attack. Over the majority of the test cases, the α derived from purely analytic considerations of geometry and inflow more closely matches the measured data (neglecting signal resonance). For the present, the analytic model seems to provide the best estimate of local angle of attack, although it does not consistently predict the instantaneous angle of attack within the tower shadow. The analytic model is also easily adopted into aerodynamic and structural modeling codes in which the local angle of attack is used to predict turbine performance.

The pressure profile comparison technique is not extremely useful for predicting instantaneous angle of attack, at least for this turbine. The radically different flow environment experienced at inboard stations and the need for a large number of wind tunnel tests to be performed limit its usefulness. However, at outboard span locations and low velocities it could be used as a corroborative check for other angle of attack determination schemes. In addition, the technique could be used as a tool for examining the conditions under which the turbine flow environment deviates from quasi-steady two-dimensional flow.

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Butterfield, C.P., W.P. Musial, and D.A. Simms, 1992, *Combined Experiment Phase 1: Final Report*, NREL/TP-257-4655, National Renewable Energy Laboratory, Golden, CO.

Hansen, A. and C. Xudong, 1989, *Yaw Dynamics of Horizontal Axis Wind Turbines*, SERI/STR-217-3476, Solar Energy Research Institute, Golden, CO.

Huyer, S.A. 1993, *Examination of Forced Unsteady Separated Flow Fields on a Rotating Wind Turbine Blade*, NREL/TP-442-4864, National Renewable Energy Laboratory, Golden, CO.

Wilson, R.E., P.B. Lissaman, and S.N. Walker, 1976, Aerodynamic Performance of Wind Turbines: Final Report, ERDA/NSF/04014-76/1, Department of Mechanical Engineering, Corvallis, OR.

APPENDIX

This appendix contains the source code developed to implement the various techniques for calculating dynamic pressure and angle of attack discussed in the paper. They were included to complete the documentation of the methods presented in this report. These programs were developed for research purposes and are constantly being updated and changed. Current copies of the codes can be obtained by contacting Dave Simms of the National Renewable Energy Laboratory's Wind Technology Division. All of the programs were written in FORTRAN 77 on a SUN SPARCstation SLC and a SUN SPARCstation 10. Compatibility with other machines and operating systems is not guaranteed. The programs contained in the appendix and the technique with which each is associated is listed below.

Dynamic Pressure:		
qaz.f	-	analytic model
qstag.f	-	stagnation point normalization technique
Angle of Attack:		
aaz.f	-	analytic model
q2aoa.f	-	stagnation point normalization technique
aoacor.f	-	pressure profile comparison method

```
       program qaz

****************************************************************************
*****  THIS PROGRAM IMPLEMENTS THE ANALYTIC MODEL FOR DYNAMIC PRESSURE *****
*****  DETAILED IN THE PAPER "TECHNIQUES FOR THE DETERMINATION OF      *****
*****  LOCAL DYNAMIC PRESSURE AND ANGLE OF ATTACK ON A HORIZONTAL AXIS *****
*****  WIND TURBINE"                                                   *****
*****                                                                  *****
*****  THIS PROGRAM COMPUTES A VALUE FOR THE LOCAL DYNAMIC PRESSURE    *****
*****  BASED UPON THE GEOMETRY OF THE TURBINE RELATIVE TO THE INFLOW.  *****
*****  THE MODEL INCORPORATES INDUCED VELOCITIES PREDICTED FOR THE     *****
*****  COMBINED EXPERIMENT ROTOR BY THE PROP CODE, A SKEWED WAKE       *****
*****  EFFECT AND A TOWER SHADOW MODEL.  THE INPUT FILE IS ASSUMED TO  *****
*****  BE AN ASCII DATA FILE CONSISTING ONLY OF INSTANTANEOUS VALUES   *****
*****  FOR THE INFLOW CONDITIONS IN THE FORMAT GIVEN BELOW.            *****
*****                                                                  *****
*****  WRITTEN BY DEREK SHIPLEY (AS MODIFIED FROM STEVE HUYER)         *****
****************************************************************************

****************************************************************************
*****  INPUT FILE FORMAT:                                              *****
*****    COLUMN 1 - AZIMUTH ANGLE                                      *****
*****    COLUMN 2 - WIND VELOCITY                                      *****
*****    COLUMN 3 - TURBINE YAW ANGLE                                  *****
*****    COLUMN 4 - HUB HEIGHT WIND DIRECTION                          *****
*****    COLUMN 5 - BI_VANE WIND DIRECTION #1                          *****
*****    COLUMN 6 - BI_VANE WIND DIRECTION #2                          *****
****************************************************************************

****************************************************************************
*****  OUTPUT FILE FORMAT:                                             *****
*****    COLUMN 1 - AZIMUTH ANGLE                                      *****
*****    COLUMN 2 - DYNAMIC PRESSURE AT 30% SPAN                       *****
*****    COLUMN 3 - DYNAMIC PRESSURE AT 47% SPAN                       *****
*****    COLUMN 4 - DYNAMIC PRESSURE AT 63% SPAN                       *****
*****    COLUMN 5 - DYNAMIC PRESSURE AT 80% SPAN                       *****
****************************************************************************

****************************************************************************
*****  VARIABLE DEFINITIONS:                                           *****
*****    az             AZIMUTH ANGLE                                  *****
*****    a??            AXIAL INDUCED VELOCITY WITH SKEWED WAKE EFFECT *****
*****    ao??           AXIAL INDUCED VELOCITY                         *****
*****    azrad          AZIMUTH ANGLE                                  *****
*****    betarad        BLADE PITCH ANGLE                              *****
*****    dia            TOWER DIAMETER                                 *****
*****    gamma          YAW (DEG)                                      *****
*****    gamrad         YAW (RAD)                                      *****
*****    indata()       INFLOW DATA READ FROM INPUT FILE               *****
*****    infil          INPUT FILE NAME                                *****
*****    omega          ROTATIONAL FREQUENCY                           *****
*****    q()            DYNAMIC PRESSURE AT ALL SPAN LOCATIONS         *****
*****    r              RADIUS OF TURBINE ROTOR                        *****
*****    rho            AIR DENSITY                                    *****
*****    sw??           SKEWED WAKE EFFECT                             *****
*****    tmn??          AZIMUTH ANGLE BLADE ENTERS TOWER SHADOW        *****
*****    tmx??          AZIMUTH ANGLE BLADE LEAVES TOWER SHADOW        *****
*****    towdef         MAX TOWER SHADOW VELOCITY DEFICIT              *****
*****    tsw            TOWER SHADOW WIDTH                             *****
*****    vinf           INFLOW VELOCITY                                *****
```

```
*****    v??c           VELOCITY CROSSFLOW COMPONENT                    *****
*****    v??n           VELOCITY COMPONENT NORMAL TO ROTOR              *****
*****    v??s           VELOCITY COMPONENT IN SPANWISE DIRECTION        *****
*****    v??t           VELOCITY COMPONENT TANGENT TO BLADE             *****
*****    v??tow         INSTANTANEOUS TOWER SHADOW VELOCITY DEFICIT     *****
*****************************************************************************

*****  VARIABLE DECLARATIONS   *****
       real q(4), indata(6)
       character infil*30, outfil*30

*****  SET CONSTANTS   *****
       pi = 4.0*atan(1.0)
       dia = 0.406
       rho = 0.0019
       r = 5.05
       omega = 2.0*pi*1.2
       betarad = 12.0*pi/180.
       towdef = 0.30

*****  DISPLAY A CHEERFUL MESSAGE TO THE USER ON THE SCREEN   *****
       print*
       print*
       print*,'***********************************************************'
       print*,'*****   Welcome to QAZ - the dynamic pressure model   *****'
       print*,'***********************************************************'
       print*

*****  PROMPT USER FOR INPUT FILE NAME AND OPEN FILE   ****
10     print*
       write (6,1)
1      format ('Enter the name of the file containing inflow data:  ',$)
       read*, infil
       open (unit=12,file=infil,iostat=inerr,status='old')
       if (inerr.ne.0) then
         print*,'Data file does not exist, please try again.'
         print*
         goto 10
       endif

*****  PROMPT USER FOR OUTPUT FILE NAME AND OPEN FILE   *****
       print*
       write (6,2)
2      format ('Enter the desired name for the output file:  ',$)
       read*, outfil
       open (unit=11, file=outfil,status='unknown')


*********************************************************************
*****  BEGIN LOOP TO READ INSTANTANEOUS INFLOW VALUES AND      *****
*****  CALCULATE THE DYNAMIC PRESSURE AT EACH SPAN LOCATION    *****
*********************************************************************

*****  READ INFLOW DATA FROM INPUT FILE FOR ONE INSTANT IN TIME  *****
15     read(12,*,end=11), (indata(j),j=1,6)
       az = indata(1)
       azrad = az*pi/180.
       vinf = indata(2)
       gamma = indata(3)-(indata(4)+indata(5)+indata(6))/3.
       gamrad = gamma*pi/180.
```

```
*************************************************************************
*****   set up parameters to calculate tower shadow velocity defecit   *****
*************************************************************************

*****   DEFINE CONSTANTS   *****
        tsw = (2.5*dia)/cos(gamrad)
        x = 0.5*(tsw + 0.457)
        twd = 0.9*tan(gamrad)

*****       30% SPAN    *****
        th30 = asin(x/(0.3*r))
        thd30 = asin(twd/(0.3*r))
        tmn30 = pi-th30-thd30
        tmx30 = pi+th30-thd30

*****       47% SPAN    *****
        th47 = asin(x/(0.466*r))
        thd47 = asin(twd/(0.466*r))
        tmn47 = pi-th47-thd47
        tmx47 = pi+th47-thd47

*****       63% SPAN    *****
        th63 = asin(x/(0.633*r))
        thd63 = asin(twd/(0.633*r))
        tmn63 = pi-th63-thd63
        tmx63 = pi+th63-thd63

*****       80% SPAN    *****
        th80 = asin(x/(0.82*r))
        thd80 = asin(twd/(0.82*r))
        tmn80 = pi-th80-thd80
        tmx80 = pi+th80-thd80


*************************************************
*****   CALCULATE DYNAMIC PRESSURE AT 30% SPAN   *****
*************************************************

*****   CALCULATE 30% TOWER SHADOW DEFICIT (ZERO IF NOT WITHIN SHADOW)  *****
        if (azrad.ge.tmn30 .and. azrad.le.tmx30) then
          v30tow = 0.5*towdef*vinf*(1.-cos(2.*pi*(azrad-tmn30)/(2.*th30)))
        else
          v30tow = 0.
        endif
        vtot30 = vinf - v30tow

*****   INCORPORATE PROP INDUCED VELOCITY AT 30% SPAN   *****
        ao30 = 1/(.000360046*vtot30**4-.0206024*vtot30**3+.415013*vtot30**2-
     2  1.32587*vtot30+3.16774)

*****   CALCULATE SKEWED WAKE EFFECT AT 30% SPAN   *****
        sw30 = (1+15*pi/32*sqrt((1-cos(gamrad))/(1+cos(gamrad)))*
     2  .30*sin(azrad))
        a30 = ao30*sw30

*****   CALCULATE 30% SPAN VELOCITY COMPONENTS AND DYNAMIC PRESSURE   *****
        v30n = vtot30*(1-a30)*cos(gamrad)
        v30c = -vtot30*sin(gamrad)
        v30t = (0.30*r*omega)+v30c*cos(azrad)
```

```
      v30s = v30c*sin(azrad)
      q(1) = 0.07475*0.5*rho*(v30n**2+v30t**2+v30s**2)


********************************************
***** CALCULATE DYNAMIC PRESSURE AT 47% SPAN   *****
********************************************

***** CALCULATE 47% TOWER SHADOW DEFICIT (ZERO IF NOT WITHIN SHADOW)  *****
      if (azrad.ge.tmn47 .and. azrad.le.tmx47) then
        v47tow = -0.5*towdef*vinf*(1.-cos(2.*pi*(azrad-tmn47)/(2.*th47)))
      else
        v47tow = 0.0
      endif
      vtot47 = vinf+v47tow

***** INCORPORATE PROP INDUCED VELOCITY AT 47% SPAN  *****
      ao47 = 1/(.000653402*vtot47**4-.0426646*vtot47**3+1.02377*vtot47**2-
     2 8.33547*vtot47+28.3554)

***** CALCULATE SKEWED WAKE EFFECT AT 47% SPAN   *****
      sw47 = (1+15*pi/32*sqrt((1-cos(gamrad))/(1+cos(gamrad)))*
     2 .466*sin(azrad))
      a47 = ao47*sw47

***** CALCULATE 47% SPAN VELOCITY COMPONENTS AND DYNAMIC PRESSURE  *****
      v47n = vtot47*(1-a47)*cos(gamrad)
      v47c = -vtot47*sin(gamrad)
      v47t = (0.466*r*omega)+v47c*cos(azrad)
      v47s = v47c*sin(azrad)
      q(2) = 0.07475*0.5*rho*(v47n**2+v47t**2+v47s**2)


********************************************
***** CALCULATE DYNAMIC PRESSURE AT 63% SPAN   *****
********************************************

***** CALCULATE 63% TOWER SHADOW DEFICIT (ZERO IF NOT WITHIN SHADOW)  *****
      if (azrad.ge.tmn63 .and. azrad.le.tmx63) then
        v63tow = -0.5*towdef*vinf*(1.-cos(2.*pi*(azrad-tmn63)/(2.*th63)))
      else
        v63tow = 0.0
      endif
      vtot63 = vinf+v63tow

***** INCORPORATE PROP INDUCED VELOCITY AT 63% SPAN  *****
      ao63 = 1/(.000857403*vtot63**4-.0580386*vtot63**3+1.45897*vtot63**2-
     2 14.2769*vtot63+55.6623)

***** CALCULATE SKEWED WAKE EFFECT AT 63% SPAN   *****
      sw63 = (1+15*pi/32*sqrt((1-cos(gamrad))/(1+cos(gamrad)))*
     2 .633*sin(azrad))
      a63 = ao63*sw63

***** CALCULATE 63% SPAN VELOCITY COMPONENTS AND DYNAMIC PRESSURE  *****
      v63n = vtot63*(1-a63)*cos(gamrad)
      v63c = -vtot63*sin(gamrad)
      v63t = (0.633*r*omega)+v63c*cos(azrad)
      v63s = v63c*sin(azrad)
      q(3) = 0.07475*0.5*rho*(v63n**2+v63t**2+v63s**2)
```

```
******************************************************
*****   CALCULATE DYNAMIC PRESSURE AT 80% SPAN   *****
******************************************************

*****   CALCULATE 80% TOWER SHADOW DEFICIT (ZERO IF NOT WITHIN SHADOW)  *****
        if (azrad.ge.tmn80 .and. azrad.le.tmx80) then
          v80tow = -0.5*towdef*vinf*(1.-cos(2.*pi*(azrad-tmn80)/(2.*th80)))
        else
          v80tow = 0.0
        endif
        vtot80 = vinf+v80tow

*****   INCORPORATE PROP INDUCED VELOCITY AT 80% SPAN  *****
        ao80 = 1/(.001142*vtot80**4-.0769829*vtot80**3+1.95194*vtot80**2-
     2  20.8757*vtot80+88.372)

*****   CALCULATE SKEWED WAKE EFFECT AT 80% SPAN  *****
        sw80 = (1+15*pi/32*sqrt((1-cos(gamrad))/(1+cos(gamrad)))*
     2  .82*sin(azrad))
        a80 = ao80*sw80

*****   CALCULATE 80% SPAN VELOCITY COMPONENTS AND DYNAMIC PRESSURE  *****
        v80n = vtot80*(1-a80)*cos(gamrad)
        v80c = -vtot80*sin(gamrad)
        v80t = (0.82*r*omega)+v80c*cos(azrad)
        v80s = v80c*sin(azrad)
        q(4) = 0.07475*0.5*rho*(v80n**2+v80t**2+v80s**2)

*****   WRITE RESULTS TO OUTPUT FILE   *****
        write(11,1000) az,(q(j), j=1,4)

        goto 15
11      continue
        close (unit=11)
        close (unit=12)

1000    format (5f9.3)
        stop
        end
```

```
        program qstag

******************************************************************************
*****   THIS PROGRAM IMPLEMENTS THE STAGNATION POINT NORMALIZATION       *****
*****   TECHNIQUE FOR DYNAMIC PRESSURE DETAILED IN THE PAPER "TECHNIQUES *****
*****   FOR THE DETERMINATION OF LOCAL DYNAMIC PRESSURE AND ANGLE OF     *****
*****   ATTACK ON A HORIZONTAL AXIS WIND TURBINE"                        *****
*****                                                                    *****
*****   THIS PROGRAM DETERMINES THE LOCAL DYNAMIC PRESSURE AT ALL FOUR   *****
*****   SPAN LOCATIONS BASED UPON THE VALUE OF Q REQUIRED TO FORCE THE   *****
*****   PRESSURE PROFILE TO HAVE A STAGNATION POINT WITH A CP = 1.0.     *****
*****   PROGRAM OPERATION REQUIRES TWO INPUT FILES.  ONE CONTAINS THE    *****
*****   LOWER SURFACE PRESSURE DATA NEEDED TO LOCATE THE STAGNATION      *****
*****   POINT. THE SECOND FILE CONTAINS THE CORRESPONDING INFLOW         *****
*****   CONDITIONS.  THE VELOCITY FROM THIS FILE IS NEEDED TO            *****
*****   UN-NORMALIZE THE PRESSURE COEFFICIENTS SO THAT THE MAXIMUM       *****
*****   PRESSURE CAN BE FOUND.  THE FIRST TWO COLUMNS OF THE VELOCITY    *****
*****   FILE ARE THE ONLY ONES ACTUALLY REQUIRED.  THE FILE FORMAT GIVEN *****
*****   CORRESPONDS TO OUR STANDARD INFLOW FILE.  THE INPUT FILES CAN    *****
*****   BE OF ANY LENGTH.                                                *****
*****                                                                    *****
*****   WRITTEN BY DEREK SHIPLEY                                         *****
******************************************************************************

******************************************************************************
*****   PRESSURE INPUT FILE FORMAT:                                      *****
*****     COLUMN 1    - AZIMUTH ANGLE                                    *****
*****     COLUMN 2-13 - 30% LOWER SURFACE PRESSURES (0%-100% chord)      *****
*****     COLUMN 14-25 - 47% LOWER SURFACE PRESSURES (0%-100% chord)     *****
*****     COLUMN 26-37 - 63% LOWER SURFACE PRESSURES (0%-100% chord)     *****
*****     COLUMN 38-49 - 80% LOWER SURFACE PRESSURES (0%-100% chord)     *****
*****                                                                    *****
*****   VELOCITY INPUT FILE FORMAT:                                      *****
*****     COLUMN 1 - AZIMUTH ANGLE                                       *****
*****     COLUMN 2 - WIND VELOCITY                                       *****
*****     COLUMN 3 - TURBINE YAW ANGLE                                   *****
*****     COLUMN 4 - HUB HEIGHT WIND DIRECTION                           *****
*****     COLUMN 5 - BI-VANE WIND DIRECTION #1                           *****
*****     COLUMN 6 - BI-VANE WIND DIRECTION #2                           *****
******************************************************************************

******************************************************************************
*****   OUTPUT FILE FORMAT:                                              *****
*****     COLUMN 1 - AZIMUTH ANGLE                                       *****
*****     COLUMN 2 - DYNAMIC PRESSURE AT 30% SPAN                        *****
*****     COLUMN 3 - DYNAMIC PRESSURE AT 47% SPAN                        *****
*****     COLUMN 4 - DYNAMIC PRESSURE AT 63% SPAN                        *****
*****     COLUMN 5 - DYNAMIC PRESSURE AT 80% SPAN                        *****
******************************************************************************

******************************************************************************
*****   VARIABLE DEFINITIONS:                                            *****
*****     az            AZIMUTH ANGLE                                    *****
*****     lowpress()    LOWER SURFACE PRESSURE COEFFICIENT AT ALL SPANS  *****
*****     omega         ROTATIONAL FREQUENCY                             *****
*****     outfil        NAME OF THE OUTPUT FILE                          *****
*****     pressfil      NAME OF THE LOWER PRESSURE INPUT FILE            *****
*****     qderived??    Q USED TO UN-NORMALIZE CE DATA                   *****
*****     qnorm??       Q THAT WOULD FORCE STAG POINT TO Cp=1.0          *****
*****     r             ROTOR RADIUS                                     *****
```

```
*****    rho            AIR DENSITY                                       *****
*****    siconst        CONST TO SWITCH DENSITY TO SI UNITS               *****
*****    stag??         PRESSURE AT THE STAGNATION POINT                  *****
*****    vel            INSTANTANEOUS VELOCITY                            *****
*****    velfil         NAME OF THE VELOCITY INPUT FILE                   *****
******************************************************************************

*****  VARIABLE DECLARATIONS   *****
       character pressfil*30,outfil*30,velfil*30
       real lowpress(40),az,vel

*****  DEFINE CONSTANTS   *****
       pi = 4.0*atan(1.0)
       omega = 2.0*pi*1.2
       r = 5.05
       siconst = 0.07475
       rho = 0.0019*siconst

*****  PROMPT THE USER FOR THE PRESSURE FILE NAME AND OPEN FILE   *****
100    print*
       write (6,1)
1      format ('Enter the name of the file containing pressure data:  ',$)
       read*, pressfil
       open (unit=11,file=pressfil,iostat=inerr,status='old')
       if (inerr .ne. 0) then
         print*,'File does not exist.  Please try again.'
         goto 100
       endif

*****  PROMPT THE USER FOR THE VELOCITY FILE NAME AND OPEN FILE   *****
200    print*
       write (6,2)
2      format ('Enter the name of the file containing velocity data:  ',$)
       read*, velfil
       open (unit=12,file=velfil,iostat=inerr,status='old')
       if (inerr .ne. 0) then
         print*,'File does not exist.  Please try again.'
         goto 200
       endif

*****  PROMPT THE USER FOR THE NAME OF THE OUTPUT FILE   *****
       print*
       write (6,3)
3      format ('Enter the name of the output file:  ',$)
       read*, outfil
       open (unit=13,file=outfil,status='unknown')

************************************************************************
*****  READ IN ALL DATA FROM PRESSURE AND VELOCITY INPUT FILES   *****
************************************************************************
400    read(11,*,end=450) az,(lowpress(j),j=1,48)
       read(12,*) tmp,vel
*********************************************************************
*****    FIND THE STAGNATION POINT AND ITS Cp FOR ALL SPANS   *****
*********************************************************************
         stag30 = 0.
         stag47 = 0.
         stag63 = 0.
         stag80 = 0.
         do 600,j=1,12
```

```
           if (lowpress(j).gt.stag30) stag30=lowpress(j)
           if (lowpress(j+12).gt.stag47) stag47=lowpress(j+12)
           if (lowpress(j+24).gt.stag63) stag63=lowpress(j+24)
           if (lowpress(j+36).gt.stag80) stag80=lowpress(j+36)
600      continue

************************************************************************
*****  CALCULATE Q NEEDED TO UN-NORMALIZE Cp DATA AT EACH SPAN    *****
************************************************************************
         qderived30=(.5*rho*(vel**2+(omega*.30*r)**2))
         qderived47=(.5*rho*(vel**2+(omega*.47*r)**2))
         qderived63=(.5*rho*(vel**2+(omega*.63*r)**2))
         qderived80=(.5*rho*(vel**2+(omega*.80*r)**2))

**************************************************************************
*****  UN-NORMALIZE THE Cp AT THE STAGNATION POINT.  THIS VALUE IS   *****
*****  THE DYNAMIC PRESSURE THAT WOULD FORCE A NORMALIZATION TO      *****
*****  Cp=1.0 AT THE STAGNATION POINT.                               *****
**************************************************************************
         qnorm30=stag30*qderived30
         qnorm47=stag47*qderived47
         qnorm63=stag63*qderived63
         qnorm80=stag80*qderived80

***********************************************
*****  WRITE RESULTS TO THE OUTPUT FILE   *****
***********************************************
         write(13,*),az,qnorm30,qnorm47,qnorm63,qnorm80

         goto 400
450    continue

       stop
       end
```

```
       program aaz

****************************************************************************
*****  THIS PROGRAM IMPLEMENTS THE ANALYTIC MODEL FOR ANGLE OF ATTACK  *****
*****  DETAILED IN THE PAPER "TECHNIQUES FOR THE DETERMINATION OF      *****
*****  LOCAL DYNAMIC PRESSURE AND ANGLE OF ATTACK ON A HORIZONTAL AXIS *****
*****  WIND TURBINE"                                                   *****
*****                                                                  *****
*****  THIS PROGRAM COMPUTES A VALUE FOR THE LOCAL ANGLE OF ATTACK     *****
*****  BASED UPON THE GEOMETRY OF THE TURBINE RELATIVE TO THE INFLOW.  *****
*****  THE MODEL INCORPORATES INDUCED VELOCITIES PREDICTED FOR THE     *****
*****  COMBINED EXPERIMENT ROTOR BY THE PROP CODE, A SKEWED WAKE       *****
*****  EFFECT AND A TOWER SHADOW MODEL.  THE INPUT FILE IS ASSUMED TO  *****
*****  BE AN ASCII DATA FILE CONSISTING ONLY OF INSTANTANEOUS VALUES   *****
*****  FOR THE INFLOW CONDITIONS IN THE FORMAT GIVEN BELOW.            *****
*****                                                                  *****
*****  WRITTEN BY DEREK SHIPLEY (AS MODIFIED FROM STEVE HUYER)         *****
****************************************************************************

****************************************************************************
*****  INPUT FILE FORMAT:                                              *****
*****    COLUMN 1 - AZIMUTH ANGLE                                      *****
*****    COLUMN 2 - WIND VELOCITY                                      *****
*****    COLUMN 3 - TURBINE YAW ANGLE                                  *****
*****    COLUMN 4 - HUB HEIGHT WIND DIRECTION                          *****
*****    COLUMN 5 - BI_VANE WIND DIRECTION #1                          *****
*****    COLUMN 6 - BI_VANE WIND DIRECTION #2                          *****
****************************************************************************

****************************************************************************
*****  OUTPUT FILE FORMAT:                                             *****
*****    COLUMN 1 - AZIMUTH ANGLE                                      *****
*****    COLUMN 2 - ANGLE OF ATTACK AT 30% SPAN                        *****
*****    COLUMN 3 - ANGLE OF ATTACK AT 47% SPAN                        *****
*****    COLUMN 4 - ANGLE OF ATTACK AT 63% SPAN                        *****
*****    COLUMN 5 - ANGLE OF ATTACK AT 80% SPAN                        *****
****************************************************************************

****************************************************************************
*****  VARIABLE DEFINITIONS:                                           *****
*****    aoa()          ANGLE OF ATTACK AT ALL SPAN LOCATIONS          *****
*****    az             AZIMUTH ANGLE                                  *****
*****    a??            AXIAL INDUCED VELOCITY WITH SKEWED WAKE        *****
*****    ao??           AXIAL INDUCED VELOCITY                         *****
*****    azrad          AZIMUTH ANGLE                                  *****
*****    betarad        BLADE PITCH ANGLE                              *****
*****    dia            TOWER DIAMETER                                 *****
*****    gamma          YAW                                            *****
*****    gamrad         YAW IN RADIANS                                 *****
*****    indata()       INFLOW DATA READ FROM INPUT FILE               *****
*****    infil          INPUT FILE NAME                                *****
*****    omega          ROTATIONAL FREQUENCY                           *****
*****    r              RADIUS OF TURBINE ROTOR                        *****
*****    sw??           SKEWED WAKE EFFECT                             *****
*****    tmn??          AZ ANGLE BLADE ENTERS TOWER SHADOW             *****
*****    tmx??          AZ ANGLE BLADE LEAVES TOWER SHADOW             *****
*****    towdef         MAXIMUM TOWER SHADOW VELOCITY DEFICIT          *****
*****    tsw            TOWER SHADOW WIDTH                             *****
*****    vinf           INFLOW VELOCITY                                *****
*****    v??c           VELOCITY CROSSFLOW COMPONENT                   *****
```

```
*****    v??n           VELOCITY COMPONENT NORMAL TO ROTOR               *****
*****    v??t           VELOCITY COMPONENT TANGENT TO BLADE              *****
*****    v??tow         INSTANTANEOUS TOWER SHADOW VELOCITY DEFICIT      *****
******************************************************************************

*****   VARIABLE DECLARATIONS   *****
        real aoa(4), indata(6)
        character infil*30, outfil*30

*****   SET CONSTANTS   *****
        pi = 4.0*atan(1.0)
        dia = 0.406
        r = 5.05
        omega = 2.0*pi*1.2
        betarad = 12.0*pi/180.
        towdef = .3

*****   DISPLAY A CHEERFUL MESSAGE TO THE USER ON THE SCREEN    *****
        print*
        print*
        print*,'*************************************************************'
        print*,'*****   Welcome to AOAAZ - the angle of attack model   *****'
        print*,'*************************************************************'
        print*

*****   PROMPT USER FOR INPUT FILE NAME AND OPEN FILE    ****
10      print*
        write (6,1)
1       format ('Enter the name of the file containing inflow data:  ',$)
        read*, infil
        open (unit=12,file=infil,iostat=inerr,status='old')
        if (inerr.ne.0) then
          print*,'Data file does not exist, please try again.'
          print*
          goto 10
        endif

*****   PROMPT USER FOR OUTPUT FILE NAME AND OPEN FILE    *****
        print*
        write (6,2)
2       format ('Enter the desired name for the output file:  ',$)
        read*, outfil
        open (unit=11, file=outfil,status='unknown')


*****************************************************************
*****   BEGIN LOOP TO READ INSTANTANEOUS INFLOW VALUES AND    *****
*****   CALCULATE THE ANGLE OF ATTACK AT EACH SPAN LOCATION   *****
*****************************************************************

*****   READ INFLOW DATA FROM INPUT FILE FOR ONE INSTANT IN TIME  *****
15      read(12,*,end=11), (indata(j),j=1,6)
        az = indata(1)
        azrad = az*pi/180.
        vinf = indata(2)
        gamma = indata(3)-(indata(4)+indata(5)+indata(6))/3.
        gamrad = gamma*pi/180.

*****************************************************************************
*****   set up parameters to calculate tower shadow velocity defecit    *****
```

```
******************************************************************************

*****   DEFINE CONSTANTS   *****
        tsw = (2.5*dia)/cos(gamrad)
        x = 0.5*(tsw + 0.457)
        twd = 0.9*tan(gamrad)

*****        30% SPAN    *****
        th30 = asin(x/(0.3*r))
        thd30 = asin(twd/(0.3*r))
        tmn30 = pi-th30-thd30
        tmx30 = pi+th30-thd30

*****        47% SPAN    *****
        th47 = asin(x/(0.466*r))
        thd47 = asin(twd/(0.466*r))
        tmn47 = pi-th47-thd47
        tmx47 = pi+th47-thd47

*****        63% SPAN    *****
        th63 = asin(x/(0.633*r))
        thd63 = asin(twd/(0.633*r))
        tmn63 = pi-th63-thd63
        tmx63 = pi+th63-thd63

*****        80% SPAN    *****
        th80 = asin(x/(0.82*r))
        thd80 = asin(twd/(0.82*r))
        tmn80 = pi-th80-thd80
        tmx80 = pi+th80-thd80


*****************************************************
*****   CALCULATE ANGLE OF ATTACK AT 30% SPAN   *****
*****************************************************

*****   CALCULATE 30% TOWER SHADOW DEFICIT (ZERO IF NOT WITHIN SHADOW)   *****
        if (azrad.ge.tmn30 .and. azrad.le.tmx30) then
          v30tow = towdef*vinf*(1.-cos(2.*pi*(azrad-tmn30)/(2.*th30)))
        else
          v30tow = 0.
        endif
        vtot30 = vinf-v30tow

*****   INCORPORATE PROP INDUCED VELOCITY AT 30% SPAN   *****
        ao30 = 1/(.000360046*vtot30**4-.0206024*vtot30**3+.415013*vtot30**2-
     2  1.32587*vtot30+3.16774)

*****   CALCULATE SKEWED WAKE EFFECT AT 30% SPAN   *****
        sw30 = (1+15*pi/32*sqrt((1-cos(gamrad))/(1+cos(gamrad))*
     2  .30*sin(azrad))
        a30 = ao30*sw30

*****   CALCULATE 30% SPAN VELOCITY COMPONENTS AND ANGLE OF ATTACK   *****
        v30n = vtot30*(1-a30)*cos(gamrad)
        v30c = -vtot30*sin(gamrad)
        v30t = (0.30*r*omega)+v30c*cos(azrad)
        aoa(1) = (atan(v30n/v30t)-betarad)*180.0/pi
```

```
****************************************************
*****   CALCULATE ANGLE OF ATTACK AT 47% SPAN   *****
****************************************************

*****   CALCULATE 47% TOWER SHADOW DEFICIT (ZERO IF NOT WITHIN SHADOW)  *****
        if (azrad.ge.tmn47 .and. azrad.le.tmx47) then
          v47tow = towdef*vinf*(1.-cos(2.*pi*(azrad-tmn47)/(2.*th47)))
        else
          v47tow = 0.0
        endif
        vtot47 = vinf-v47tow

*****   INCORPORATE PROP INDUCED VELOCITY AT 47% SPAN  *****
        ao47 = 1/(.000653402*vtot47**4-.0426646*vtot47**3+1.02377*vtot47**2-
     2  8.33547*vtot47+28.3554)

*****   CALCULATE SKEWED WAKE EFFECT AT 47% SPAN  *****
        sw47 = (1+15*pi/32*sqrt((1-cos(gamrad))/(1+cos(gamrad)))*
     2  .466*sin(azrad))
        a47 = ao47*sw47

*****   CALCULATE 47% SPAN VELOCITY COMPONENTS AND ANGLE OF ATTACK  *****
        v47n = vtot47*(1-a47)*cos(gamrad)
        v47c = -vtot47*sin(gamrad)
        v47t = (0.466*r*omega)+v47c*cos(azrad)
        aoa(2) = (atan(v47n/v47t)-betarad)*180.0/pi


****************************************************
*****   CALCULATE ANGLE OF ATTACK AT 63% SPAN   *****
****************************************************

*****   CALCULATE 63% TOWER SHADOW DEFICIT (ZERO IF NOT WITHIN SHADOW)  *****
        if (azrad.ge.tmn63 .and. azrad.le.tmx63) then
          v63tow = towdef*vinf*(1.-cos(2.*pi*(azrad-tmn63)/(2.*th63)))
        else
          v63tow = 0.0
        endif
        vtot63 = vinf-v63tow

*****   INCORPORATE PROP INDUCED VELOCITY AT 63% SPAN  *****
        ao63 = 1/(.000857403*vtot63**4-.0580386*vtot63**3+1.45897*vtot63**2-
     2  14.2769*vtot63+55.6623)

*****   CALCULATE SKEWED WAKE EFFECT AT 63% SPAN  *****
        sw63 = (1+15*pi/32*sqrt((1-cos(gamrad))/(1+cos(gamrad)))*
     2  .633*sin(azrad))
        a63 = ao63*sw63

*****   CALCULATE 63% SPAN VELOCITY COMPONENTS AND ANGLE OF ATTACK  *****
        v63n = vtot63*(1-a63)*cos(gamrad)
        v63c = -vtot63*sin(gamrad)
        v63t = (0.633*r*omega)+v63c*cos(azrad)
        aoa(3) = (atan(v63n/v63t)-betarad)*180./pi


****************************************************
*****   CALCULATE ANGLE OF ATTACK AT 80% SPAN   *****
****************************************************
```

```
*****   CALCULATE 80% TOWER SHADOW DEFICIT (ZERO IF NOT WITHIN SHADOW)   *****
        if (azrad.ge.tmn80 .and. azrad.le.tmx80) then
          v80tow = towdef*vinf*(1.-cos(2.*pi*(azrad-tmn80)/(2.*th80)))
        else
          v80tow = 0.0
        endif
        vtot80 = vinf-v80tow

*****   INCORPORATE PROP INDUCED VELOCITY AT 80% SPAN   *****
        ao80 = 1/(.001142*vtot80**4-.0769829*vtot80**3+1.95194*vtot80**2-
      2 20.8757*vtot80+88.372)

*****   CALCULATE SKEWED WAKE EFFECT AT 80% SPAN   *****
        sw80 = (1+15*pi/32*sqrt((1-cos(gamrad))/(1+cos(gamrad)))*
      2 .82*sin(azrad))
        a80 = ao80*sw80

*****   CALCULATE 80% SPAN VELOCITY COMPONENTS AND ANGLE OF ATTACK   *****
        v80n = vtot80*(1-a80)*cos(gamrad)
        v80c = -vtot80*sin(gamrad)
        v80t = (0.82*r*omega)+v80c*cos(azrad)
        aoa(4) = (atan(v80n/v80t)-betarad)*180.0/pi

*****   WRITE RESULTS TO OUTPUT FILE   *****
        write(11,1000) az,(aoa(j), j=1,4)

        goto 15
11      continue
        close (unit=11)
        close (unit=12)

1000    format (5f9.3)
        stop
        end
```

```
      program q2aoa

***************************************************************************
*****   THIS PROGRAM IMPLEMENTS THE STAGNATION POINT NORMALIZATION      *****
*****   TECHNIQUE FOR ANGLE OF ATTACK DETAILED IN THE PAPER "TECHNIQUES *****
*****   FOR THE DETERMINATION OF LOCAL DYNAMIC PRESSURE AND ANGLE OF    *****
*****   ATTACK ON A HORIZONTAL AXIS WIND TURBINE"                       *****
*****                                                                   *****
*****   THIS PROGRAM CALCULATES INSTANTANEOUS ANGLE OF ATTACK GIVEN A   *****
*****   TIME SERIES OF DYNAMIC PRESSURE DATA AND A FILE WITH THE        *****
*****   CORRESPONDING YAW DATA.  IT TREATS ANGLE OF ATTACK AND          *****
*****   DYNAMIC PRESSURE AS A FUNCTION OF AZIMUTH ANGLE, INFLOW         *****
*****   VELOCITY, YAW, AND ROTATIONAL VELOCITY.   ALL OF THESE ARE      *****
*****   ASSUMED TO BE KNOWN EXCEPT VELOCITY.  IT BACKS OUT THE INFLOW   *****
*****   VELOCITY FROM THE DYNAMIC PRESSURE USING THE GEOMETRY OF THE    *****
*****   TURBINE RELATIVE TO THE INFLOW.  THEN, ALL PARAMETERS ARE       *****
*****   KNOWN, AND THE ANGLE OF ATTACK CAN BE CALCULATED.  ONLY THE     *****
*****   LAST FOUR COLUMNS OF THE YAW FILE ARE ACTUALLY REQUIRED.  THE   *****
*****   GIVEN FORMAT CORRESPONDS TO OUR STANDARD INFLOW FILE.  THE      *****
*****   PROGRAM IS EXPECTING ONLY A SINGLE CYCLE OF DATA.  FOR LONGER   *****
*****   FILES INCREASE THE SIZE OF maxpts.                              *****
*****                                                                   *****
*****   WRITTEN BY DEREK SHIPLEY                                        *****
***************************************************************************

***************************************************************************
*****   DYNAMIC PRESSURE INPUT FILE FORMAT:                             *****
*****     COLUMN 1 - AZIMUTH ANGLE                                      *****
*****     COLUMN 2 - DYNAMIC PRESSURE AT 30% SPAN                       *****
*****     COLUMN 3 - DYNAMIC PRESSURE AT 47% SPAN                       *****
*****     COLUMN 4 - DYNAMIC PRESSURE AT 63% SPAN                       *****
*****     COLUMN 5 - DYNAMIC PRESSURE AT 80% SPAN                       *****
*****                                                                   *****
*****   YAW INPUT FILE FORMAT:                                          *****
*****     COLUMN 1 - AZIMUTH ANGLE                                      *****
*****     COLUMN 2 - WIND VELOCITY                                      *****
*****     COLUMN 3 - TURBINE YAW ANGLE                                  *****
*****     COLUMN 4 - HUB HEIGHT WIND DIRECTION                          *****
*****     COLUMN 5 - BI-VANE WIND DIRECTION #1                          *****
*****     COLUMN 6 - BI-VANE WIND DIRECTION #2                          *****
***************************************************************************

***************************************************************************
*****   OUTPUT FILE FORMAT:                                             *****
*****     COLUMN 1 - AZIMUTH ANGLE                                      *****
*****     COLUMN 2 - ANGLE OF ATTACK AT 30% SPAN                        *****
*****     COLUMN 3 - ANGLE OF ATTACK AT 47% SPAN                        *****
*****     COLUMN 4 - ANGLE OF ATTACK AT 63% SPAN                        *****
*****     COLUMN 5 - ANGLE OF ATTACK AT 80% SPAN                        *****
***************************************************************************

***************************************************************************
*****   VARIABLE DEFINITIONS:                                           *****
*****     alpha()       ANGLE OF ATTACK AT ALL SPANS (deg)              *****
*****     az()          AZIMUTH ANGLE (deg)                             *****
*****     azrad         AZIMUTH ANGLE (rad)                             *****
*****     betarad       BLADE PITCH ANGLE (rad)                         *****
*****     gamma         YAW (deg)                                       *****
*****     gamrad        YAW (rad)                                       *****
*****     hh?()         WIND DIRECTION MEASUREMENTS                     *****
```

```
*****    ncol          NUMBER OF COLUMNS OF Q DATA                         *****
*****    nmax          NUMBER OF DATA POINTS IN EACH COLUMN                *****
*****    omega         ROTATIONAL FREQUENCY (rad/s)                        *****
*****    outfil        OUTPUT FILE NAME                                    *****
*****    qfil          DYNAMIC PRESSURE INPUT FILE NAME                    *****
*****    span          RADIAL DISTANCE TO PRESSURE TAPS (m)                *****
*****    r             TURBINE ROTOR RADIUS (m)                            *****
*****    tol           DESIRED ACCURACY FOR ROOT-FINDING                   *****
*****    vc            VELOCITY CROSSFLOW COMPONENT (m/s)                  *****
*****    vhigh         MAXIMUM VELOCITY FOR ROOT FINDER (m/s)              *****
*****    vinf          INFLOW VELOCITY DERIVED FROM Q (m/s)                *****
*****    vlast()       INFLOW VELOCITY AT LAST DATA POINT (m/s)            *****
*****    vlow          MINIMUM VELOCITY FOR ROOT FINDER (m/s)              *****
*****    vn            VELOCITY COMPONENT NORMAL TO ROTOR (m/s)            *****
*****    vt            VELOCITY COMPONENT TANGENT TO BLADE (m/s)           *****
*****    wsize         HALF WINDOW SIZE FOR SMOOTHING (points)             *****
*****    ya()          INSTANTANEOUS TURBINE YAW ANGLE (deg)               *****
*****    yawfil        YAW INPUT FILE NAME                                 *****
******************************************************************************


*****   DECLARE VARIABLES   *****
        parameter (maxpts=450)
        character qfil*30,outfil*30,yawfil*30
        integer ncol
        real az(maxpts),q(4,maxpts),ya(maxpts)
        real hh1(maxpts),hh2(maxpts),hh3(maxpts)
        real alpha(4),rtbis,vlast(4)

*****   DEFINE CONSTANTS   *****
        pi = 4.0*atan(1.0)
        r = 5.05
        omega = 2.0*pi*1.2
        betarad = 12.0*pi/180.
        tol = .01
        ncol = 4
        vlow = 0.
        vhigh = 40.

*****   PROMPT THE USER FOR THE DYNAMIC PRESSURE FILE NAME AND OPEN IT   *****
100     print*
        write(6,1)
1       format ('Enter the name of the file containing q data:  ',$)
        read*, qfil
        open (unit=11,file=qfil,iostat=inerr,status='old')
        if (inerr .ne. 0) then
          print*, 'File does not exist.  Please try again.'
          goto 100
        endif

*****   PROMPT THE USER FOR THE YAW FILE NAME AND OPEN FILE   *****
200     print*
        write(6,2)
2       format ('Enter the name of the file containing yaw data:  ',$)
        read*, yawfil
        open (unit=12,file=yawfil,iostat=inerr,status='old')
        if (inerr .ne. 0) then
          print*, 'File does not exist.  Please try again.'
          goto 200
        endif
```

```
*****   PROMPT THE USER FOR THE HALF WINDOW SIZE USED IN THE MOVING    *****
*****   AVERAGE ROUTINE TO SMOOTH THE DATA.  ZERO MEANS NO FILTERING   *****
300     print*
        write(6,3)
3       format ('Enter the half window size for filtering ',
     2  '(0 for no filter):  ',$)
        read*, wsize
        if (wsize .lt. 0) then
          print*,'Window size must be positive.  Please try again.'
          goto 300
        endif

*****   PROMPT THE USER FOR THE NAME OF THE OUPUT FILE AND OPEN IT   *****
        print*
        write(6,4)
4       format ('Enter the name of the output file:  ',$)
        read*, outfil
        open (unit=13,file=outfil,status='unknown')

*****************************************************************
*****   READ IN ALL DATA FROM DYNAMIC PRESSURE AND YAW FILES   *****
*****************************************************************
        n = 1
400     read(11,*,end=450) az(n),(q(j,n),j=1,4)
        read(12,*) tmp1,tmp2,ya(n),hh1(n),hh2(n),hh3(n)
          n = n+1
          goto 400
450     continue
        nmax = n-1

*****************************************************
*****   FILTER DYNAMIC PRESSURE DATA IF REQUESTED   *****
*****************************************************
          call filtersub(q,nmax,ncol,wsize)

**********************************************************************
*****   BEGIN LOOP TO DERIVE ANGLE OF ATTACK FROM DYNAMIC PRESSURE   *****
**********************************************************************
        do 700,n=1,nmax
         azrad = az(n)*pi/180.
         gamma = ya(n)-(hh1(n)+hh2(n)+hh3(n))/3.
         gamrad = gamma*pi/180.
*****   SET SPAN LOCATION FOR DATA COLUMN   *****
         do 780,j=1,4
          if (j .eq. 1) then
            span = 0.30
          elseif (j .eq. 2) then
            span = 0.47
          elseif (j .eq. 3) then
            span = 0.63
          elseif (j .eq. 4) then
            span = 0.80
          endif
*****   CALL RTBIS TO FIND INFLOW VELOCITY   *****
          qinst = q(j,n)
          vinf = rtbis(vlow,vhigh,tol,gamrad,azrad,qinst,span)
*****   IF THERE IS NOT ROOT, SET VELOCITY EQUAL TO PREVIOUS POINT   *****
          if (vinf .lt. 0) vinf=vlast(j)
          vlast(j) = vinf
```

```
*****   CALCULATE ANGLE OF ATTACK FROM INFLOW PARAMETERS   *****
          vn = vinf*cos(gamrad)
          vc = -vinf*sin(gamrad)
          vt = (span*r*omega)+vc*cos(azrad)
          alpha(j) = (atan(vn/vt)-betarad)*180./pi
780      continue
*****   WRITE AZIMUTH ANGLE AND ANGLE OF ATTACK TO THE OUTPUT FILE   *****
         write(13,*) az(n),(alpha(j),j=1,4)
700     continue

        stop
        end

******************************************************************************
******************************************************************************

        subroutine filtersub (dat,nm,nc,wsiz)

******************************************************************************
*****   THIS SUBROUTINE IS A MOVING AVERAGE ROUTINE USED TO SMOOTH A     *****
*****   TIME SERIES OF DATA.  IT TAKES THE AVERAGE OF ALL DATA POINTS    *****
*****   IN A USER SPECIFIED WINDOW AROUND A POINT AND SUBSTITUTES IT     *****
*****   FOR THE POINT.  THE ROUTINE THEN MOVES ON TO THE NEXT POINT      *****
*****   AND REPEATS THE PROCESS.  AT THE BEGINNING OR END OF THE SERIES *****
*****   IT TAKES THE AVERAGE FROM THE BEGINNING (OR END) TO THE POINT    *****
*****   +/- HALF WINDOW SIZE.                                            *****
*****                                                                    *****
*****   WRITTEN BY DEREK SHIPLEY                                         *****
******************************************************************************

******************************************************************************
*****   SUBROUTINE ARGUMENTS:                                            *****
*****     dat              ARRAY OF DATA TO BE SMOOTHED                  *****
*****     nmax             NUMBER OF DATA POINTS IN EACH COLUMN          *****
*****     ncol             NUMBER OF COLUMNS IN ARRAY                    *****
*****     wsize            HALF WINDOW SIZE                              *****
******************************************************************************

*****   DEFINE VARIABLES   *****
        real dat(nc,nm)

        do 100,j=1,nc
          do 200,n=1,nm
**********************************************
*****    SET WINDOW SIZE TO BE AVERAGED   *****
**********************************************
            if (n-wsiz .lt. 1) then
              nlow = 1
            else
              nlow = n-wsiz
            endif
            if (n+wsiz .gt. nm) then
              nhigh = nm
            else
              nhigh = n+wsiz
            endif
            window = nhigh-nlow+1
*************************************************************************
*****   AVERAGE POINTS IN WINDOW AND SUBSTITUTE FOR CENTER POINT   *****
*************************************************************************
```

```
          sum = 0.
          do 300,k = nlow,nhigh
            sum = sum+dat(j,k)
300       continue
          dat(j,n) = sum/window
200     continue
100   continue

      return
      end

*****************************************************************************
*****************************************************************************

      function rtbis(x1,x2,xacc,gamrad,azrad,qinst,span)

*****************************************************************************
*****   THIS FUNCTION USES THE BISECTION METHOD TO FIND A ROOT OF A     *****
*****   FUNCTION.  THE ROOT MUST BE BRACKETED FOR THE METHOD TO SUCCEED. *****
*****   IF THE ROOT IS NOT BRACKETED, THE FUNCTION RETURNS A VALUE OF -1 *****
*****   (THE ONLY MODIFICATION TO THE ORIGINAL ROUTINE.                 *****
*****                                                                   *****
*****   WRITTEN BY W.H. PRESS, B.P. FlANNERY, S.A. TEUKOLSKY, AND W.T.  *****
*****   VETTERLING. NUMERICAL RECIPES: THE ART OF SCIENTIFIC COMPUTING. *****
*****   CAMBRIDGE UNIVERSITY PRESS, CAMBRIDGE. 1989.                    *****
*****************************************************************************

*****************************************************************************
*****   SUBROUTINE ARGUMENTS:                                           *****
*****     x1          LOWER BOUND FOR INTERVAL                          *****
*****     x2          UPPER BOUND FOR INTERVAL                          *****
*****     xacc        DESIRED ACCURACY OF ROOT                          *****
*****     gamrad      YAW (RAD)                                         *****
*****     azrad       AZIMUTH ANGLE (RAD)                               *****
*****     qinst       INSTANTANEOUS DYNAMIC PRESSURE (psi)              *****
*****     span        RADIAL DISTANCE TO PRESSURE TAPS (m)              *****
*****************************************************************************

      parameter (jmax=40)
      real qdiff

*****   FIND THE INITIAL VALUES OF THE FUNCTION AT EXTREMES   *****
      fmid = qdiff(x2,gamrad,azrad,qinst,span)
      f = qdiff(x1,gamrad,azrad,qinst,span)
*****   RETURN A VALUE OF -1 IF ROOT IS NOT BRACKETED *****
       if (f*fmid.ge.0.) then
        rtbis = -1.
        return
      endif
*****   SET INITIAL VALUES   *****
      if (f .lt. 0.) then
         rtbis = x1
         dx = x2-x1
      else
         rtbis = x2
         dx = x1-x2
      endif
*****   BEGIN LOOP TO BISECT INTERVAL UNTIL ROOT IS FOUND   *****
      do 11 j=1,jmax
         dx = dx*.5
```

```
         xmid = rtbis+dx
         fmid = qdiff(xmid,gamrad,azrad,qinst,span)
         if (fmid .le. 0.) rtbis=xmid
*****  RETURN IF ROOT FOUND TO SPECIFIED TOLERANCE   *****
         if (abs(dx) .lt. xacc .or. fmid .eq. 0.) then
           return
         endif
11     continue
*****  PRINT ERROR MESSAGE IF EXCEEDED MAX NUMBER OF BISECTIONS   *****
       pause 'too many bisections'
       end

*****************************************************************************
*****************************************************************************

       function qdiff(vel,gam,az,q,span)

*****************************************************************************
*****  THIS FUNCTION FINDS THE DIFFERENCE BETWEEN A VALUE FOR DYNAMIC   *****
*****  PRESSURE ARGUMENT AND THAT CALCULATED FROM THE GEOMETRY OF THE   *****
*****  INFLOW RELATIVE TO THE TURBINE.                                  *****
*****                                                                   *****
*****  WRITTEN BY DEREK SHIPLEY                                         *****
*****************************************************************************

*****************************************************************************
*****  SUBROUTINE ARGUMENTS:                                            *****
*****    vel            LOCAL INFLOW VELOCITY (m/s)                     *****
*****    gamrad         YAW (RAD)                                       *****
*****    azrad          AZIMUTH ANGLE (RAD)                             *****
*****    qinst          INSTANTANEOUS DYNAMIC PRESSURE (psi)            *****
*****    span           RADIAL DISTANCE TO PRESSURE TAPS (m)            *****
*****************************************************************************

*****  DEFINE CONSTANTS   *****
       pi = 4.0*atan(1.0)
       r = 5.05
       omega = 2.0*pi*1.2

*****  CALCULATE VELOCITY COMPONENTS AND Q, AND CALCULATE   *****
*****  THE DIFFERENCE WITH THE INPUT ARGUMENT FOR Q        *****
       vn = vel*cos(gam)
       vc = -vel*sin(gam)
       vt = r*span*omega+vc*cos(az)
       vs = vc*sin(az)
       qdiff = q-.5*.0019*.07475*(vn**2+vt**2+vs**2)

       end
```

```
       program aoacor

****************************************************************************
*****  THIS PROGRAM IMPLEMENTS THE PRESSURE PROFILE COMPARISON METHOD  *****
*****  FOR ANGLE OF ATTACK DETAILED IN THE PAPER "TECHNIQUES FOR THE   *****
*****  DETERMINATION OF LOCAL DYNAMIC PRESSURE AND ANGLE OF ATTACK ON  *****
*****  A HORIZONTAL AXIS WIND TURBINE"                                 *****
*****                                                                  *****
*****  THIS PROGRAM ESTIMATES ANGLE OF ATTACK AT ALL FOUR SPAN         *****
*****  LOCATIONS THROUGH COMPARISONS OF UPPER AND LOWER SURFACE        *****
*****  PRESSURE DATA TO THAT MEASURED DURING WIND TUNNEL TESTING       *****
*****  AT COLORADO STATE UNIVERSITY.  THE ANGLE ATTACK CORRESPONDING   *****
*****  TO THE WIND TUNNEL PROFILE THAT CORRELATES MOST HIGHLY (AS      *****
*****  DEFINED BY PEARSON'S LINEAR CORRELATION COEFFICIENT) IS ASSIGNED*****
*****  TO THE ROTATING PROFILES.  IN THIS WAY THE ANGLE OF ATTACK IS   *****
*****  DICTATED BY THE SURFACE PRESSURE.  THIS METHOD BREAKS DOWN IF   *****
*****  THE COMBINED EXPERIMENT PRESSURE PROFILES DO NOT RESEMBLE THOSE *****
*****  MEASURED IN THE WIND TUNNEL.  SINCE A DIFFERENCE EXISTS BETWEEN *****
*****  THE CHORD LOCATIONS OF PRESSURE MEASUREMENTS FOR WIND TUNNEL    *****
*****  TESTING AND DIFFERENT SPAN LOCATIONS, FOUR WIND TUNNEL PRESSURE *****
*****  FILES ARE REQUIRED (ONE FOR EACH SPAN).  THESE FILES HAVE HAD   *****
*****  THE PRESSURE DATA FROM TAPS THAT DO NOT EXIST IN THE COMBINED   *****
*****  EXPERIMENT REMOVED. THE REQUIRED FILES ARE NAMED csuall30.dat,  *****
*****  csuall47.dat, csuall63.dat, and csuall80.dat.  FOUR USER        *****
*****  SPECIFIED FILES CONTAINING COMBINED EXPERIMENT PRESSURE DATA IN *****
*****  THE FOLLOWING FORMAT ARE ALSO      REQUIRED.  THE TRAILING EDGE *****
*****  PRESSURE IS IN BOTH THE FIRST AND LAST COLUMN TO ENABLE PLOTTING*****
*****  OF THE PROFILES.                                                *****
*****                                                                  *****
*****  WRITTEN BY DEREK SHIPLEY                                        *****
****************************************************************************

****************************************************************************
*****  30% SPAN PRESSURE INPUT FILE:                                   *****
*****    COLUMN 1    - AZIMUTH ANGLE                                   *****
*****    COLUMN 2-26 - ALL 30% SURFACE PRESSURE EXCEPT 8% LOWER        *****
*****             CHANNEL ID: 804-822,824-828,804                      *****
*****                                                                  *****
*****  47% SPAN PRESSURE INPUT FILE:                                   *****
*****    COLUMN 1    - AZIMUTH ANGLE                                   *****
*****    COLUMN 2-28 - ALL 47% SURFACE PRESSURE EXCEPT 28% UP, 8% LOW  *****
*****             CHANNEL ID: 833-839,841-854,856-860,833              *****
*****                                                                  *****
*****  63% SPAN PRESSURE INPUT FILE:                                   *****
*****    COLUMN 1    - AZIMUTH ANGLE                                   *****
*****    COLUMN 2-28 - ALL 63% SURFACE PRESSURE EXCEPT 28% UP, 8% LOW  *****
*****             CHANNEL ID: 903-909,911-924,926-930,903              *****
*****                                                                  *****
*****  80% SPAN PRESSURE INPUT FILE:                                   *****
*****    COLUMN 1    - AZIMUTH ANGLE                                   *****
*****    COLUMN 2-28 - ALL 80% SURFACE PRESSURE EXCEPT 28% UP, 8% LOW  *****
*****             CHANNEL ID: 427-433,534-448,450-454,427              *****
****************************************************************************

****************************************************************************
*****  OUTPUT FILE FORMAT:                                             *****
*****    COLUMN 1 - AZIMUTH ANGLE                                      *****
*****    COLUMN 2 - ANGLE OF ATTACK AT 30% SPAN                        *****
*****    COLUMN 3 - ANGLE OF ATTACK AT 47% SPAN                        *****
*****    COLUMN 4 - ANGLE OF ATTACK AT 63% SPAN                        *****
```

```
*****    COLUMN 5 - ANGLE OF ATTACK AT 80% SPAN                         *****
*****************************************************************************

*****************************************************************************
*****  VARIABLE DEFINITIONS:                                            *****
*****    alpha()        ANGLE OF ATTACK AT ALL FOUR SPANS (deg)         *****
*****    expfil()       FILE NAMES OF EXPERIMENTAL PRESSURE DATA        *****
*****    exp??()        PRESSURE DATA FROM ONE INSTANT IN TIME          *****
*****    ntaps          NUMBER OF PRESSURE TAPS AT 47%, 63%, and 80%    *****
*****    ntaps30        NUMBER OF PRESSURE TAPS AT 30% SPAN             *****
*****    outfil         OUTPUT FILE NAME                                *****
*****    r()            PEARSON'S LINEAR CORRELATION COEFFICIENT        *****
*****    rmax()         HIGHEST CORR COEFF AT ONE POINT IN TIME         *****
*****    rtmp           TEMPORARY VALUE FOR CORRELATION COEFFICIENT     *****
*****    span           SPAN LOCATION OF EACH SET OF TAPS               *****
*****    un             UNIT NUMBER FOR OPENING EXP. DATA FILES         *****
*****    wt??(,)        ALL WIND TUNNEL DATA FOR EACH SPAN LOCATION     *****
*****    wtdat??()      WIND TUNNEL DATA FROM ONE ANGLE OF ATTACK       *****
*****************************************************************************


*****  DECLARE VARIABLES   *****
       character expfil(4)*30,outfil*30
       real alpha(4),rmax(4),r(4)
       real exp30(30),exp47(30),exp63(30),exp80(30)
       real wt30(30,40),wt47(30,40),wt63(30,40),wt80(30,40)
       real wtdat30(30),wtdat47(30),wtdat63(30),wtdat80(30)
       integer un,span

*****  SET CONSTANTS   *****
       ntaps = 27
       ntaps30 = 25

*****  PROMPT THE USER FOR THE NAMES OF THE FILES CONTAINING    *****
*****  EXPERIMENTAL SURFACE PRESSURE DATA AND OPEN FILES        *****
       print*
       do 150,j=1,4
200      if (j .eq. 1)  then
           span = 30
         elseif (j .eq. 2) then
           span = 47
         elseif (j .eq. 3) then
           span = 63
         else
           span = 80
         endif
         write(6,2) span
2        format('Enter the name of the file containing ',i2,
     2   '% pressure data:  ',$)
         read*,expfil(j)
         un=j+10
         open(unit=un,file=expfil(j),iostat=inerr,status='old')
         if (inerr.ne.0) then
           print*,'File does not exist, please try again.'
           goto 200
         endif
150    continue

*****  PROMPT THE USER FOR THE NAME OF THE OUTPUT FILE AND OPEN IT    *****
       print*
```

```
      write(6,6)
6     format('Enter the name of the output file:  ',$)
      read*,outfil
      open(unit=16,file=outfil,status='unknown')
      print*

*******************************************************
*****  OPEN FILES CONTAINING CSU WIND TUNNEL DATA  *****
*******************************************************
      open(unit=21,file='csuall30.dat',status='old')
      open(unit=22,file='csuall47.dat',status='old')
      open(unit=23,file='csuall63.dat',status='old')
      open(unit=24,file='csuall80.dat',status='old')

**********************************************************************
*****  READ IN ALL DATA FROM THE FILES CONTAINING WINDTUNNEL DATA  *****
**********************************************************************
      n=1
250   read(21,*,end=275)(wt30(j,n),j=1,ntaps30+1)
      read(22,*)(wt47(j,n),j=1,ntaps+1)
      read(23,*)(wt63(j,n),j=1,ntaps+1)
      read(24,*)(wt80(j,n),j=1,ntaps+1)
      n=n+1
      goto 250
275   continue
      nmax=n-1

*****************************************************************
*****  BEGIN LOOP TO COMPARE INDIVIDUAL PRESSURE PROFILES TO  *****
*****  WINDTUNNEL DATA TO FIND THE HIGHEST CORRELATION        *****
*****************************************************************

*****  READ IN EXPERIMENTAL DATA FROM ONE INSTANCE IN TIME  *****
300   read(11,*,end=600)az,(exp30(j),j=1,ntaps30)
      read(12,*)tmp,(exp47(j),j=1,ntaps)
      read(13,*)tmp,(exp63(j),j=1,ntaps)
      read(14,*)tmp,(exp80(j),j=1,ntaps)
        rmax(1) = 0.
        rmax(2) = 0.
        rmax(3) = 0.
        rmax(4) = 0.
*****  BEGIN LOOP TO FIND ANGLE OF ATTACK AT ALL SPANS  *****
        do 400, n=1,nmax
          do 500, i=1,ntaps
            if (i .le. ntaps30) wtdat30(i) = wt30(i+1,n)
            wtdat47(i) = wt47(i+1,n)
            wtdat63(i) = wt63(i+1,n)
            wtdat80(i) = wt80(i+1,n)
500       continue
*****  CALL ROUTINE TO FIND LEVEL OF CORRELATION BETWEEN PROFILES  *****
          call pearsn(exp30,wtdat30,ntaps30,rtmp)
          r(1) = rtmp
          call pearsn(exp47,wtdat47,ntaps,rtmp)
          r(2) = rtmp
          call pearsn(exp63,wtdat63,ntaps,rtmp)
          r(3) = rtmp
          call pearsn(exp80,wtdat80,ntaps,rtmp)
          r(4) = rtmp
*****  IF IT CORRELATES HIGHER THEN PREVIOUS MAXIMUM,  *****
*****  ASSIGN WINDTUNNEL AOA TO EXPERIMENTAL PROFILE   *****
```

```
           do 525, m=1,4
             if (r(m) .gt. rmax(m)) then
               rmax(m) = r(m)
               alpha(m) = wt30(1,n)
             endif
525        continue
400      continue
*****  WRITE AZIMUTH AND ANGLE OF ATTACK TO THE OUTPUT FILE   *****
         write(16,9000) az,(alpha(j),j=1,4)
         goto 300
600    continue

9000   format (5f8.3)
       stop
       end

*****************************************************************************
*****************************************************************************

       subroutine pearsn(x,y,n,r)

*****************************************************************************
*****  THIS SUBROUTINE COMPUTES THE LINEAR CORRELATION COEFFICIENT OF   *****
*****  TWO TIME SERIES OF DATA.  THE COEFFICIENT RANGES FROM -1.0 TO    *****
*****  1.0.  A VALUE OF 1.0 MEANS THE TWO SERIES ARE PERFECTLY          *****
*****  CORRELATED.  A VALUE OF -1.0 MEANS PERFECT NEGATIVE CORRELATION. *****
*****  A VALUE OF 0 INDICATES THE SERIES ARE UNCORRELATED.              *****
*****                                                                   *****
*****  WRITTEN BY W.H. PRESS, B.P. FLANNERY, S.A. TEUKOLSKY, AND W.T.   *****
*****  VETTERLING.  NUMERICAL RECIPES:  THE ART OF SCIENTIFIC           *****
*****  COMPUTING.  CAMBRIDGE UNIVERSITY PRESS, CAMBRIDGE. 1989.         *****
*****                                                                   *****
*****************************************************************************

*****************************************************************************
*****  SUBROUTINE ARGUMENTS:                                            *****
*****    x()            ARRAY CONTAINING DATA FOR FIRST SERIES          *****
*****    y()            ARRAY CONTAINING DATA FOR SECOND SERIES         *****
*****    n              NUMBER OF DATA POINTS IN SERIES                 *****
*****    r              LINEAR CORRELATION COEFFICIENT                  *****
*****************************************************************************

*****  DECLARE VARIABLES   *****
       parameter (tiny=1.e-20)
       dimension x(n),y(n)

*****  INITIALIZE VARIABLES   *****
       ax = 0.
       ay = 0.
       sxx = 0.
       syy = 0.
       sxy = 0.

*****  FIND MEAN FOR EACH DATA SERIES   *****
       do 11 j=1,n
         ax = ax+x(j)
         ay = ay+y(j)
11     continue
       ax = ax/n
       ay = ay/n
```

```
*****   DETERMINE LINEAR CORRELATION COEFFICIENT   *****
        do 12 j=1,n
          xt = x(j)-ax
          yt = y(j)-ay
          sxx = sxx+xt**2
          syy = syy+yt**2
          sxy = sxy+xt*yt
12      continue
        r = sxy/sqrt(sxx*syy)

        return
        end
```

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Data from the National Renewable Energy Laboratory's "Combined Experiment" has been utilized to develop techniques for indirectly calculating the instantaneous local dynamic pressure and angle of attack on a horizontal axis wind turbine. First, an analytic model based upon inflow geometry relative to the wind turbine was developed for both parameters. Second, dynamic pressure and angle of attack were inferred from the pressure required to normalize the blade stagnation point to $C_p = 1.0$. Third, rotor blade pressure profiles were compared to those from wind tunnel tests to determine angle of attack. Test results are shown over a variety of typical inflow conditions and are corroborated by measured data. Differences between the calculated and measured values are also discussed.

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