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A COMPARISON OF SPANWISE AERODYNAMIC LOADS ESTIMATED FROM MEASURED BENDING MOMENTS VERSUS DIRECT PRESSURE MEASUREMENTS ON HORIZONTAL AXIS WIND TURBINE BLADES

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ABSTRACT

Two methods can be used to determine aerodynamic loads on a rotating wind turbine blade. The first is to make direct pressure measurements on the blade surface. This is a difficult process requiring costly pressure instrumentation. The second method uses measured flap bending moments in conjunction with analytical techniques to estimate airloads. This method, called ALEST, was originally developed for use on helicopter rotors and was modified for use on horizontal axis wind turbine blades. Estimating airloads using flap bending moments is much simpler and less costly because measurements can be made with conventional strain gages and equipment. This paper presents results of airload estimates obtained using both methods under a variety of operating conditions. Insights on the limitations and usefulness of the ALEST bending moment technique are also included.

INTRODUCTION

Current methods used to estimate performance of horizontal axis wind turbines (HAWTs) typically under-predict machine power production, especially for stall-controlled turbines operating in deep stall in medium to high winds. Wind turbine performance estimates are usually based on two-dimensional wind tunnel aerodynamic data applied to blade element moment theory analyses. These estimates assume that airfoils perform the same on a rotating blade as in a wind tunnel. Results are usually accurate for nonstalled operation in low-wind conditions. However, during deep stall in higher winds or yawed operation, unsteady aerodynamics and delayed stall conditions exist. Significantly greater peak power levels than predicted occur under these circumstances (Viterna and Corrigan, 1981). Three-dimensional flow effects and other phenomena not yet clearly understood are suspected to be the cause (Rasmussen et al.,1988, Butterfield, et .al., 1990). To design and build cost-effective turbines, a better understanding of how airfoils perform during these high-load conditions is important.

One aspect of the Combined Experiment conducted at the Solar Energy Research Institute (SERI) was to study spanwise rotational flow effects on wind turbine airfoil performance. A 10-m, three-bladed downwind HAWT was used as a test platform. A high-tolerance mold of the SERI S809 airfoil shape was used to construct constant-chord, zero-twist blades and wind tunnel test sections. In order to accurately quantify aerodynamic load distribution, one blade was instrumented to provide detailed surface pressure measurements at four spanwise locations (Butterfield, 1989). In addition, many other parameters were measured to characterize machine loads and performance. Included were many spanwise-distributed strain gage bridges to measure blade flap bending moments.

Surface pressures provide a direct measurement of spanwise blade aerodynamic load distribution. Air load distribution can also be estimated using strain gage bending moment measurements (DuWaldt and Statler, 1966). The Combined Experiment data set provides an excellent resource for comparing air loads obtained using either method. Since accurate pressure measurements from a rotating blade are difficult and expensive to obtain, a simpler strain gage method could be a valuable tool in better understanding aerodynamic behavior. Blade air load data are especially useful for validating wind turbine analytical tools. To explore this further, we have evaluated a technique in which flapwise bending moment data are used in conjunction with known blade mass and stiffness properties to estimate airloads. This technique was originally developed for use on helicopter rotors as a computer code called ALEST (Air Load ESTimation) (Bousman, 1987).

BACKGROUND

In ALEST, free vibration modes of the blade are used in a single-rotating-blade model to determine modal displacements based on measured bending moment distributions. An empirical least-squares method is used to determine modal amplitudes. This information is used in the blade model to estimate aerodynamic loads. The airloads are a function of the mode shapes, modal amplitudes, mass distribution, and frequency information. ALEST solves the dynamic uncoupled flap equation of motion to determine resultant aerodynamic forces.

The original version of ALEST used for helicopter blade airload estimation was modified for use on wind turbines. This required adding terms to include gravity loading affected by precone angle and blade pitch. A set of test conditions were devised to verify modifications made to ALEST. First, the code was checked by comparing estimated airloads and bending moments with those obtained from simple beam theory using an analytical continuous beam model. Estimated results from ALEST were identical to those from theory (Schnepp, et al., 1991). Second, the modifications to ALEST were checked by comparisons with the Force and Loads Analysis Program (FLAP) (Wright and Thresher, 1987). FLAP uses wind inflow characteristics and machine properties in conjunction with known blade aerodynamic data to calculate blade loads. Bending moments calculated by FLAP were input directly into ALEST. Comparisons between ALEST and FLAP showed good correlation (Simms, 1990).

METHOD

In this report, measured airloads are compared to those determined from ALEST using corresponding measured bending moment data. The second phase of the Combined Experiment provided measured airload distributions from pressure data at four span locations: 30%, 47%, 63% and 80%. At each of these locations approximately 28 pressure taps were distributed around the blade chord. Tap distribution was concentrated more toward the leading edge suction side of the blade to better characterize the active peak pressure region. Each individual pressure measurement was normalized into a pressure coefficient by dividing by the total pressure, P_{tot}, which was obtained using:

$$P_{tot} = \frac{\rho}{2}[(\Omega r)^2 + V_w^2]$$

where ρ is the air density, Ω is the blade rotation speed, r is the radius, and V_w is the hub-height wind velocity.

The normal aerodynamic force coefficient, Cn, is determined by integrating the blade normal component of each pressure coefficient over all pressure coefficients around each chord section. Spanwise airloads, Fs, are then obtained at each span location using:

$$Fs = Cn \cdot P_{tot} \cdot c$$

where Cn is the normal force coefficient, P_{tot} is the total pressure, and c is the blade chord length (.457 m or 18 in). Since the spanwise airloads are calculated at a particular span location, they are in units of force per length of span. They can be multiplied by span length to determine overall blade load in the blade-normal direction.

Strain gage bridges configured to measure flapwise bending moments were located at the blade root, 20%, 40%, 50%, 70%, and 90% span locations. These were used to provide bending moment inputs to ALEST. Because ALEST requires inputs expressed in terms of harmonic content, strain gage data were azimuth averaged over the number of blade cycles shown in Table 1 into 5-degree bins and then converted into a mean term with eight Fourier terms. Since the blade rotates at 1.2 Hz, this provides bandwidth close to 10 Hz. The original pressure data were sampled with 100 Hz bandwidth, and were digitally low-pass filtered to 10 Hz for these comparisons. Higher-bandwidth data could be used in ALEST; however, this would require characterizing higher frequency response with increasing numbers of harmonic terms.

Three test cases were chosen: low wind, high yaw, and high wind. Minimal yaw error existed in both low-wind and high-wind cases. In the high-yaw case, dynamic stall causes large cyclic aerodynamic load variations. In all cases, there was no significant yaw motion. ALEST was not set up to model yaw motion effects. Statistics summarizing the three cases are shown in Table 1.

ALEST also required blade natural frequency flap mode shapes. These were obtained from blade mass and stiffness distribution characteristics and were estimated using a program called TMQ. TMQ uses the transmission matrix method (Murthy, 1976) to provide flap natural frequency mode shapes, slopes, bending moments, and shear. The first three flapwise modes for the Combined Experiment blade occurred at approximately 5, 20, and 50 Hz. Only the first mode shape data were used in these comparisons. Modal tests could be conducted to directly measure blade natural frequencies and mode shapes. The measured results could be input to ALEST instead of using TMQ. Two other operational parameters, precone angle and mean pitch angle, are the final required inputs to ALEST.

Table 1. Case Study Parameter Statistics

Parameter	Low-Wind	High-Yaw	High-Wind
Time duration (sec)	30	20	60
# of blade cycles	36	24	72
Wind speed(m/s)	8.3	13.7	18.3
Wind direction(deg)	279	276	288
Yaw angle(deg)	287	306	283
Pitch angle(deg)	12.1	11.3	12.4

RESULTS

Comparisons of blade airload distributions obtained using ALEST versus direct blade measured airloads were performed on data from three test cases. Results are summarized in Figures 1 through 4. In Figures 1 through 3, each plot shows an airload distribution over the full (azimuth-averaged) blade cycle. Zero degrees corresponds to the instrumented blade pointing straight up, and 180 degrees is in the tower shadow. Airload distributions from the 30%, 47%, 63%, and 80% span locations are shown in the four rows on each figure. Data from each of the test cases are shown in the three columns. In each plot, ALEST results are shown as a dotted line, and direct pressure measurements are a solid line.

Airloads estimated by ALEST show good agreement with those observed in both the high-wind and high-yaw cases. Mean values are close, and harmonic content is similar. ALEST works best when predicting outboard airloads in higher winds. In the low-wind case, however, ALEST does not work well, especially inboard. This is because the aerodynamic forces under these conditions are extremely small compared to the other gravitational, inertial, and centrifugal forces. The code can not extract small differences from large load values with enough precision to provide accurate estimates for this case.

Sensitivity studies were performed to show how variations in input parameters affect resulting airload estimation. Shaded regions in Figures 1 through 3 show these results. The sensitivity studies also give an idea as to the level of accuracy required of the measured input parameters.

Figure 1 shows the sensitivity to input bending moment. The upper boundary of the shaded region was obtained by adding a 5% full-scale bias error with a ± 5% of measured-value random error to the input data. Similarly, the lower boundary was obtained by subtracting a 5% bias error, and then adding the oscillating 5% random error. This was done to strain gage data at the six spanwise locations as summarized in Table 2.

Table 2. Input Bending Moment Channels

Location (% of Span)	Full-Scale Measurement Range (N-m)	Bias Error (N-m)	Random Error (%)
0 (Root)	±3200	±160	+5
20	±3000	±150	-5
40	±2300	±115	+5
50	±1400	±70	-5
70	±800	±40	+5
90	±300	±15	-5

Table 3. Blade Mass Distribution

Location (% of Span)	Mass (kg/m)	Stiffness (N-m^2)	Random Error (%)
0 (Root)	17.98	4.75X10^5	+5%
10	17.98	4.34X10^5	-5%
20	17.00	3.55X10^5	+5%
30	12.14	2.36X10^5	-5%
40	9.715	1.16X10^5	+5%
50	8.750	1.07X10^5	-5%
60	8.018	9.50X10^4	+5%
70	7.286	7.85X10^4	-5%
80	6.572	5.37X10^4	+5%
90	5.590	7.02X10^4	-5%
100 (Tip)	5.590	4.13X10^4	+5%

Figure 2 shows the sensitivity to a ±10% variation in precone angle. The measured precone angle is 3.5 degrees. The upper and lower limits of the shaded regions correspond to precone angles of 3.85 and 3.15 degrees, respectively. Figure 3 shows the sensitivity to blade mass distribution. Blade mass (and stiffness) are input in segments as shown in Table 3. The blade mass input values were varied by ±10% of value to simulate random measurement uncertainty. Similar parameter variations were performed on the input stiffness distribution values, but results were not shown because effects were minimal.

The sensitivity studies show that measurement error does not adversely affect results. All cases show similar error band width, with measurement errors having increased impact outboard. This is somewhat unfortunate because outboard airloads are usually of greatest interest. It is also unfortunate because outboard bending moment measurements are most susceptible to error from low strain gage signal level and high gain. This means that care must be taken to ensure accurate measurements outboard. Overall, the technique is shown to be robust in predicting airloads and tolerating typical measurement uncertainty levels. Furthermore, relative effects of measurement error becomes less significant as the blade is subjected to higher loading conditions.

Figure 4 shows full spanwise blade airload estimates from ALEST averaged over a complete blade cycle for each test case. The averaged measured pressures are also indicated with triangular symbols. This is probably the most useful form of result that could be used to verify airload inputs to a blade performance model such as PROP. Cyclic data, as shown in Figures 1 through 3, would be useful in verifying airloads in analytical tools such as FLAP.

Figure 5 summarizes the ALEST analysis procedure, showing how flap bending moments, blade properties, and machine operating conditions are used to produce an airload distribution. Figure 6 is a schematic representation of the data processing procedure. It shows an example in which the 80% pressure measurement data are used to calculate airload at one span location. Figure 6 also shows how this airload value is then compared to the corresponding ALEST airload distribution. It is important to note that results are produced in terms of rotational harmonics, which enable comparisons to be made over a full blade cycle.

CONCLUSIONS

ALEST requires measured strain gage flap bending moments, blade properties, and machine operating parameters as input to estimate blade aerodynamic loads. It works well during higher-wind loading conditions, even if input parameters have high measurement uncertainty. ALEST accurately depicts both mean and cyclic airload content under these conditions.

The ALEST technique becomes less reliable as airloads decrease. The point at which this occurs cannot easily be determined. It depends on blade configuration, aerodynamic loads relative to other loads, mode shape, measured bending moment accuracy, and deflection.

ALEST could be used to show the impact of aerodynamic phenomena, such as unsteady effects and delayed stall, because these are most likely to occur at higher wind conditions. This is evidenced in the high-yaw case presented, where dynamic stall is occurring as seen in the measured airloads, and is corroborated in the ALEST results. This lends support to the hypothesis that aerodynamically induced loads can be imparted into a machine and adversely affect structural response.

The technique works well on the particular blade configuration presented here because of the simple blade planform and zero twist, and because the blade does not have any edgewise or torsional mode frequencies near the first flap mode frequency to introduce false flap bending moment signals. Other blade configurations would have to be carefully considered as to their feasibility for this technique.

ALEST is probably most suited for use as a research tool to provide airload estimations for verifying analytical models such as FLAP or PROP. It might also be used to study effects of relative changes made to a blade configuration.

The code is undergoing refinement by incorporating a weighting matrix technique to be used to equalize strain distribution and thus improve mode-shape curve fitting. This should provide better airload estimation under low load conditions, however, it requires a more in-depth knowledge of the ALEST analysis technique.

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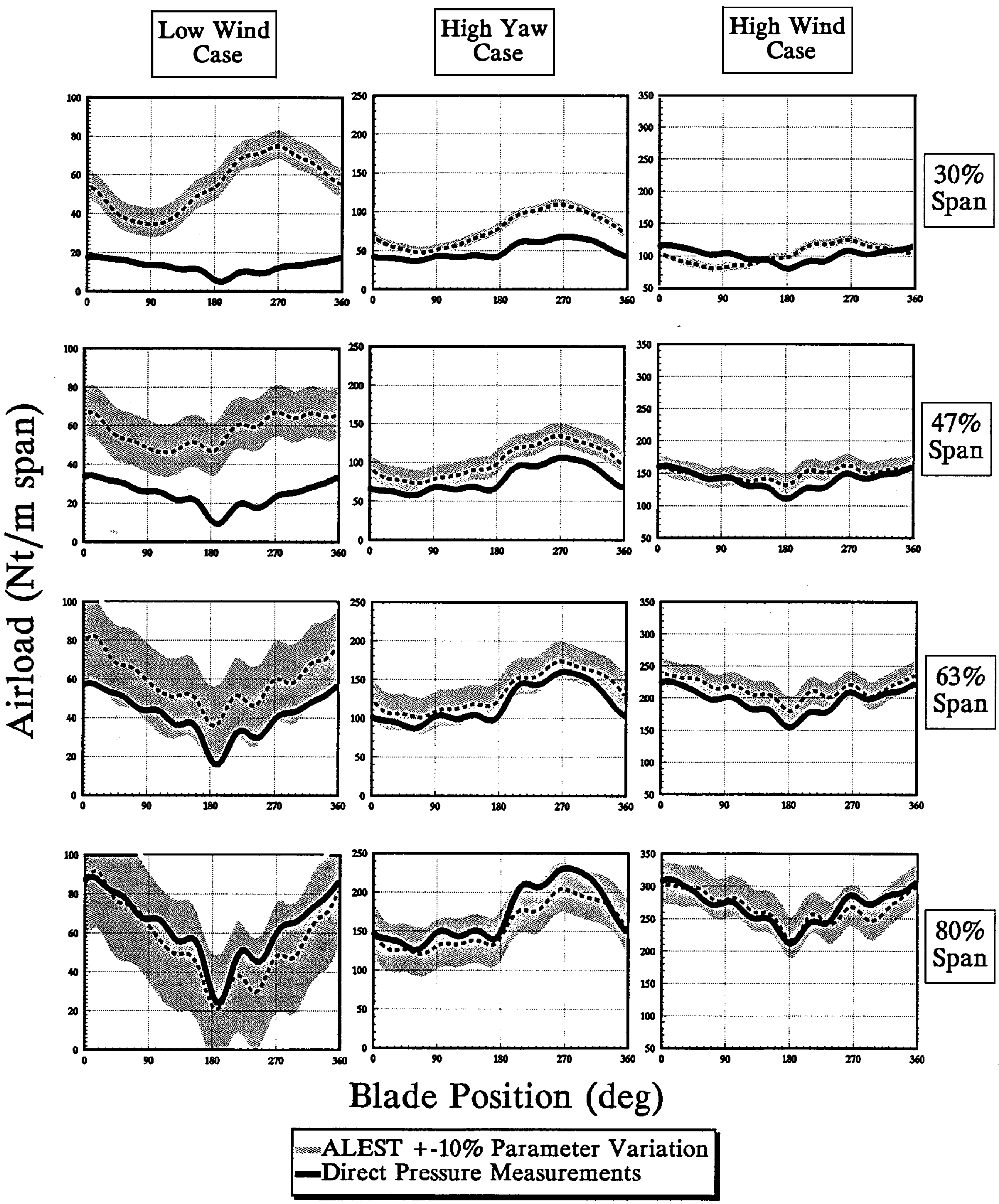

Figure 1. ALEST Sensitivity to Bending Moments

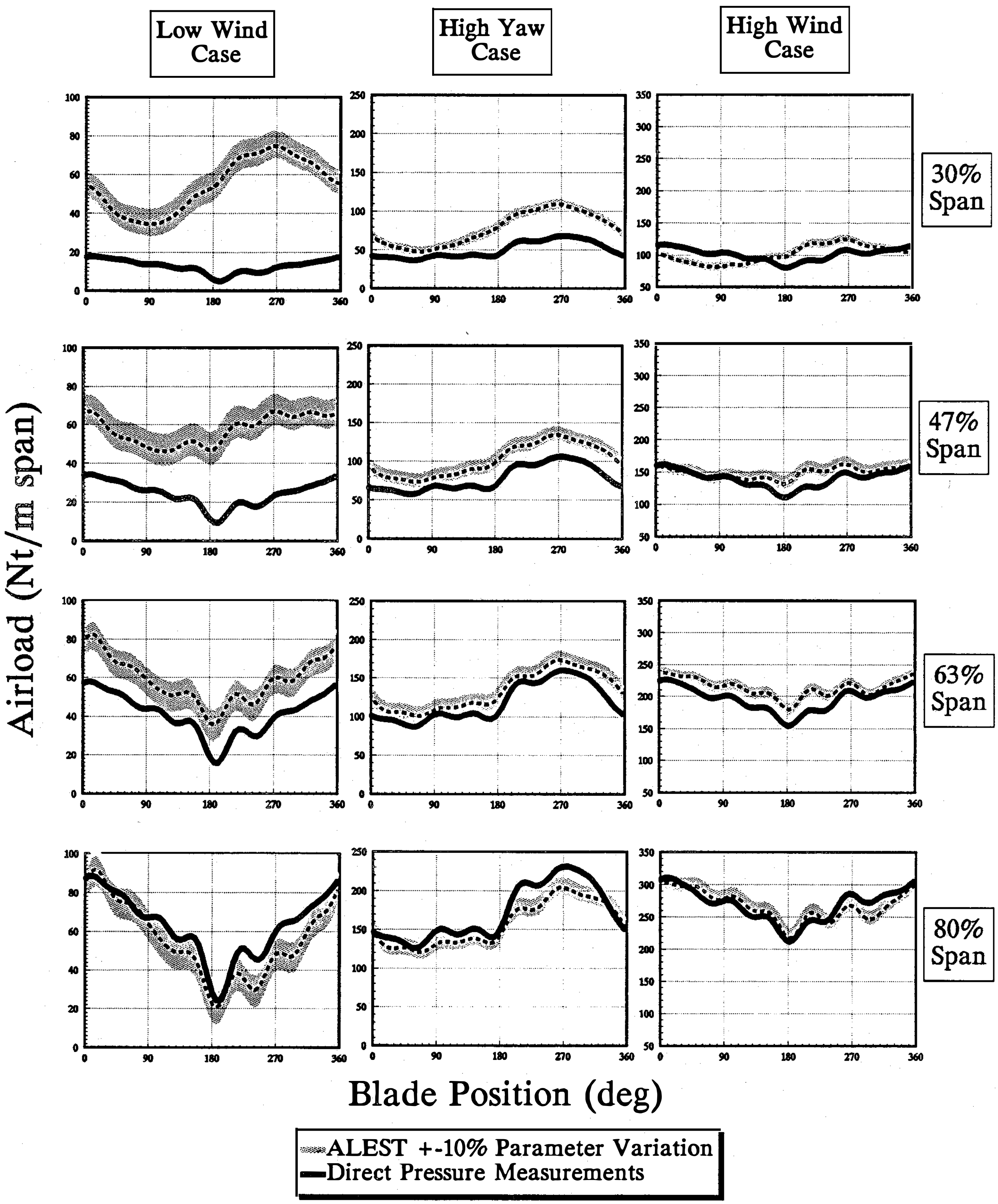

Figure 2. ALEST Sensitivity to Precone Angle

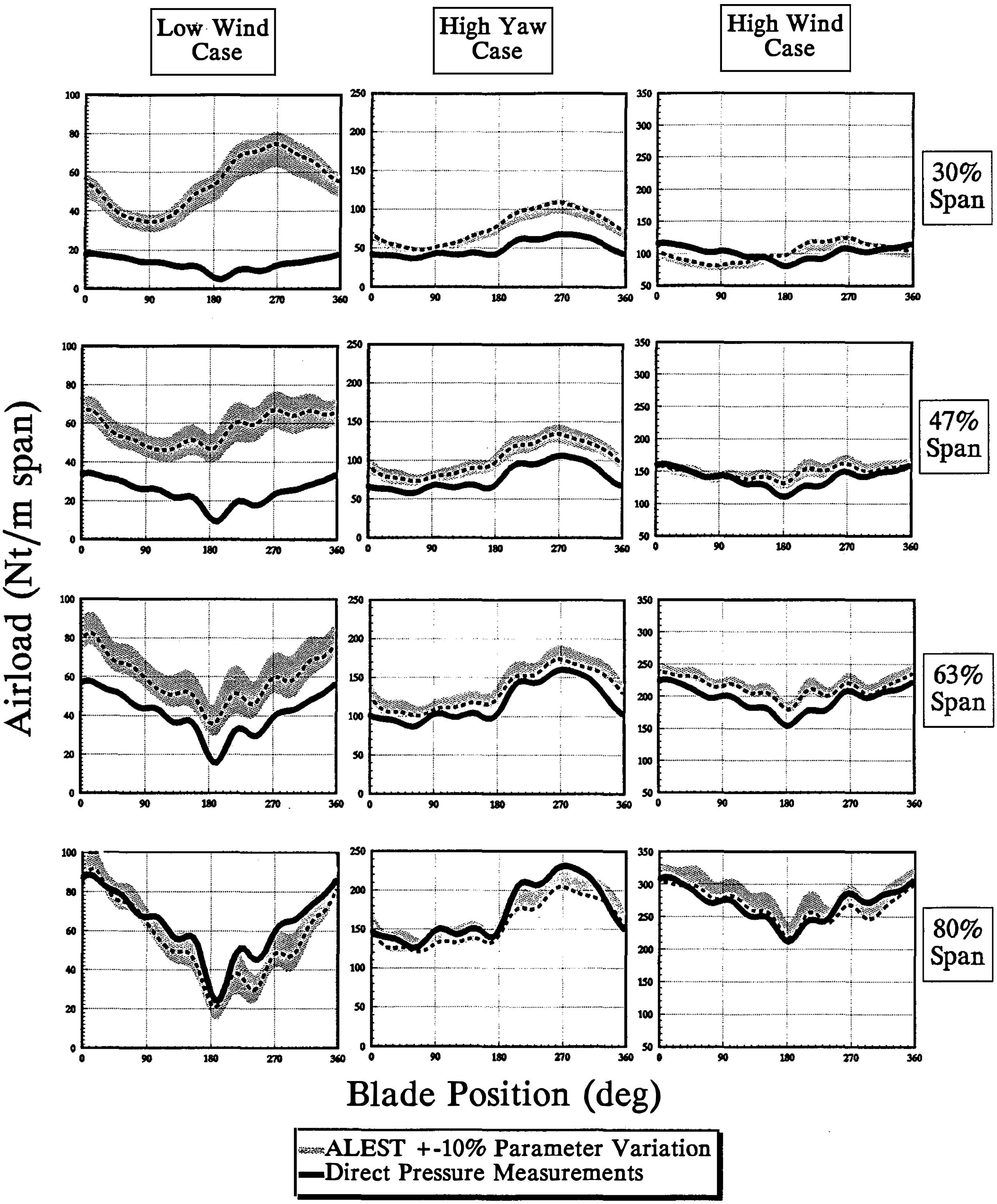

Figure 3. ALEST Sensitivity to Blade Mass Distribution

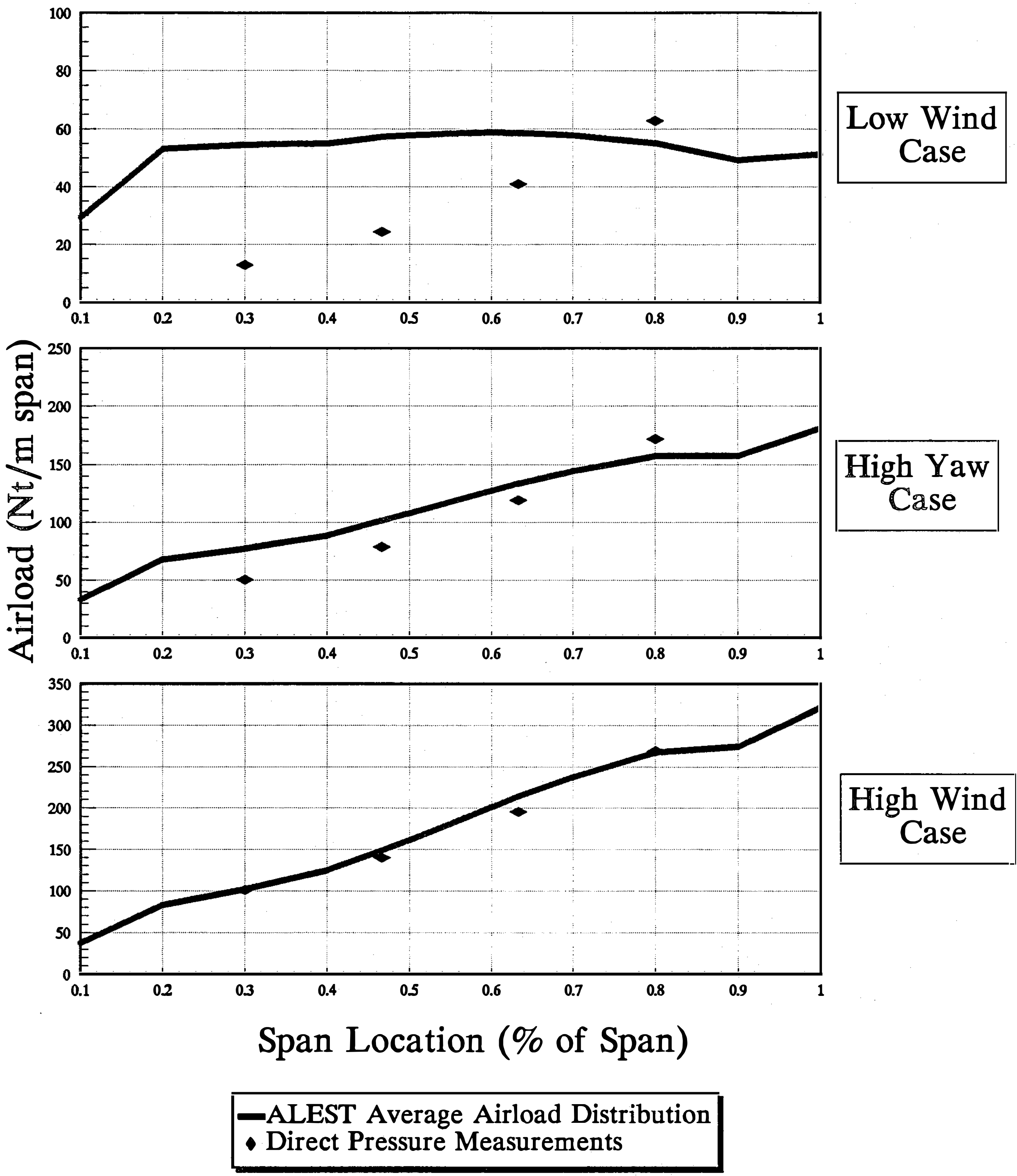

Figure 4. Spanwise Airload Distributions

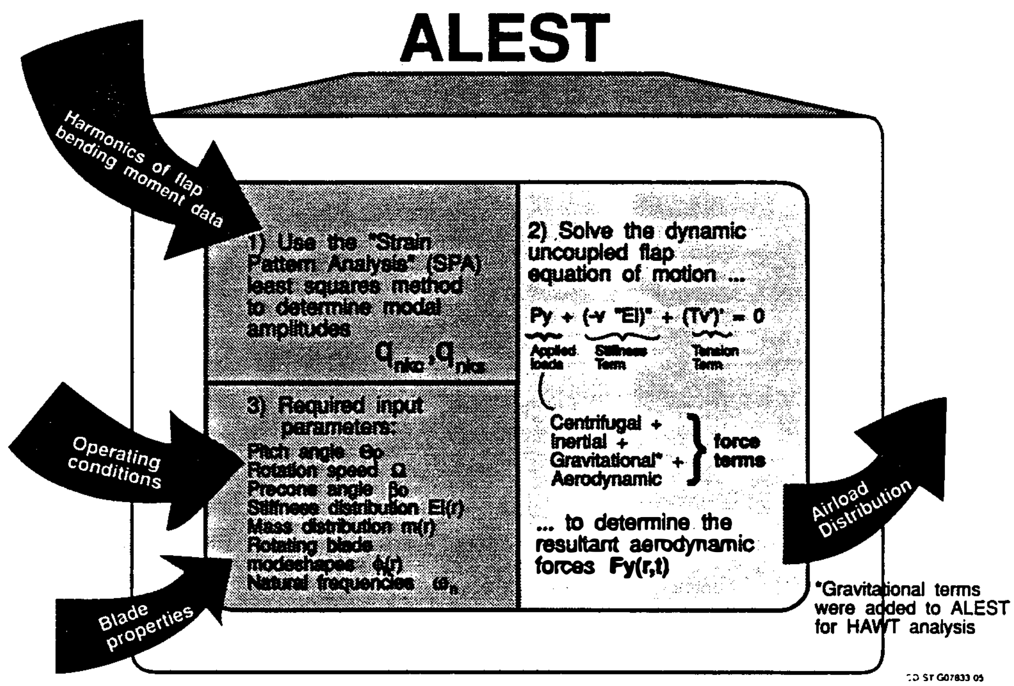

Figure 5. ALEST Analysis Procedure

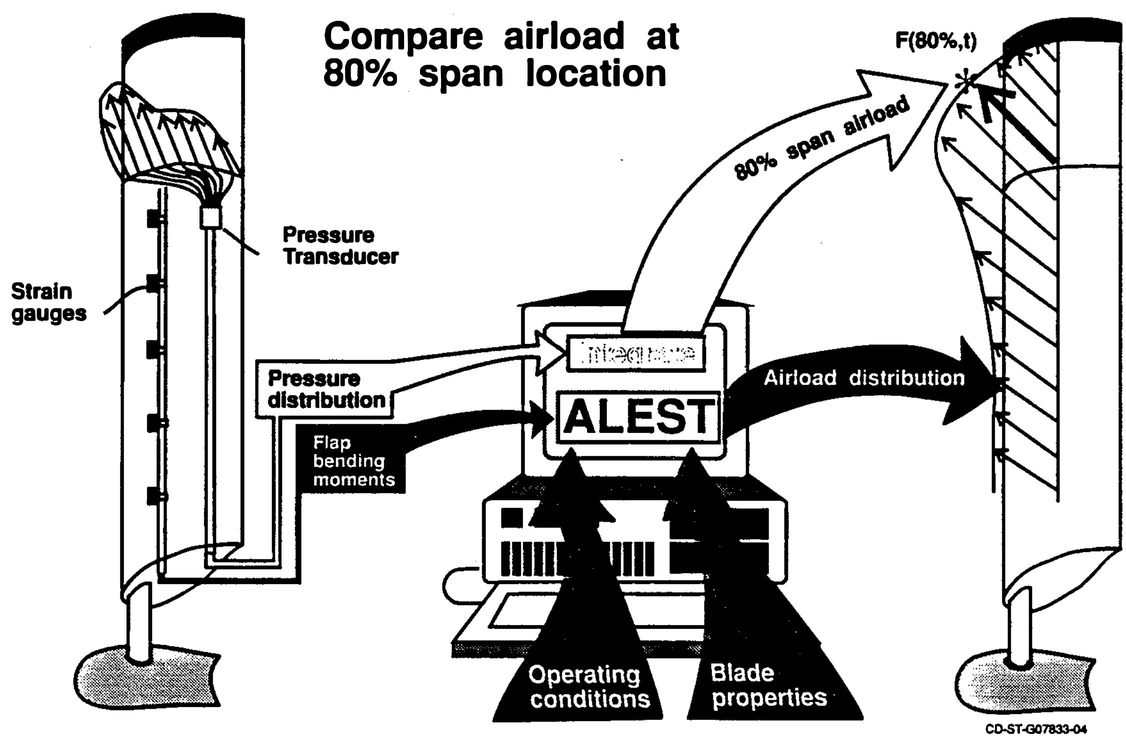

Figure 6. Data Processing Procedure