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Report on a Workshop Concerning Code Validation

National Wind Technology Center
Boulder, Colorado
August 8-9, 1996

National Renewable Energy Laboratory
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Golden, Colorado 80401-3393
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1. INTRODUCTION

The design of wind turbine components is becoming more critical as turbines become lighter and more dynamically active. Computer codes that will reliably predict turbine dynamic response are, therefore, more necessary than before. However, predicting the dynamic response of very slender rotating structures that operate in turbulent winds is not a simple matter. Even so, codes for this purpose have been developed and tested in North America and in Europe, and it is important to disseminate information on this subject.

The purpose of this workshop was to allow those involved in the wind energy industry in the United States to assess the progress in validation of the codes most commonly used for structural/aero-elastic wind turbine simulation. The theme of the workshop was, "How do we know it's right?" This was the question that participants were encouraged to ask themselves throughout the meeting in order to avoid the temptation of presenting information in a less-than-critical atmosphere. Other questions posed at the meeting are summarized below.

- What is the proof that the codes we use can truthfully represent the field data?
- At what steps were the codes tested against known solutions, or against reliable field data?
- How should the designer or user validate results?
- What computer resources are needed?
- How do codes being used in Europe compare with those used in the United States?
- How does the code used affect industry certification?
- What can we expect in the future?

This workshop was organized by David Malcolm of Advanced Wind Turbines Inc. and Alan Wright of NREL. The workshop was held at NREL at the National Wind Technology Center.

2. SUMMARY OF PRESENTATIONS

Nine invited experts spoke on the first day of the workshop. The speakers' presentations are appended to this report, and the following comments attempt only to highlight important aspects of the workshop.

2.1 A. Elliott, Mechanical Dynamics Inc., "Sources of error in ADAMS"

Andy Elliott described some of the common pitfalls in the use of ADAMS in wind turbine modeling. He concluded the following:

- It is very important to crawl-walk-run in developing ADAMS models. Start with a simple model of your system first and get that model running correctly with ADAMS. Develop a YawDyn equivalent model of your turbine first. Then add complexity in steps, checking for correct code results at each step.
- Some common pitfalls leading to improper development of models include
  - bad connectivity (joint or force misalignment),
  - incorrect or improperly formed equations (nonlinear considerations: sudden discontinuities, sudden changes, etc.), and
  - bad component properties (physically not realizable or unrealistic) can cause lots of numerical difficulties and iteration failures.
- Other problems with simulation can be due to
  - redundant constraints,
  - uncommunicative subroutines (slow convergence),
  - scaling (can lead to poor Jacobian conditioning),
  - damping coefficients,
  - constraint selection and arrangement,
  - formulation problems (Euler singularities),
  - nonlinearity considerations,
  - improper error limit sizes, and
  - improper step sizes.
- Remember that multiple solutions can exist.

2.2 E. Moroz and C. Wu, University of Texas at El Paso, "HAWT analysis codes applied to non-standard configurations and situations"

The speakers highlighted some of their problems in the use of FAST and ADAMS in the modeling of their two-bladed teetering hub test machine. E. Moroz concluded:

- It can be difficult to use ADAMS/WT to produce an ADAMS model of a nonstandard configuration. ADAMS/WT is most useful for developing ADAMS models for machines similar to the case examples in the ADAMS/WT user's guide. Additional case examples may need to be added to assist in modeling nonstandard configurations.
- The speakers noted some problems with the other codes, YawDyn and FAST:

  Some discrepancies were noticed for the value of teeter at high yaw angles between UTEP's TEETER code and YawDyn. In general, teeter should be small at zero yaw angle (depending, for example, upon the amount of steady vertical windshear, or gravity), should increase as the yaw angle increases, and then should approach zero teeter as the yaw angle approaches 90 degrees of yaw. The YawDyn code seems to do this differently than their TEETER code and their test data. The figures in the presentation (pages 4 and 5) show that YawDyn predicts a much more sudden collapse to zero teeter than does the TEETER code. Both the TEETER code and the test data show a much more gradual approach to zero teeter for high yaw angles. An explanation may lie in the way the TEETER code treats induced effects because it uses a disk average, whereas the YawDyn code calculates the induced effects on a elemental basis, using standard blade-element momentum strip theory. The dynamic inflow being used in YawDyn may need further refinement.

The FAST code was used for an investigation of the effect of delta-3 and several problems were identified:

a) phase shift error with nonzero delta-3 compared to zero delta-3 case,
b) free yaw stability anomaly,
c) underlying equations and assumptions for nonzero delta-3 questioned.

- The phase shift problem has been corrected by L. Freeman of Oregon State University. The corrections appear in version 2.3 of FAST.
- The free-yaw stability problem has not yet been resolved. Other codes such as YawDyn and ADAMS show that for large delta-3 angles, the machine will reach a stable solution at a high yaw angle. The FAST code shows that a much smaller yaw angle is reached. There may still be an error in a coordinate transformation for nonzero delta-3 angles.
- Wu added a possible explanation for these anomalies, especially in FAST, and presented coordinate transformations between the hub and yaw column, for nonzero delta-3 angles. He showed a possible error in the transformation matrix. He also went on to describe possible problems with the assumed tower deformations and transformations between tower top rotation and ground if the tower has large deflections and slopes. This problem is related to the sequence of rotations in the coordinate transformation, when tower deformations and slopes become moderate or large. To date, the FAST code assumes small tower and blade deflections, so that the sequence of rotations is not important.
- Wu went on to pose the question of "how much model tuning do we allow? Could excessive model tuning mask possible code errors?"

2.3 G. Bir, National Renewable Energy Laboratory, "Assessment of ADAMS' modal analysis capabilities"

Gunjit Bir showed work to date that assesses the use of ADAMS/Linear to correctly linearize a wind turbine model about a stationary state and also to calculate operational modal characteristics. He showed results of modeling some simple rotating beams and compared results with known analytical solutions. Some of the most important points from his presentation were these:

- Results for simplified beams (uniform and tapered) were compared to known analytical solutions. Bir extracted modal information for a rotating beam using ADAMS in two ways: i) use of ADAMS/Linear, and ii) results of applying an impulse.
- The ADAMS/Linear method worked well at low rotorspeeds. At moderate rotorspeeds, the results deteriorated gradually. At medium to high rotorspeeds, the results broke down suddenly. The higher the blade taper ratio, or the higher the blade flexibility, the lower the rotorspeed at which results began to deteriorate.
- The deterioration in ADAMS/Linear results for a rotating beam may be due to incorrect linearization or neglect of certain important rotation-related terms in the Jacobian in the linearization process.
- Participants disagreed about the need to develop a full-blown stability analysis capability. Craig Hansen suggested that we add some "rules of thumb" for the impulse application process for determining rotating modal properties. Bill Holley considered that this work was important, because it is used in the helicopter industry to validate models. He also thought we should formally document this work to assist in getting codes accepted by certification agencies.

2.4 D. Malcolm, Advanced Wind Turbines, Inc., "Steps in the validation of models"

D.Malcolm showed the difficulties and successes in modeling the AWT-type machines with ADAMS. He posed several questions and made several suggestions.

- Blade static tests are often overlooked in favor of modal tests. In the future we may need to perform some blade static tests in addition to modal tests to validate our codes.
- There can be difficulties in using modal test results for code validation.
  - During blade modal tests, are the boundary conditions known?
  - It is often difficult to get agreement of first flap and first edge natural frequencies. If one agrees with measured data, the other usually does not.
  - When modes involve rigid body motions such as teeter and yaw (as in the rotor symmetric edge modes when the rotor is vertical), it is often difficult to obtain agreement between model results and modal test data. This may be due to difficulty in modeling friction of these bearings, especially for the small motions and deflections that are characteristic of a static modal test. We need to better understand the dynamics of bearings.
  - Operating frequencies are hard to determine from operating test data.
  - Agreement between model and measured modes is usually good for those modes which do not involve periodicity in the supports, e.g., symmetric flap modes. Those modes which do involve periodicity (e.g., symmetric edge modes and asymmetric flap modes) seem to be consistently higher compared to measured results by about 0.3P. This discrepancy can be critical in avoiding operating resonances.
  - A question raised was, What is the involvement of aerodynamic loads in the natural modes?
  - Some problems involved with simulation of transient events:
  - does turbulence really contain realistic events as seen in the field?
  - response of the system to transient events is highly dependent on the characteristics of the teeter damper (very nonlinear),
  - use of 2-D airfoil characteristics in modeling highly nonlinear behavior,
  - how do we really describe and correlate the overall effects of turbulence on the rotor?
  - Some general conclusions made in this presentation:
  - ADAMS cpu time is becoming more acceptable with the use of a Pentium and Windows/NT.
  - The convergence of ADAMS in wind turbine simulation is still a "black art."
  - Confirmation of all component properties is a common requirement for all models.
  - System dynamics are equally effected by rotor, drive-train, and tower.

2.5 R. Wilson, Oregon State University, "The FAST code"

Bob Wilson discussed the development and validation of the FAST code. He also raised some important issues for further thought.

- Results of the FAST code validation for the ESI-80 machine contain some discrepancies with the teeter results (see the histogram of teeter as compared to test data).
- One issue Bob Wilson has raised at previous meetings is the correct reference frame in which to resolve aerodynamic forces. He thinks it is important that the aerodynamic forces be resolved into the deflected blade coordinate system, as is done in FAST. This force resolution will be very important for flexible machines.
- Other issues raised by the speaker or others during this presentation:
  - In simulating turbulence, what coherence should we really use (what other people use usually)?
  - How do we determine blade stiffness? Do we include skin effects? Should we back stiffness out of an Euler model?
  - Cl and Cd values for high angles of attack - are they a big issue as many people seem to think?
  - What is the real physical source of drive-train damping? Most drive-trains seem to be more highly damped than analytical predictions predict. What is the source of this damping?

Is the assumption in the AeroDyn aerodynamic subroutine package of a stable yaw solution correct? This assumption may need to be reviewed.

2.6 A. C. Hansen, University of Utah, "Validation of the YAWDYN and AERODYN codes"

Craig Hansen presented results of the validation of YawDyn, AeroDyn, and ADAMS using data from NREL's Combined Experiment Rotor (CER).

- Craig and group attempted to do first-cut validation with CER data without any model tuning. In general the four-per-revolution content of the blade flap moments was underpredicted. Craig then described how they had to soften the tower top of the CER machine in order to obtain better correlations. (This problem is reminiscent of that encountered in modeling the AWT-26 P1 machine, in which the upper tower top elements had to be softened in order to correctly model the symmetric edge activity.)
- Predicted lift coefficients for the CER machine near the blade tip did not match field data.
- General conclusions from this presentation:

    Models do fairly well when inputs are accurate on the first try. Usually inputs are not very accurate for the first modeling attempt and they need refinement.

    Airfoil data, especially for high angles of attack, is a big problem. A standardized table of airfoil data, compiled by NREL, was suggested.

    Detailed structural data is difficult to obtain on the first try. FEA and modal test data is very helpful.

    The bearing and joint stiffness and damping characteristics are very difficult to obtain and understand. These can have a major impact in accurate modeling.
- The largest void in validation studies is in teetering rotors. Use of a two-bladed teetering CER may help.

2.7 N. Kelley, NREL, "Turbulent models; are they correct?"

Neil Kelley gave highlights of modeling turbulence with the SNLWIND-3D code.

- The biggest issue is that the SNLWIND-3D code has not been thoroughly validated against test data.
- How can this code be validated? What kind of test data?
- Only a "backhanded approach" has been taken in validation of this code because of a lack of atmospheric test data. This approach has used "validated" models of actual field turbines and compared predicted loads to measured loads under a range of inflow conditions. So far, the three-bladed rigid hub Micon turbine and the two-bladed teetering hub AWT-26 machine have been simulated.
- In general it was found that

    the combination of a good representative turbulent inflow model and a good turbine model produce realistic results;

    the character of inflow is very important in assessing simulation results;

    we need corroborating data to totally confirm hypothetical results.
- Other comments:

    We need to characterize "terrible turbs" from simulation and use this information to help guide a future measurement program to confirm results using test data.

    Bill Holley indicated that it was very important at Kenetech to tune the turbulence model to the site parameters in order to even begin to get realistic results.
- The big issue still remained: how do we finally and completely validate this turbulence model and code?

2.8 W. Holley, consultant, "Certification issues"

Bill Holley gave a general presentation on requirement for certification. Some of his main highlights included the following:

- He outlined what can be done to get our codes accepted by certifying agencies. NREL should start to collect all validation studies into one volume.
- He outlined the various types of certification: i) formal, ii) informal. In most types of validation, certifying agencies will require a review of all input parameters. There is no standard set of conditions for code validation upon which an agency will put its stamp of approval. The requirements for code approval seem very ambiguous.
- NREL might also run side-by-side comparisons between each code and compare the results to measured loads for two or three different machines. Publish results in one volume.
- Some general conclusions:
  - use of validated codes is a requirement for certification,
  - proof of validation is akin to convincing a jury in a court of law,
  - there are no standards for code validation, only general guidelines,
  - the most expedient strategy may be to use codes developed by a member of the "club."
- The requirement to get codes accepted by certifying agencies seemed fuzzy at best. Bill suggested gathering all of the validation work performed for the codes to date and publish as one document.

2.9 D. Quarton, Garrad Hassan, "The BLADED code"

David Quarton gave highlights on validation and progress with Garrad Hassan's BLADED code. The BLADED code has the following degrees of freedom: blade flap and edge bending, rotor teeter, nacelle yaw, tower fore-aft and tower lateral. It also has drive-train torsion of the low- and high-speed shafts. The code uses assumed modes, which are calculated using a finite element model. These modes are then used in the equations of motion for the main dynamic response and loads calculations. It also provides for some drive-train mounting dynamics. It can model wind shear, turbine wake flow, tower shadow, and turbulence (based on von Karman). It uses standard blade-element momentum theory with inflow options: equilibrium wake, frozen wake, or Pitt and Peters dynamic inflow. The dynamic stall is based on the Beddoes method. Various control systems can be modelled, including fixed speed-fixed pitch, fixed speed-variable pitch, variable speed-fixed pitch, and variable speed-variable pitch. It can also implement various aero controls such as full span pitch, partial span pitch, ailerons, and spoilers.

- Conclusions from modeling of the Carter 300:
  - good predictions of steady performance and loads,
  - reasonable prediction of low frequency modes, but higher modes more difficult to predict,
  - modal approach successful for predicting dynamic behavior in operation, but may not be true for parked rotor loads,
  - poor prediction of dynamic behavior and loads for stalled flow Further work is needed to improve representation of unsteady aerodynamic stall and interaction with the flexible structure,
  - preliminary indications of good representation of the free yaw dynamic behavior.
- Three main areas need further code validation and enhancement:
  - wind modeling in complex terrain and extreme wind conditions,
  - aerodynamics: steady and dynamic stall. Accurate Cl and Cd data for high angles of attack. Aerodynamics of highly deflected blades.
  - structural dynamics of very light-weight flexible turbines: use of modal methods, aeroelastic stability and dynamic loading.

2.10 D. Quarton, Garrad Hassan, "The European scene"

David Quarton also gave highlights on the 28th IEA Experts Meeting on State of the Art of Aeroelastic Codes for Wind Turbine Calculations, held in Lyngby, Denmark on April 11-12, 1996. Some of his main highlights include the following:

- Funding for code development and validation in Europe is almost gone. There are two main areas of turbine development activities in Europe:
  - rigid-stiff machines employing sophisticated electrical solutions, and
  - flexible machines. Most emphasis seems to be directed at the continued development of relatively stiff machines employing sophisticated electrical solutions for the alleviation of loads.
- There is a general consensus in Europe that a further code benchmark exercise would be beneficial, especially modeling a flexible machine. (There was considerable interest in the group of having the United States join in on such a benchmark exercise, or if a benchmark exercise is carried out in the United States, having the Europeans participate. NREL will look further into how to join the European community in a benchmark exercise.)

3. SUMMARY OF DISCUSSION

On Friday morning a session for general discussion allowed each person to express his views regarding code validation.

Tom Carne gave some ideas on how to perform more thorough validation. He suggested performing component tests (blades, towers, etc.) before trying to validate the full system. It is also important to validate the non-rotating parked machine, which eliminates rotating frame and aerodynamic effects. Once the model is validated for these conditions, then go on to do the full operating machine. There is no need to go any further if parked modal predictions do not agree with measured results. He outlined ways developed at Sandia National Labs to determine the natural frequencies of operating VAWTs.

Ken Deering stressed understanding of which loads are the most important to predict. There is no sense trying to improve codes to better prediction of loads in the low amplitude-high frequency range. We need to focus on what affects predictions in the low-frequency high-amplitude range, where most fatigue damage occurs.

Dave Quarton stressed the need for better quality Cl and Cd data for input to the models, especially for higher angles of attack (at stall and above). He also stressed further research on 3-D effects and its effect on Cl and Cd. He mentioned that the BLADED code overpredicted cyclic loads for the Carter 300 machine and that the reason might be the dynamic stall model. The dynamic stall models provide some aerodynamic damping but not enough, and thus the overprediction in loads and response for this type of machine. He pointed to the need for further research in the area of extreme loads, and the prediction of winds for those conditions.

Chris Wu described the need for better documentation of codes, especially FAST. He also thinks we should start development of a specialized code for use by controls engineers, especially reduced order models.

Craig Hansen talked about how we can get manufacturers to make more use of our codes. Perhaps a code benchmark exercise would help. He talked about gaps in code validation especially for teetering rotors. He spoke of use of the data from the two-bladed teetering hub version of the CER machine. He did not think there is a pressing need to perform further code validation for stiff machines, but he does think we should progress to flexible systems.

George James spoke of the need for accurately predicting structural damping and gave some suggestions on how we might do this. This was balanced somewhat by the issue of aerodynamic damping dominating some modes. This may not be true for modes involving blade lag which can have very light aerodynamic damping.

Ganesh Rajagopalan spoke of the need to have software specialists perform code cleanup activities instead of engineers within the laboratories.

Herb Sutherland talked about the need for choosing a turbine and intensely testing this machine with a wealth of strain gages and other instrumentation. He also spoke of the need to take a turbine as designed and use drawings to determine code input and see how the codes perform before doing any model tuning. These results need to be documented. After this has been done, then perform more in-depth validation, from more refined input data.

Bill Holley spoke of the tough situation David Malcolm faces with turbine certification. We must get the codes approved by a certifying agency. Get documentation collected together. Bill also spoke of the fact that the codes were ahead of what we can measure (they have more input parameters [knobs to turn] than can be measured).

Sandy Butterfield spoke of the fact that the inflow may be the area in which we are doing the most guesswork. We are also making some mistakes in how we put models together (probably with ADAMS).

4. CONCLUSIONS

The following aspects were agreed to be of the most concern.

The different requirements of validation of the **system modeling**, **input** to the model, and the **code** itself were noted.

- **Inflow and aerodynamics** need the most improvement. We need further validation of the wind models (SNL-3D etc.) and assurance that they can include the characteristics of extreme events. We need validated statistical procedures to extrapolate to extreme loads. It is also necessary that we design for reality rather than for a particular regulation such as the IEC code.

- More work must be done on **dynamic stall** models, especially in conjunction with flexible rotors. The next phase of CER data (two-bladed teetering rotor) from field operation or from wind tunnel testing will be of great use. Input into this test program from outside of NREL would be appropriate.

- Performance of a **code benchmark exercise**. This would be of use to several parts of the industry. It must be carefully planned and coordinated with other countries.

- **Control system design**. We may need codes other than ADAMS with a reduced number of degrees of freedom. This topic will be the focus of another meeting similiar to this one and organized by NREL.

- Determination of **operating turbine modal characteristics**. This is is important and NREL should solicit opinions from elsewhere in the industry.

In general there is much to do with limited resources that should be coordinated and not wasted. Meetings such as this are one way to disseminate information, exchange ideas and avoid duplication.

The next ASME/AIAA meeting will be used to submit NREL's code development plan to this group and discuss further issues.

Final announcement of a 1-1/2 day workshop on

"CODE VALIDATION,
or
HOW DO WE KNOW IT'S RIGHT?"

Dates: **Thursday, August 8th and Friday August 9th, 1996 (until 1200 noon)** (immediately following the NREL subcontractors' review and the AWEA R&D meetings)

Place: **National Wind Technology Center, Rocky Flats, Colorado, main auditorium**

Objective: The purpose of this informal meeting is to allow all involved in the wind energy industry in the United States to assess the progress that has been made in validating the codes most commonly used for structural/aero-elastic wind turbine simulation.

Theme:
* What is the proof that the codes we use can truthfully represent the field results?
* At what steps were the codes tested against known solutions, or against reliable field data?
* How should the designer/user validate results?
* What computer resources are needed?
* How do codes being used in Europe compare?
* How does the code used affect industry certification?
* What can we expect in the future?

Format: The first day will be occupied by a number of informal presentations by invited speakers who will address topics that include those listed above. Each presentation will last approximately 30 minutes and will be followed by 10 minutes for questions and discussion. Speakers are encouraged to hand out copies of any viewgraphs or slides that they may use.

Friday morning will be spent entirely in a general discussion and summary of the previous day's talks.

Program: See accompanying program details

Information: More information can be obtained from

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206-292-0070/138, Fax: 206-292-0075, email: 102262.735@compuserve.com

Cost: There is no cost for the workshop. NREL will provide lunch on the first day.

Registration: Contact David Malcolm at the above address(es)

Code validation workshop, NWTC, August 8,9, 1996

Program (rev B)

Thursday, August 8th

time		speaker	subject
8:30		R. Thresher	general introduction
8:40		D. Malcolm A. Wright	specific introduction workshop objectives/theme
9:00 - 10:30	Code algorithms		
chair: Sandy Butterfield	9:00	A. Elliott, MDI	Source of errors in ADAMS
	9:45	C. Wu, E. Moroz, UTEP	HAWT analysis codes applied to non-standard configurations
10:30 - 10:50	break		
10:50 - 12:10	structural		
chair: Tom Carne	10:50	G. Bir, NREL	ADAMS vs known solutions
	11:30	D. Malcolm, AWT	Steps in validation of models
12:10 - 1:10	lunch		
1:10 - 3:10	aero		
chair Mike Robinson	1:10	R. Wilson, OSU	The FAST code
	1:50	A.C. Hansen, U of Utah	NREL's combined experiment
	2:30	N. Kelley, NREL	Turbulent models: are they correct?
3:10 - 3:30	break		
3:30 - 4:50	general		
chair: Herb Sutherland	3:30	W. Holley	Certification issues
	4:10	D. Quarton, Garrad Hassan	Validation of the Bladed code

Friday, August 9th

time	participants	subject
8:30 - 9:15	D. Quarton, Garrad Hassan A. Wright, NREL	panel discussion: The European scene
9:15 - 10:15	chair: A. Wright/ D. Malcolm	general discussion
10:15 - 10:30		break
10:30 - 11:30	chair: A. Wright/ D. Malcolm	summary of the workshop

Sources of Error in ADAMS

Virtual Prototyping

Formulation of E.O.M.

- Lagrangian approach

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}}\right) - \frac{\partial T}{\partial q} + \left(\frac{\partial \Phi}{\partial q}\right)^T \lambda = F$$

- Gives a system of algebraic and 2nd-order differential equations (DAE's)
- Differential equations are transformed to 1st order
- Constraint equations are appended

Mechanical Dynamics

Sources of Error in ADAMS

Virtual Prototyping

Solution Methodology

- System of 1st order DAE's

$$F(\dot{Y}, Y, t) = 0$$

- Jacobian is formed semi-symbolically
  - Standard elements are done symbolically
  - "Function-based" elements are done numerically
- Backward differentiation formula used to substitute for derivatives
- Predictor-corrector scheme used to integrate

Mechanical Dynamics

Sources of Error in ADAMS

Virtual Prototyping

Predictor-Corrector Method

- Consistent set of initial conditions required
- Variable-order predictor

$$Y_{n+1} = F(Y_n, Y_{n-1}, \ldots)$$

- Full system is solved using modified Newton-Rhaphson algorithm.
- If result is sufficiently close to prediction, step is accepted and we go forward.
- Otherwise solution is corrected until convergence is reached or corrector fails.

Mechanical Dynamics

Sources of Error in ADAMS

Virtual Prototyping

Predictor-Corrector Method - 2

- Predictor is tried again with new step size.
- Cycle repeats until success or abandonment.

- Important Components
  - Predictor algorithm
  - Corrector algorithm
  - Solver choice
  - Error control

Sources of Error in ADAMS

Virtual Prototyping

BDF Integrator Predictors

- Approximate 1st derivatives with some backward differentiation forward:

$$\dot{x} = \frac{x - x_{n-1}}{h}$$

$$\dot{x} = \frac{3x - 4x_{n-1} + x_{n-2}}{2h}$$

- Fixed/Variable Coefficient
- Fixed/Variable Order
- Fixed/Variable Time Step

Mechanical Dynamics

Sources of Error in ADAMS

Virtual Prototyping

Corrector Algorithms

- Basic Approach

$$G(\dot{Y}, Y, t) = 0$$

$$J * \Delta Y = -G$$

$$Y \leftarrow Y + \Delta Y$$

- Residual

$$r = G(\dot{Y}, Y, t_{n+1})$$

$$J * \Delta Y = -r$$

Mechanical Dynamics

Sources of Error in ADAMS

Error Control

- Corrector convergence uses λ_{∞} norm
- Corrector divergence uses λ_1 norm
- Divergence checked using relative error from corrector iteration to iteration
- For convergence and advancement
  - error is less than T*1E-3
  - max residual for any redundant constraint less than T*1E-3
- For WSTIFF, uses T*0.57*1E-3

Sources of Error in ADAMS

Sources of Simulation Errors

- Incorrect Models
  - Bad connectivity
    - Joint or Force alignment
  - Incorrect or improperly-formed equations
    - Nonlinear considerations
    - Parameter lists
  - Bad component properties
    - Not realistic
    - Not realizable
    - Bad guesses?

Sources of Error in ADAMS

Virtual Prototyping

Sources of Simulation Errors

- "Less-than-optimum" Modeling Choices
  - Redundant constraints
    - model configuration may be unexpected
  - Uncommunicative subroutines
    - can slow convergence
  - Scaling
    - can lead to poor Jacobian conditioning
  - Damping coefficients
    - ?????
  - Constraint selection and arrangement

Mechanical Dynamics

Sources of Error in ADAMS

Virtual Prototyping

Sources of Simulation Errors

- Numerically-Induced Errors
  - Nonlinearity considerations
  - Numerical mathematics' limitations
  - Formulation problems
    - Euler singularities
    - Undocumented code features
  - Insufficient results checking
    - Proper error limits
    - Proper step size
  - Multi-turn angle limits?
- We try hard, but you must do reality checking!

Sources of Error in ADAMS

Virtual Prototyping

Handouts

- Integrator Selection and Control Strategies
  - Which integrator
  - What error
  - What to do about corrector failures
- Solving Corrector Problems
  - Calahan or Harwell
  - Using BDFPAR
  - Verification / Validation

HAWT Dynamic Analysis Codes Applied to Non-Standard Configurations and Situations

by

Kung Chris Wu and Emil Moroz

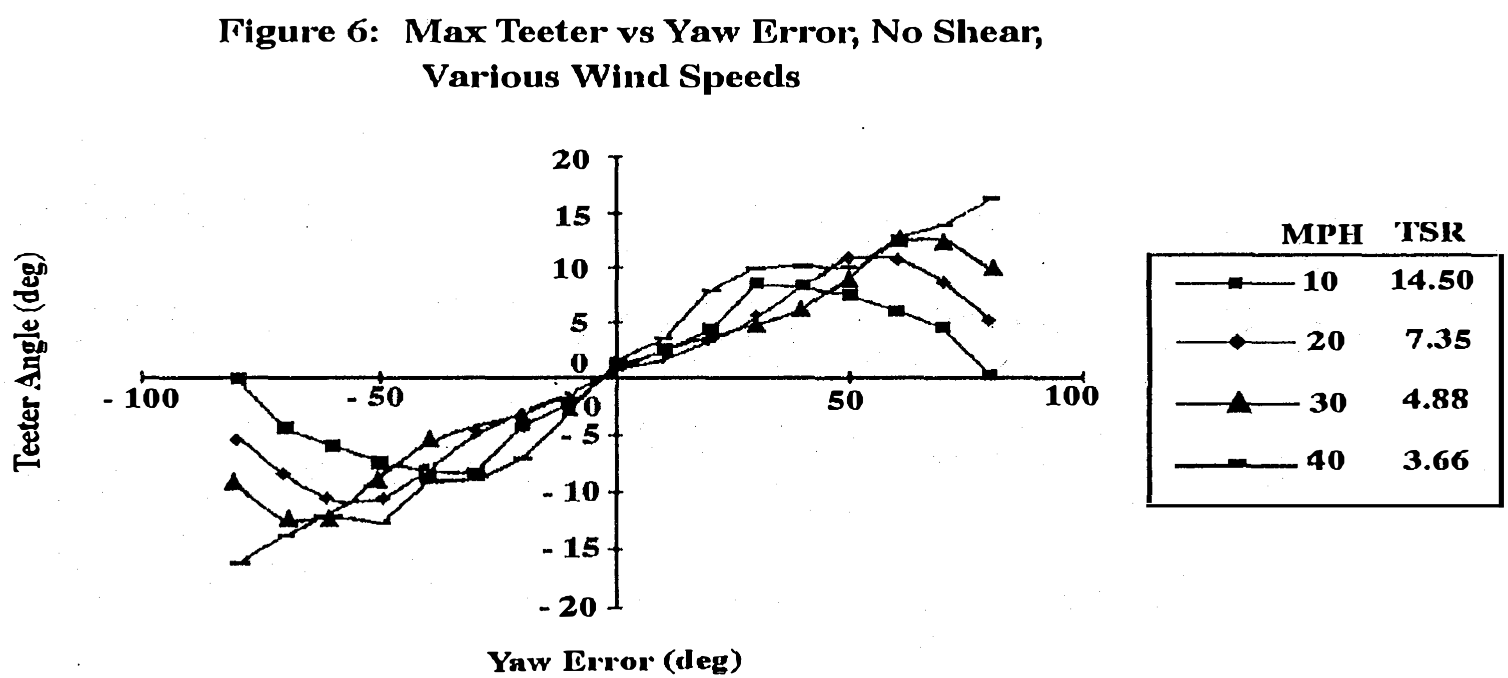
The University of Texas at El Paso

UTEP

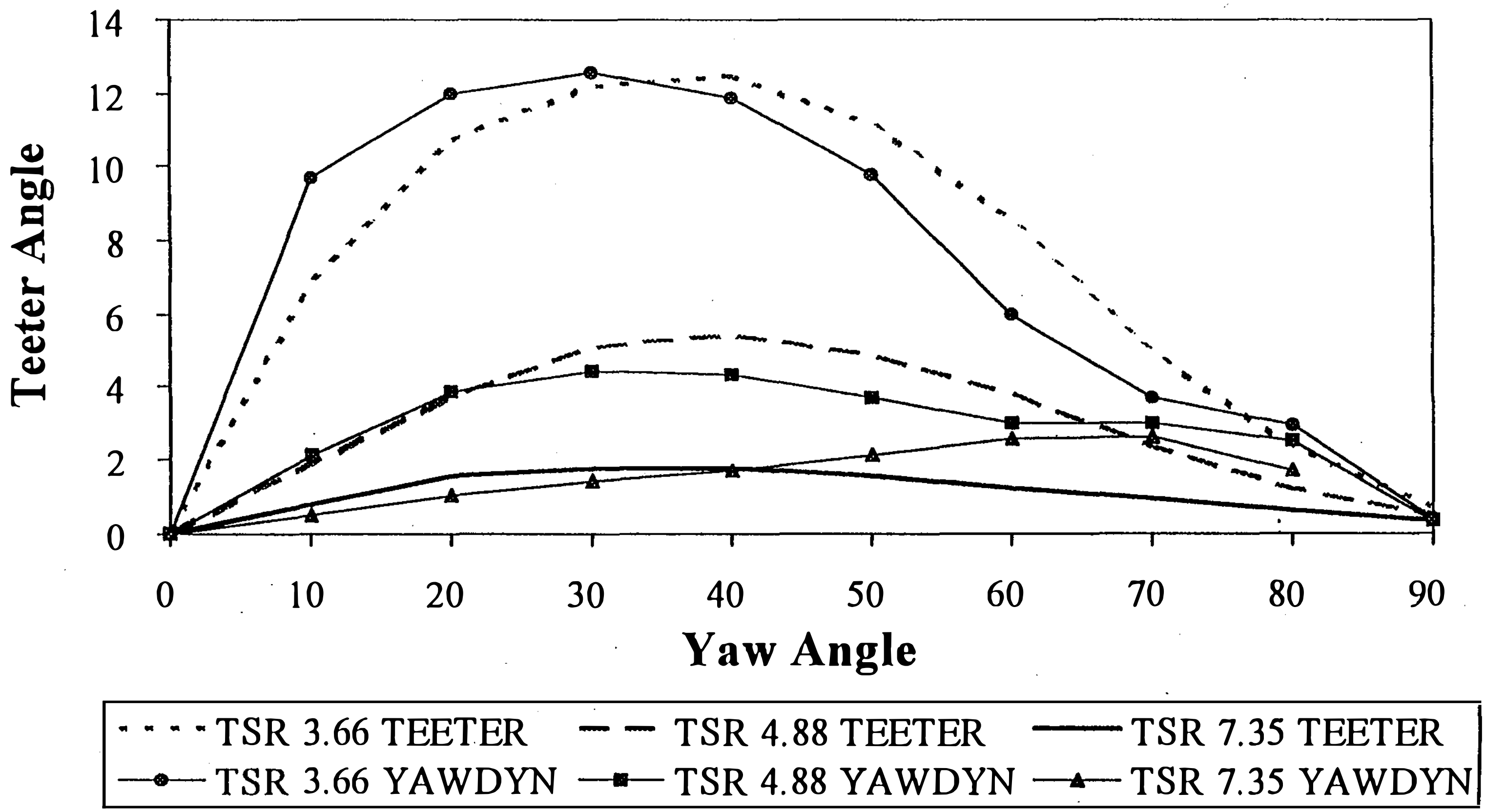
Overview

- Experiences with Yawdyn, FAST2 and ADAMS/WT (Emil)
- Issues associated with basic equations of motion of FAST2 (Chris)
- Questions Raised

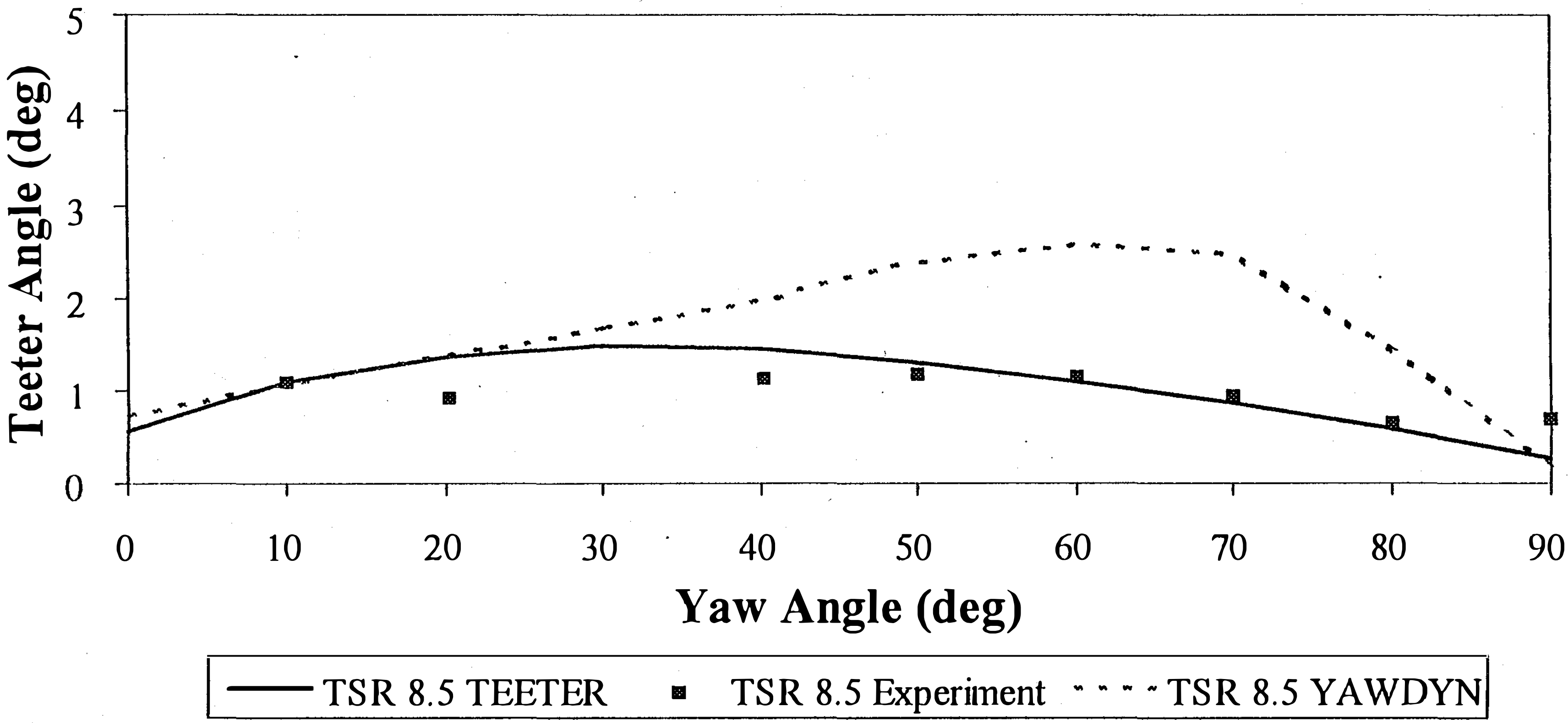
Reproduction of Figure 6 from Olsen and Coleman (1994)



TEETER and YAWDYN Predictions



Comparison Between TEETER, Yawdyn and Experimental Data

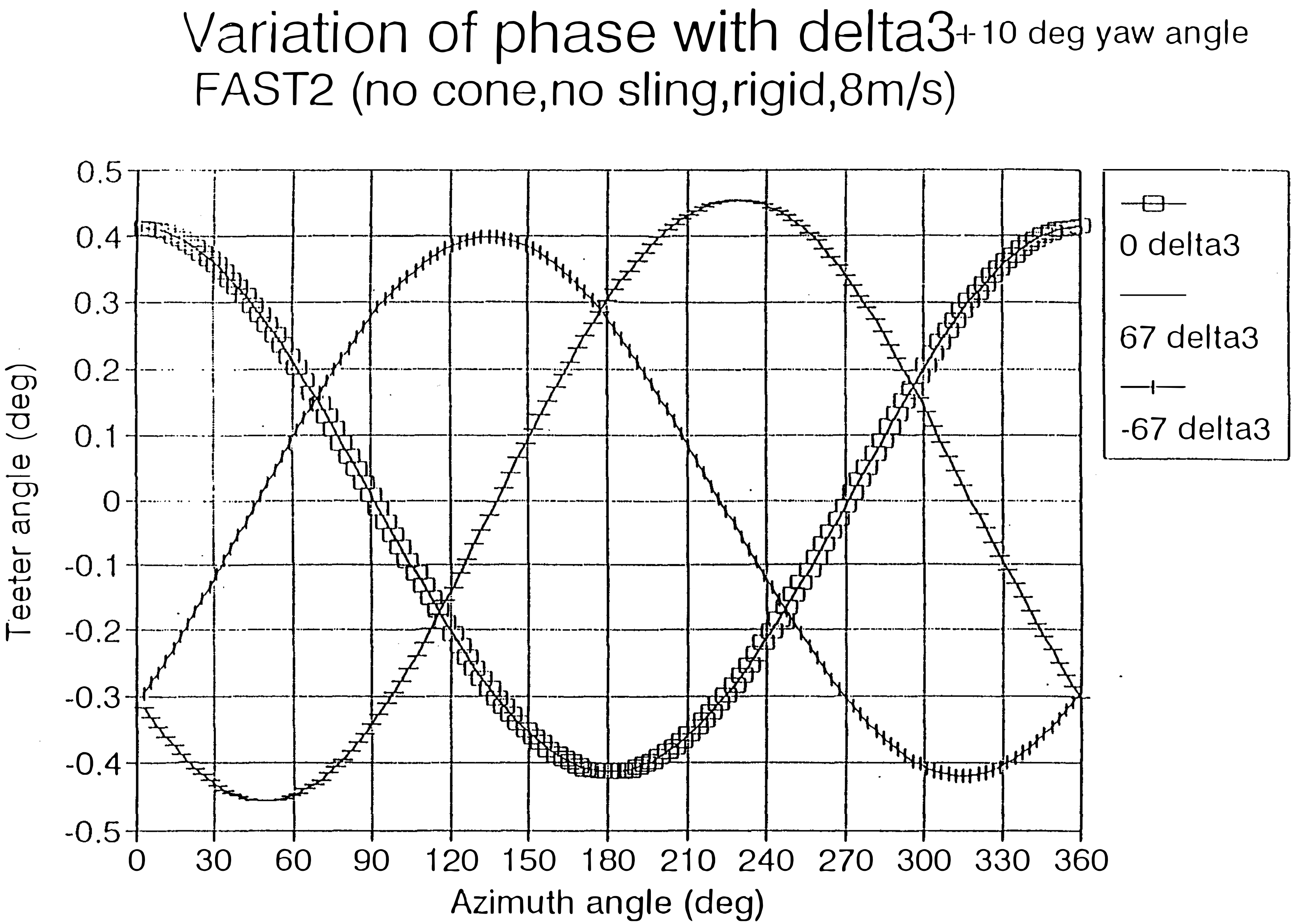


Summary : Yawdyn experiences

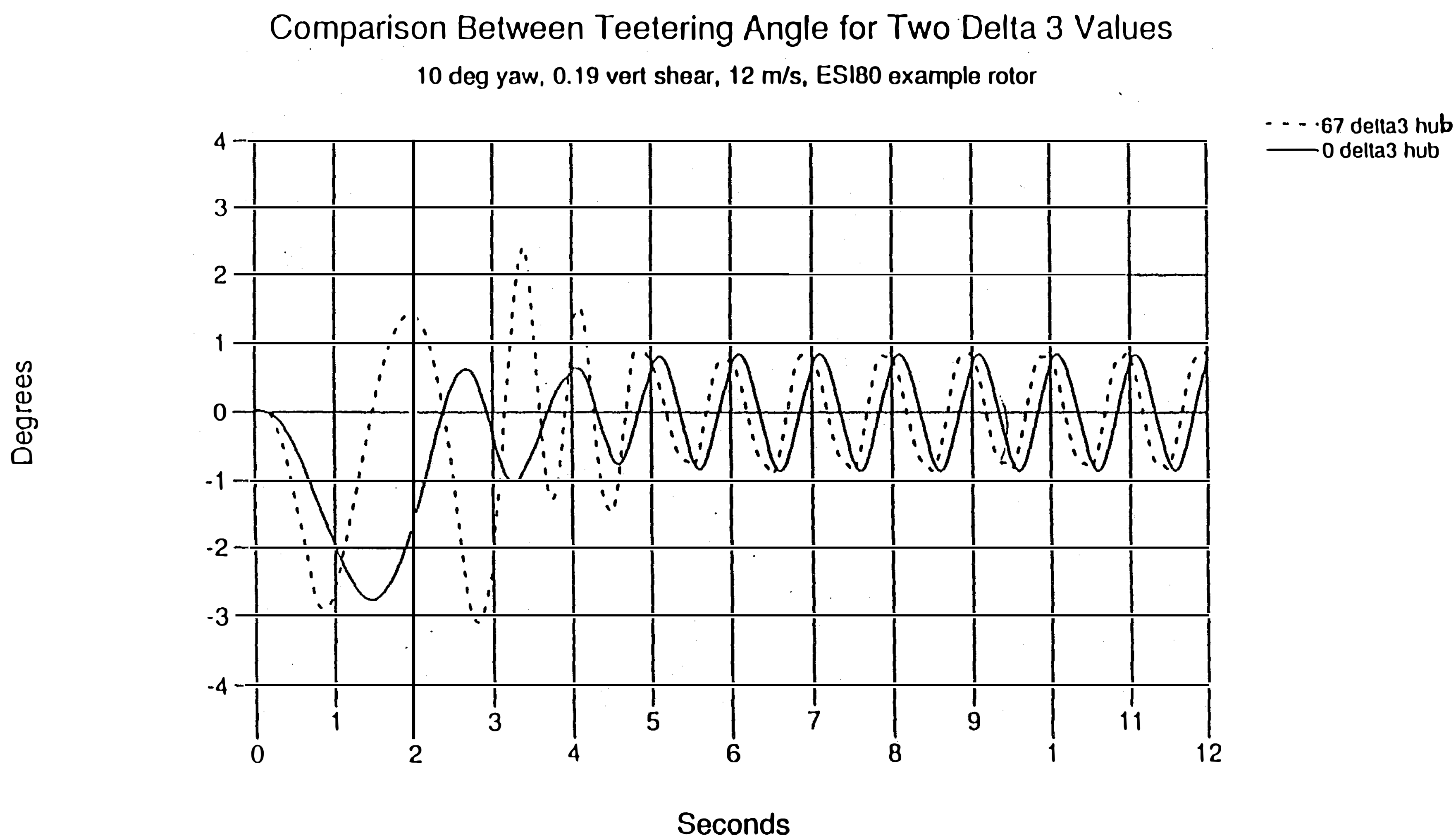
- High yaw operation is relevant to all wind turbines (IEC test case.)
- Comparisons with UTEP field data helped build a case for review of Yawdyn assumptions
- Perfecting Yawdyn is important since basis for ADAMS/WT aerodynamics

Overview : FAST experiences

- Used for quick investigation of effect of delta3 (several serious problems identified.)
- Phase shift error
- Free yaw stability anomaly
- Underlying equations/assumptions (Chris)
- Questions raised



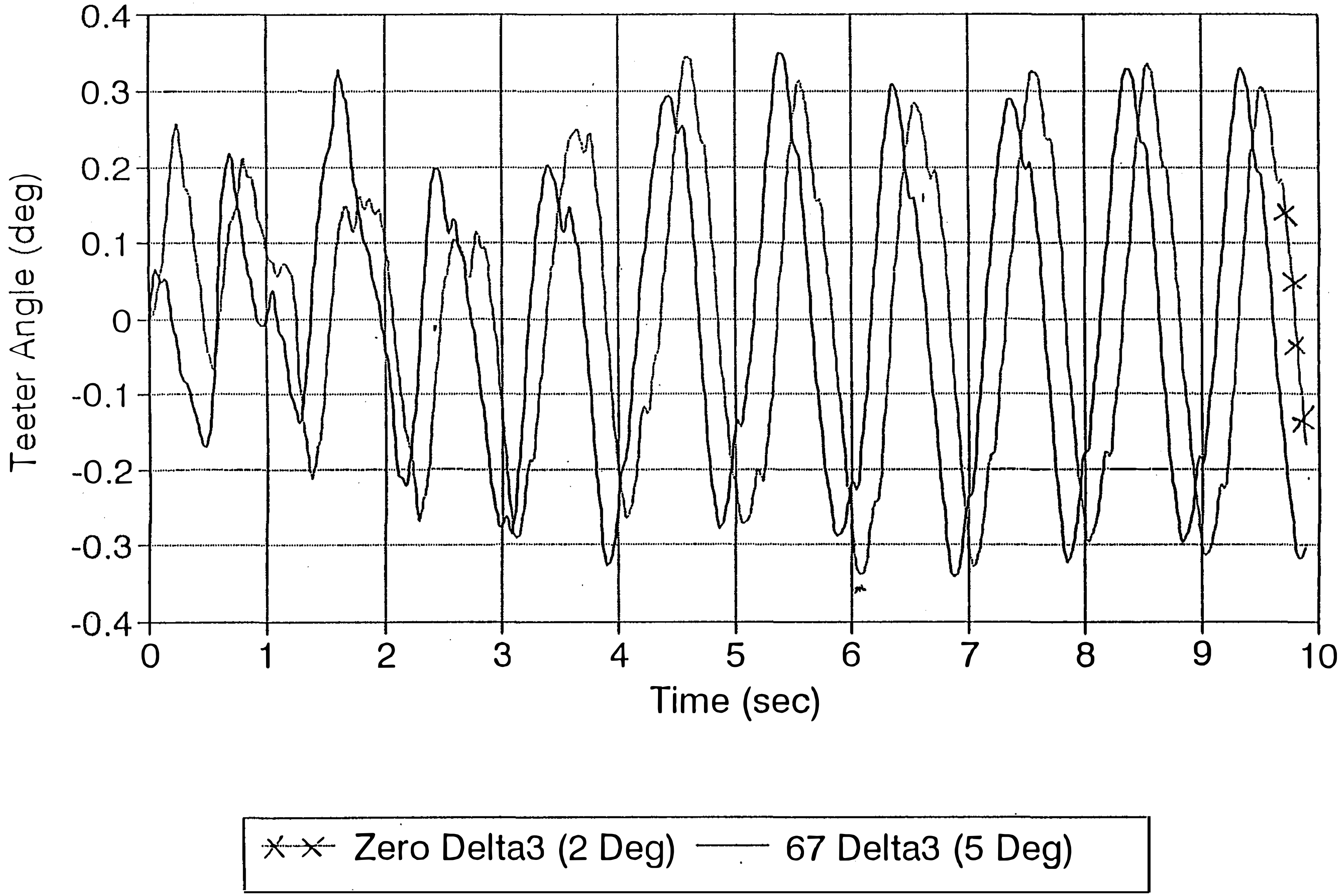
Phase Lag Inconsistencies in FAST2



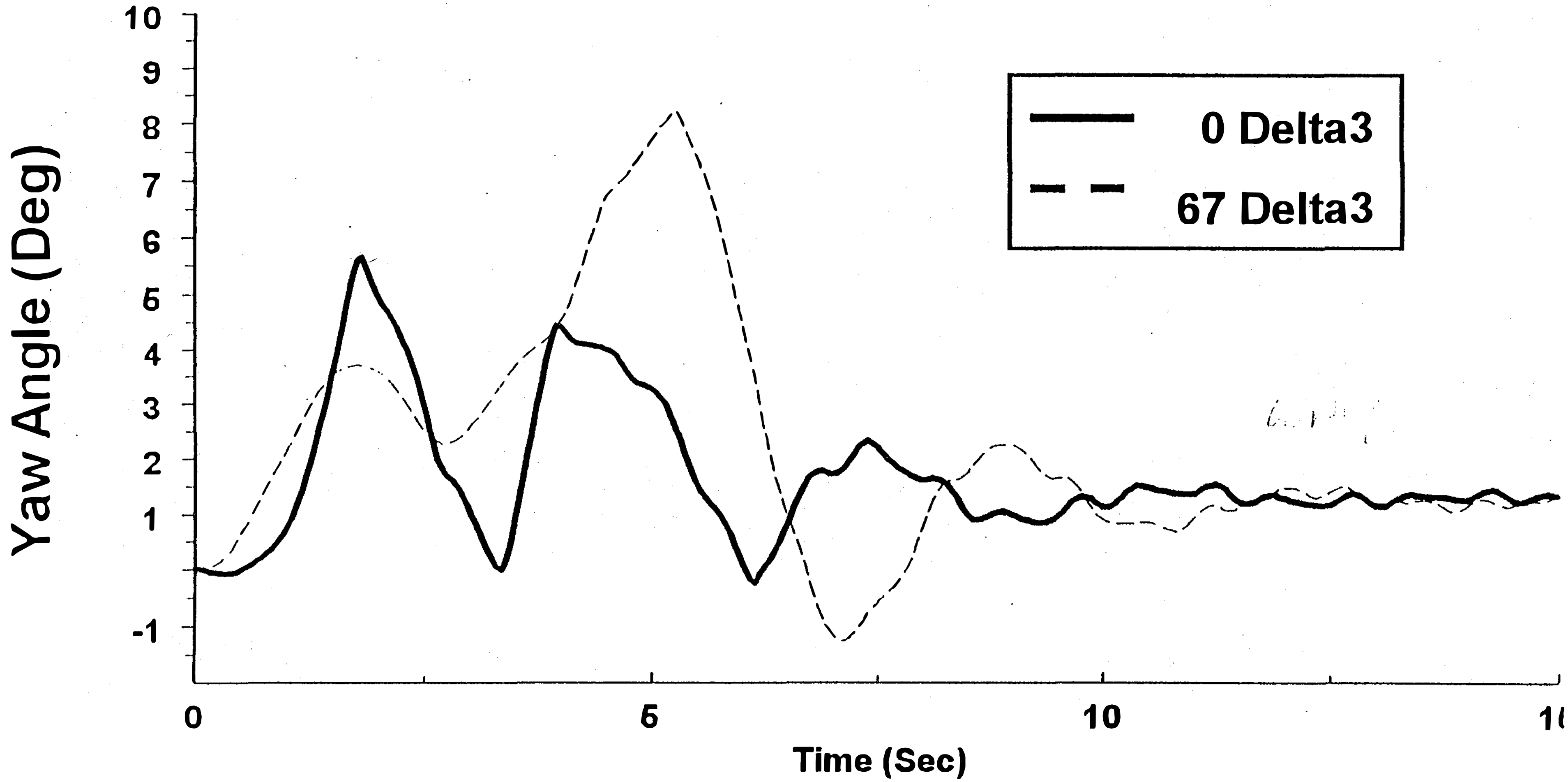
ADAMS/WT Prediction showing expected phase lag

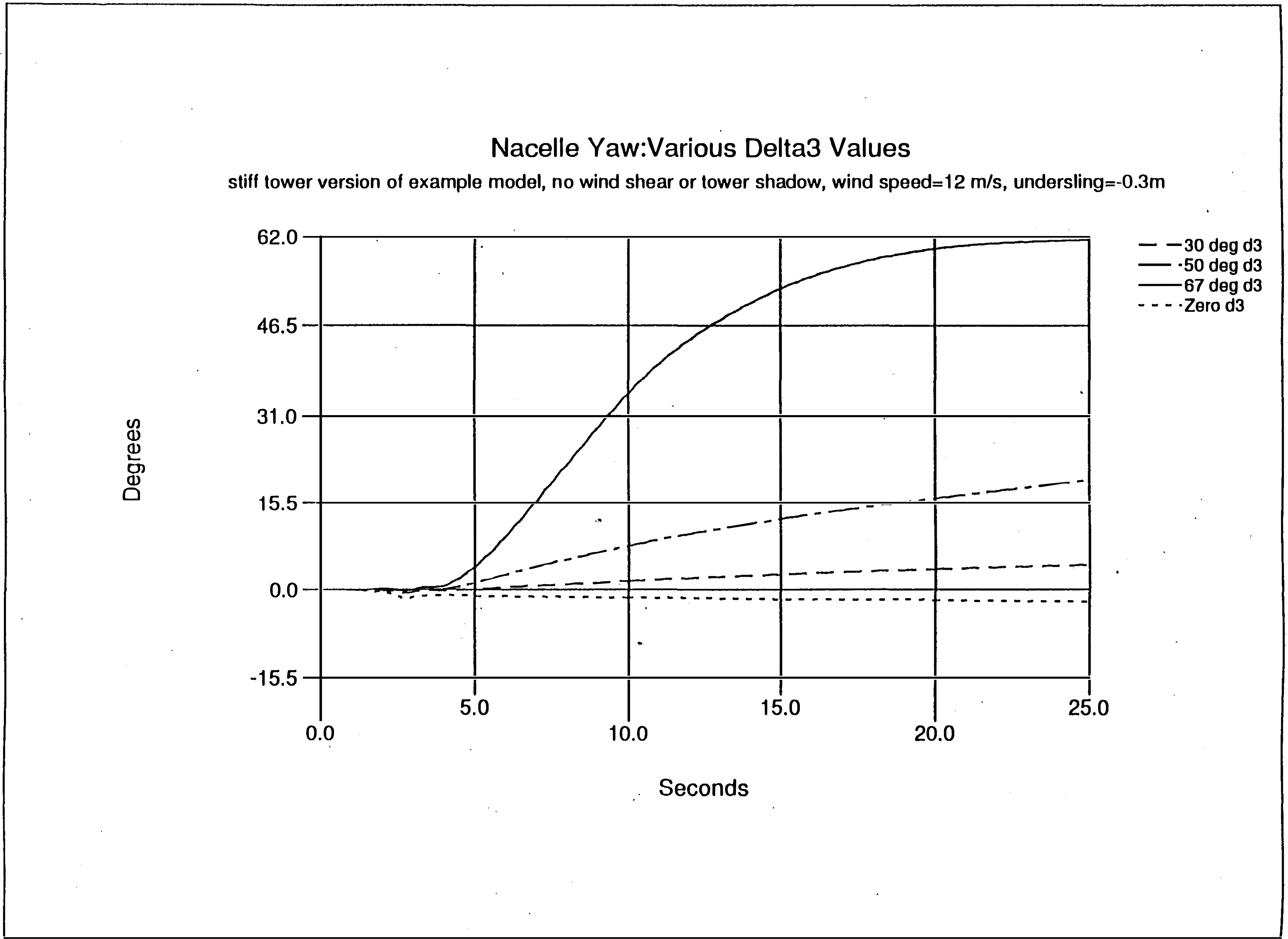
Teeter Response FAST2 (ver2.3d)

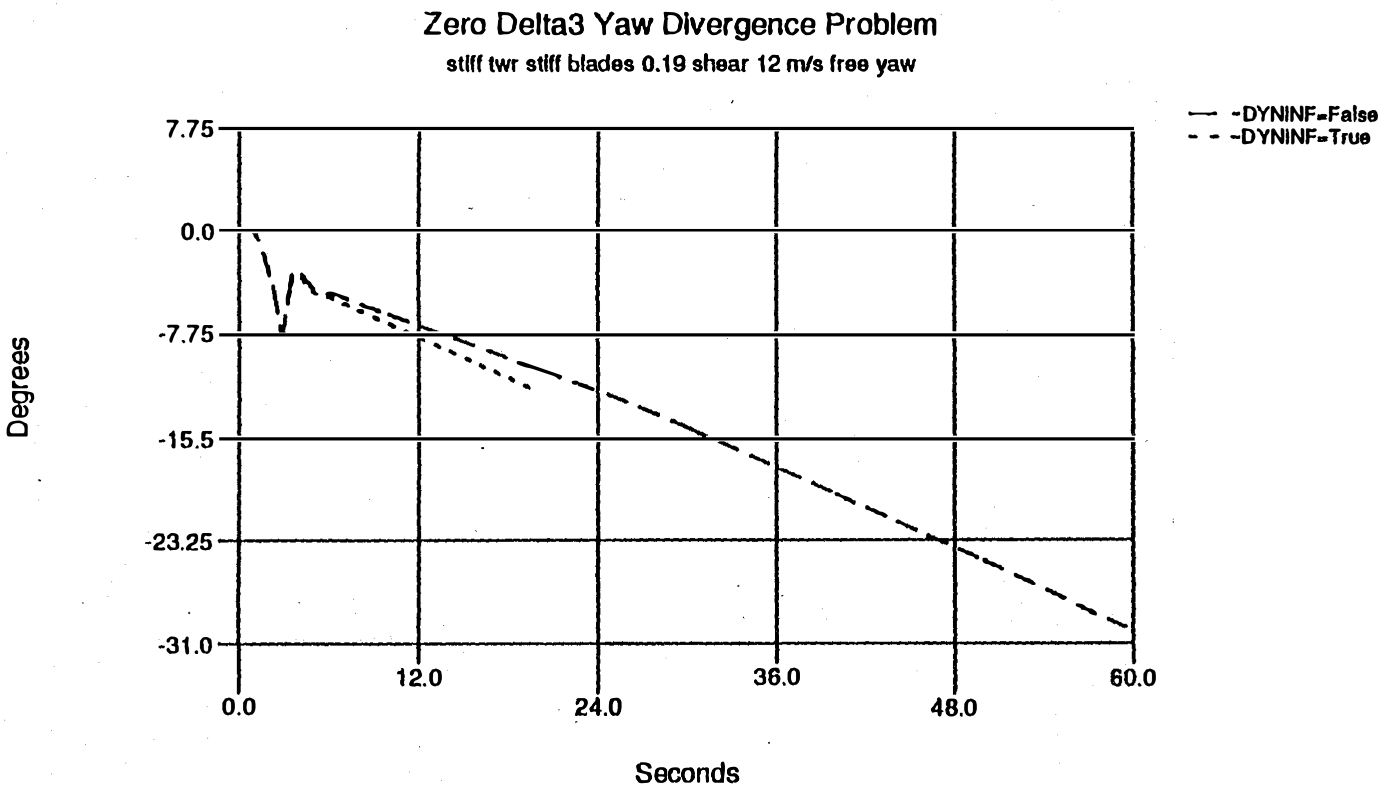
67 v's 0 Delta3 (Teeter margin 5&2 deg)



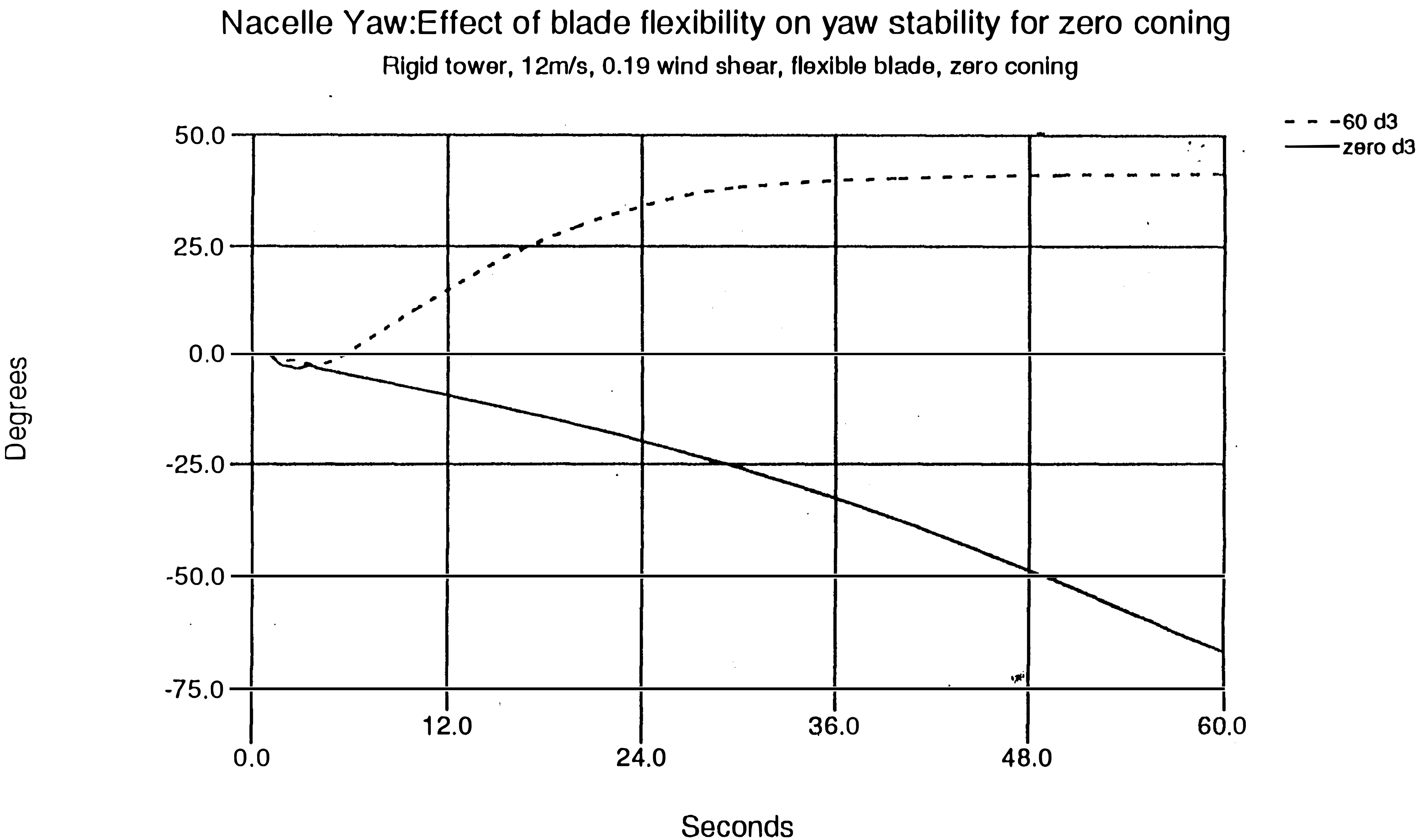
Free Yaw Start: FAST2




Nacelle Yaw:Various Delta3 Values
stiff tower version of example model, no wind shear or tower shadow, wind speed=12 m/s, undersling=-0.3m
62.0
46.5
31.0
15.5
0.0
-15.5
Degrees
0.0
5.0
10.0
15.0
20.0
25.0
Seconds
30 deg d3
50 deg d3
67 deg d3
Zero d3



Zero Delta3 Yaw Divergence Problem
stiff twr stiff blades 0.19 shear 12 m/s free yaw
-DYNINF=False
-DYNINF=True
7.75
0.0
-7.75
-15.5
-23.25
-31.0
Degrees
0.0
12.0
24.0
36.0
48.0
60.0
Seconds



Nacelle Yaw:Effect of blade flexibility on yaw stability for zero coning
Rigid tower, 12m/s, 0.19 wind shear, flexible blade, zero coning
60 d3
zero d3
50.0
25.0
0.0
-25.0
-50.0
-75.0
Degrees
0.0
12.0
24.0
36.0
48.0
60.0
Seconds

BASIC EQUATIONS OF MOTION (FAST2 CODE)

Motivations:

- Resolve problems associated with δ_3 angle
- No misuse of FAST2 code
- FAST2 provides "reasonable" documentation
- Adapt the structural dynamics to Matlab for controls study

PHASE SHIFT PROBLEM WITH δ_3 ANGLE (FAST2 CODE)

FAST-2 User's Manual OSU/NREL 95-01

From Azimuth to Teeter:

$$\begin{Bmatrix} e_1 \\ e_2 \\ e_3 \end{Bmatrix} = \begin{bmatrix} cq_3 & 0 & sq_3 \\ 0 & 1 & 0 \\ -sq_3 & 0 & cq_3 \end{bmatrix} \begin{Bmatrix} f_1 \\ f_2 \\ f_3 \end{Bmatrix}$$

From Teeter to Delta-3:

$$\begin{Bmatrix} f_1 \\ f_2 \\ f_3 \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c\delta_3 & -s\delta_3 \\ 0 & s\delta_3 & c\delta_3 \end{bmatrix} \begin{Bmatrix} g_1 \\ g_2 \\ g_3 \end{Bmatrix}$$

- **FAST User's Manual OSU/NREL 96-01**

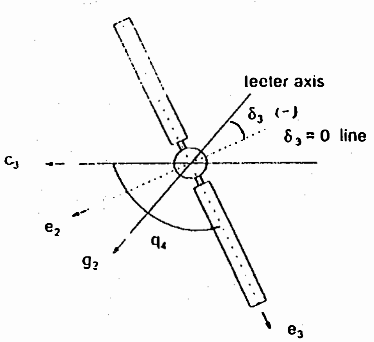
From Azimuth to Delta-3: angle

$$\begin{Bmatrix} e_1 \\ e_2 \\ e_3 \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c\delta_3 & -s\delta_3 \\ 0 & s\delta_3 & c\delta_3 \end{bmatrix} \begin{Bmatrix} g_1 \\ g_2 \\ g_3 \end{Bmatrix}$$

From Delta-3 to Teeter: angle

$$\begin{Bmatrix} g_1 \\ g_2 \\ g_3 \end{Bmatrix} = \begin{bmatrix} cq_3 & 0 & sq_3 \\ 0 & 1 & 0 \\ -sq_3 & 0 & cq_3 \end{bmatrix} \begin{Bmatrix} f_1 \\ f_2 \\ f_3 \end{Bmatrix}$$

PHASE SHIFT PROBLEM WITH δ_3 ANGLE (FAST2 CODE)

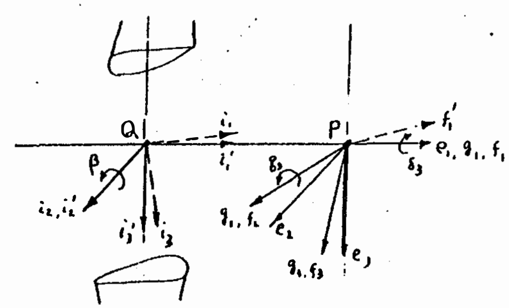


$$^{e}R^{g} = \begin{vmatrix} 1 & 0 & 0 \\ 0 & c\delta_3 & -s\delta_3 \\ 0 & s\delta_3 & c\delta_3 \end{vmatrix}$$

must be corrected to

$$^{e}R^{g} = \begin{vmatrix} 1 & 0 & 0 \\ 0 & c\delta_3 & s\delta_3 \\ 0 & -s\delta_3 & c\delta_3 \end{vmatrix}$$

YAW ANGLE PROBLEM WITH δ_3 ANGLE (FAST2 CODE)



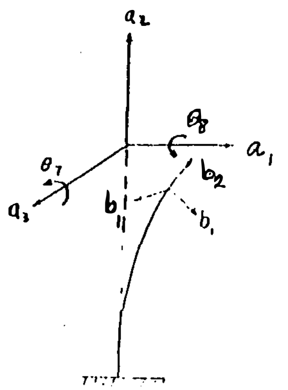
e_1 = Azimuth axis
g_2 = Teeter axis (q_3)
{f} = Fixed frame on hub
i_2 = Coning axis (β)

$$^{f}R^{i} = \begin{vmatrix} c\beta & 0 & s\beta \\ 0 & 1 & 0 \\ -s\beta & 0 & c\beta \end{vmatrix}$$

must be corrected to

$$^{f}R^{i} = \begin{vmatrix} c\beta & 0 & 0 \\ s\beta s\delta_3 & c\delta_3 & -s\beta s\delta_3 \\ -s\beta c\delta_3 & s\delta_3 & -c\beta c\delta_3 \end{vmatrix}$$

DECOMPOSITION OF TOWER VIBRATION (FAST2 CODE)



$$^{a}V^{b} = (\dot{q}_7+\dot{q}_9)\, a_1 + (\dot{q}_8+\dot{q}_{10})\, a_3$$

$$^{a}\omega^{b} = \dot{\theta}_8\, a_1 - \dot{\theta}_7\, a_3$$

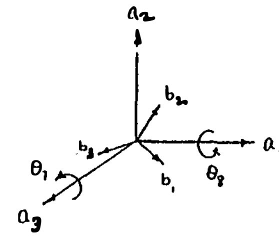
(down wind configuration)

$$^{a}R^{b} = \begin{vmatrix} c\theta_7 & -s\theta_7 & 0 \\ s\theta_7 c\theta_8 & c\theta_7 c\theta_8 & -s\theta_8 \\ s\theta_7 s\theta_8 & c\theta_7 s\theta_8 & c\theta_8 \end{vmatrix}$$

ORIENTATION MATRIX FROM {B} TO {A} (FAST2 CODE)

$$\{a\} = {}^{a}R^{b}\,\{b\}$$

$$^{a}R^{b} = \begin{vmatrix} c\theta_7 & -s\theta_7 & 0 \\ s\theta_7 c\theta_8 & c\theta_7 c\theta_8 & -s\theta_8 \\ s\theta_7 s\theta_8 & c\theta_7 s\theta_8 & c\theta_8 \end{vmatrix}$$

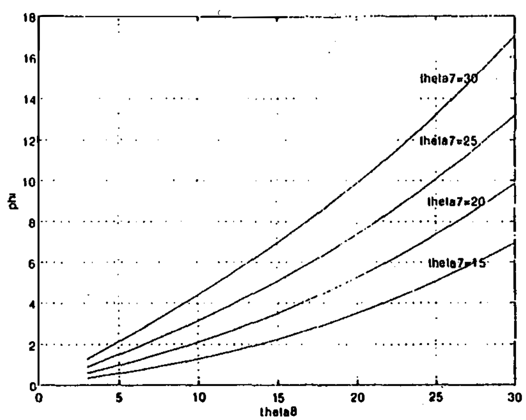


$$= \begin{vmatrix} 1 & 0 & 0 \\ 0 & c\theta_8 & -s\theta_8 \\ 0 & s\theta_8 & c\theta_8 \end{vmatrix} \begin{vmatrix} c\theta_7 & -s\theta_7 & 0 \\ c\theta_7 & -s\theta_7 & 0 \\ 0 & 0 & 1 \end{vmatrix} \qquad \text{(Eq. 1)}$$

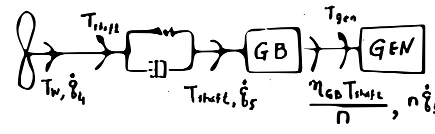
$$\neq \begin{vmatrix} c\theta_7 & -s\theta_7 & 0 \\ c\theta_7 & -s\theta_7 & 0 \\ 0 & 0 & 1 \end{vmatrix} \begin{vmatrix} 1 & 0 & 0 \\ 0 & c\theta_8 & -s\theta_8 \\ 0 & s\theta_8 & c\theta_8 \end{vmatrix} \qquad \text{(Eq. 2)}$$

ORIENTATION DIFFERENCES BETWEEN EQ. 1 AND EQ. 2 (FAST2 CODE)

$$\phi = \mathrm{COS}^{-1}(s^2\theta_7\, c\theta_8 + c^2\theta_7\, c^2\theta_8 + c\theta_7\, s^2\theta_8)$$



DRIVE TRAIN LOADING (FAST2 CODE)



η_{GB} = efficiency of gear box

$$T_{shaft} = K_d\,(q_4 - q_5) + C_d\,(\dot{q}_4 - \dot{q}_5)$$

$$(\eta_{GB}\, T_{shaft} / n) - T_{gen} = I_{gen}\, n\, \ddot{q}_5$$

$$\ddot{q}_5 = \{\, (\eta_{GB}\, T_{shaft} / n) - T_{gen}\, \} / I_{gen}\, n$$

$$\ddot{q}_5 = (\eta_{GB}\, T_{shaft} - n\, T_{gen}) / I_{gen}\, n^2$$

Compared to $\ddot{q}_5 = (\eta_{GB}\, T_{shaft} - \; T_{gen}) / I_{gen}\, n^2$ (error ?)

QUESTIONS RAISED FROM UTEP'S CODE EXPERIENCES

- Does excessive model tuning "mask" potential code error?
- To what extent can a user use a "validated" code for non-standard configurations, especially in the case of new turbine configurations?
- Are there enough well documented HAWTs for standard code validation? Have they all been used?
- Has the mathematical formulations of existing codes been carefully examined and approved?
- How can researchers in disciplines other than structural and aerodynamics, like controls, benefit from the existing codes?

SUMMARIES (FAST2 CODE)

- FAST2 code is limited to
  - 2 bladed, teetered rotor, zero δ_3 angle, down wind, free yaw, and fixed pitch
- Subroutines involving δ_3 angle must be corrected
- FAST2 code does not produce reliable results if
  - Excessive tower deflections exist, say more than 15^0 slope at the tower top, along both a_1 and a_3 axes
  - Same but less a problem with the blade vibrations due to high in-plane stiffness
- Drive train equation must be validated

Assessment of ADAMS' Modal Analysis Capability

Code Validation Workshop, NWTC, Colorado, August 8-9, 1996

Gunjit Bir

NREL

Motivation

- Areas where modal characterization plays a key role:
  - design of modern controllers/state estimators
  - efficient loads computation & interpretation schemes
  - flexible rotors and soft towers
  - understanding dynamics; avoiding resonances, instabilities, and excessive loads
  - code validation
  - model validation; model update

- ADAMS: comprehensive modeling capabilities; primary analysis tool for wind industry. Assess its direct modal analysis capability.

Code Assessment Approach

- Build turbine models of increasing complexity.
- Model three types of blades:
  - uniform blade
  - tapered blade
  - typical utility-scale flexible blade with non-uniform properties
- Get operating modal characteristics of each blade using **direct eigenanalysis** and **transient analysis** approaches.
- Compare modal results with results from a finite element code and exact results, if possible.

Direct Eigenanalysis Technique

- Build the blade and attach it to ground-fixed hub
- Rev up the blade smoothly to the desired rotor speed, Ω (no aero, no controls, no damping; structural damping gradually removed to achieve transient-free rotor operation)
- Once steady Ω is reached, invoke ADAMS/Linear to linearize EOM (linearization azimuth-independent).

Direct Eigenanalysis Technique (cont'd)

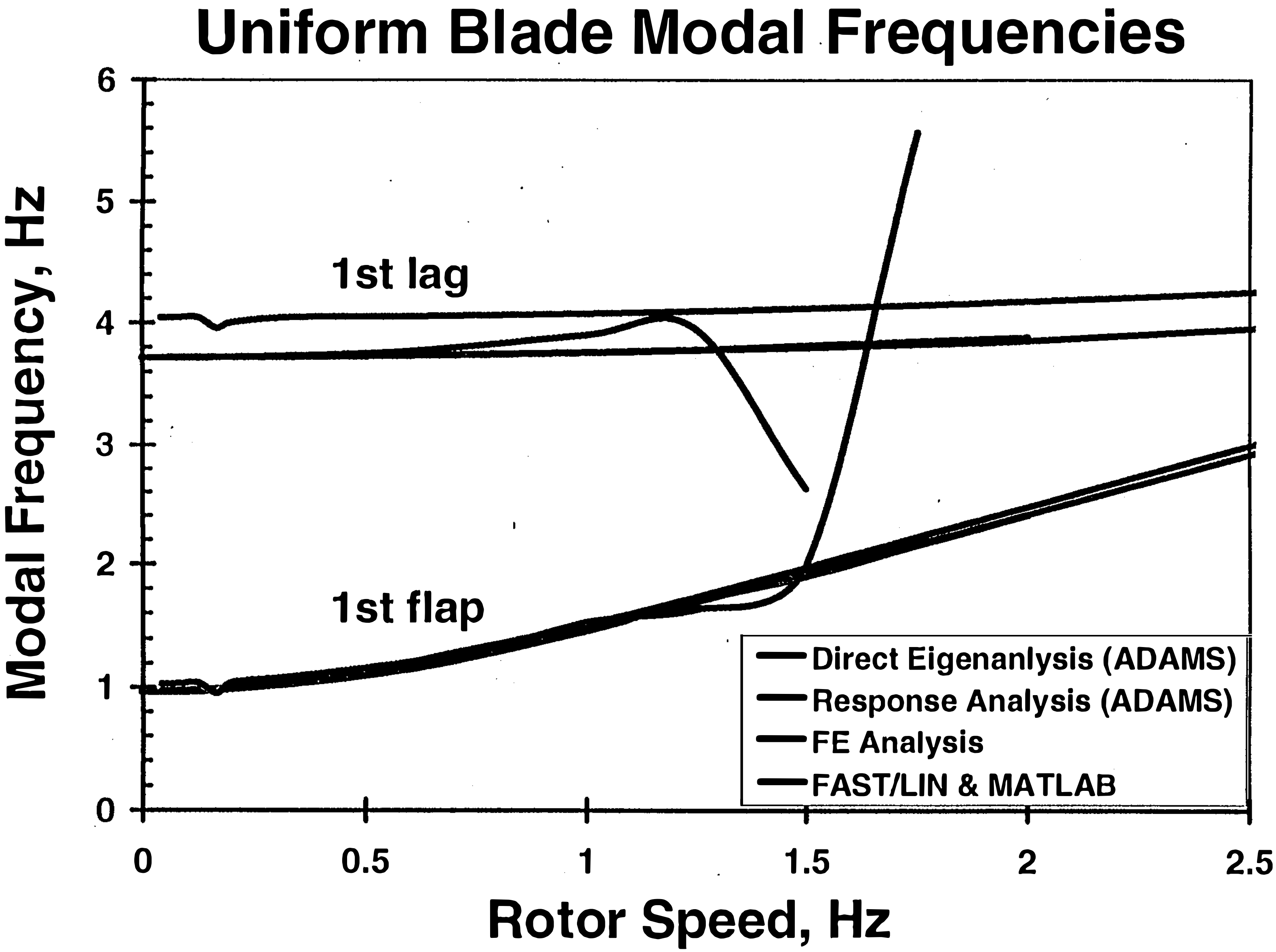
- Perform eigenanalysis on the linearized system:

  - eigenvectors: identify mode shapes

  - eigenvalues : real parts provide modal dampings
    imaginary parts provide frequencies

Transient Response Technique

- Build the blade and rev it up to the desired rotor speed
- Ping the blade at appropriate locations and with appropriate force levels
- FFT the transient response and identify modal frequencies (mode shape identification not attempted at this stage)



Uniform Blade Modal Frequencies
Modal Frequency, Hz
0
1
2
3
4
5
6
1st lag
1st flap
Direct Eigenanlysis (ADAMS)
Response Analysis (ADAMS)
FE Analysis
FAST/LIN & MATLAB
0
0.5
1
1.5
2
2.5
Rotor Speed, Hz

Modal Frequencies of a Rotating Uniform Blade

(Ω_0 = 1 Hz)

Mode	Computation Method	Modal Frequency (Hz)											
		Rotor Operating Speed, Ω/Ω_0											
		0.0	0.2	0.6	1.0	1.25	1.5	1.75	2.0	5.0	10.0	20.0	50.0
1st Flap	FEA & Exact	0.9600	0.9859	1.1717	1.4716	1.6895	1.9205	2.1596	2.4041	5.4532	10.607	20.964	52.154
	ADAMS/LIN	0.9603	0.9827	1.1505	1.5237	1.6301	1.9885	5.567					
	ADAMS/Resp	0.9600	0.999	1.1489	1.4586	1.6983	1.8981	2.1479	2.3977				
1st Lag	FEA	3.718	3.719	3.7308	3.7528	3.7719	3.7951	3.8220	3.8527	4.4407	5.8010	8.6046	16.766
	ADAMS/LIN	3.716	3.7209	3.7696	3.9008	3.9480	2.6244						
	ADAMS/Resp	3.717	3.722	3.734	3.758	3.7790	3.816	3.849	3.881				
2nd Flap	FEA & Exact	6.017	6.0400	6.2183	6.5608	6.8477	7.1826	7.5590	7.9708	14.310	26.409	51.399	127.250
	ADAMS/LIN	5.981	6.0184	6.1681	6.5888	6.7000	6.6089						
	ADAMS/Resp	5.981	5.9941	6.1440	6.4937	6.7434	7.0931	7.4427	7.7924				
3rd Flap	FEA & Exact	16.850	16.879	17.057	17.4080	17.709	18.070	18.486	18.954	27.230	45.132	83.675	281.560
	ADAMS/LIN	16.516	16.708	16.894	17.2461								
1st Torsion	FEA	17.970	17.971	17.980	17.996	18.010	18.027	18.047	18.071	18.589	20.333	26.17	50.841
	ADAMS/LIN	17.952	17.963	17.973	17.993								
2nd Lag	FEA	23.300	23.309	23.349	23.429	23.449	23.584	23.685	23.800	26.250	33.453	53.273	120.280
	ADAMS/LIN	23.013	23.089	23.129	23.241								
4th Flap	FEA & Exact	33.110	32.185	33.294	33.658	33.975	34.358	34.804	35.311	45.008	68.183	120.07	202.550
	ADAMS/LIN	31.653	32.315	32.516	32.888								
2nd Torsion	FEA	53.910	53.916	53.919	53.924	53.929	53.935	53.941	53.949	54.125	54.748	57.174	71.894
	ADAMS/LIN	53.414	53.691	53.691	53.222								

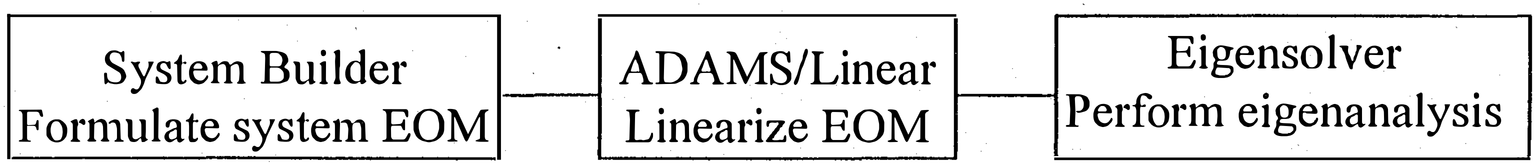
Comments

- Response technique works fine across rotor speeds typical of wind turbines. However, it is time-intensive, highly user-interactive, and extracts only few modes.
- Direct eigenanalysis capability very desirable. It is fast, accurate, automated, and extracts all modes.
- The direct eigenanalysis technique works fine over low- Ω range. Over low-to-moderate Ω range, results deteriorate gradually.

Comments (continued)

- Beyond a certain rotor speed, the modal results diverge abruptly. The higher the blade taper or the blade flexibility, the lower the Ω at which abrupt deterioration occurs.

- Direct eigenanalysis in ADAMS requires three steps:



Comments (continued)

- Success of response technique implies system EOM are formulated correctly.
- Tests performed that indicate Eigensolver works correctly.
- Conclusion: ADAMS/Linear probably does not capture or correctly linearize certain Ω-related terms.

ADAMS Linearization Scheme

- EOM formulation using Lagrangian approach:

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{\underset{\sim}{q}}}\right) - \frac{\partial T}{\partial \underset{\sim}{q}} - \left[\frac{\partial \phi}{\partial \underset{\sim}{q}}\right]^T \underset{\sim}{\lambda} = \underset{\sim}{f}$$

$$\underset{\sim}{\phi}(\underset{\sim}{q}, t) = 0 \qquad \text{[constraint equations]}$$

$$\Downarrow$$

$$g(\ddot{\underset{\sim}{q}}, \dot{\underset{\sim}{q}}, \underset{\sim}{q}, \lambda, \underset{\sim}{f}, t) = 0$$

$$\Downarrow \qquad y = [q \;\; \dot{q} \;\; \lambda]^T \; : \text{ first order transf}\underline{\text{n}}$$

$$\boxed{g(\dot{y}, y, \underset{\sim}{f}, t) = 0} \qquad \text{(system EOM)}$$

ADAMS Linearization Scheme (cont'd)

- Response evaluation using Gear multi-step integration:

$$y^{n+1} = -h\beta_0\,\dot{y}^{n+1} + \sum_{j=1}^{k}\left(\alpha_j\,y^{n-j+1} + h\beta_j\,\dot{y}^{n-j+1}\right) \qquad \text{[predictor]}$$

$$\underbrace{\left[\frac{\partial g}{\partial y}\right] - \frac{h}{\beta_0}\left[\frac{\partial g}{\partial \dot{y}}\right]}_{J}\Delta y = -g \qquad \text{[corrector]}$$

$$J\Delta y = -g$$

- Linearization:

$$\delta g = \underbrace{\left[\frac{\partial g}{\partial y}\right]_{y^*}}_{=A}\delta y + \underbrace{\left[\frac{\partial g}{\partial \dot{y}}\right]_{y^*}}_{=-B}\delta\dot{y} + \left[\frac{\partial g}{\partial \underset{\sim}{f}}\right]_{y^*}\delta\underset{\sim}{f} + \left[\frac{\partial g}{\partial t}\right]_{y^*}\delta t = 0$$

Time-invariace $\Rightarrow \left[\frac{\partial g}{\partial t}\right] \equiv 0$. $\delta\underset{\sim}{f} = 0$ for modal/stability analysis.

ADAMS Linearization Scheme (cont'd)

- Linearized eqns: $A\,\delta y - B\,\delta\dot{y} = 0$

  $\downarrow$ $\delta y = e^{\sigma t} z$ (for time-invariant system)

  $\boxed{A z = \sigma B z}$ (generalized eivalue problem)

  z = eigenvectors

  σ = eivalues

- $J = \left[A - \frac{h}{\beta_0} B\right]$

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ADAMS Linearization Scheme (cont'd)

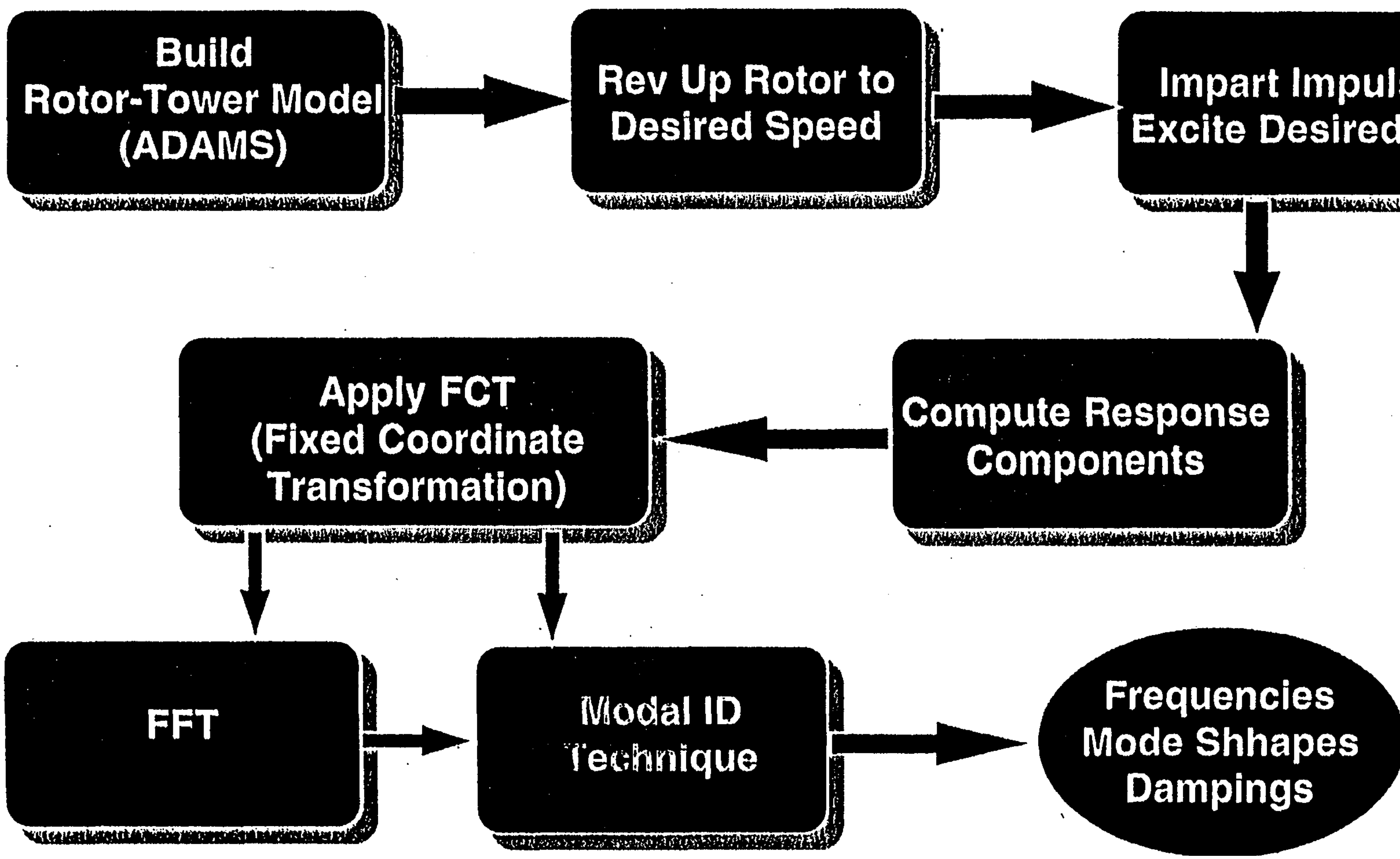
- Linearization problem --> A & B incorrect, i.e., J not computed correctly during response evaluation.
- Incorrect evaluation may still yield correct response provided J matrix retains the right gradients.
- J evaluation tricky, especially for time-varying constraints.

Modal & Stability Analysis of a Four-Bladed Wind Turbine using the Transient Analysis Technique

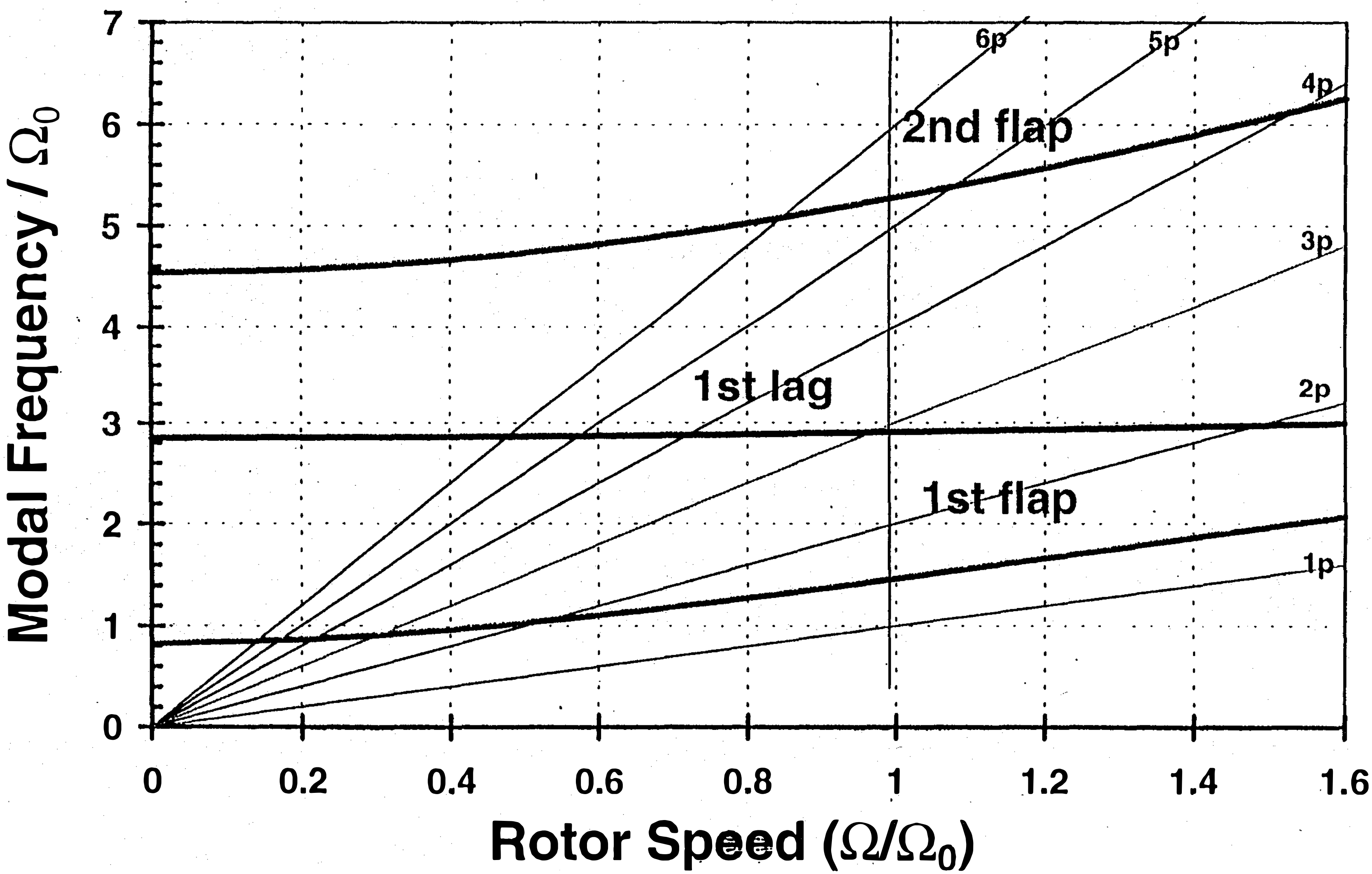
Gunjit Bir

NREL

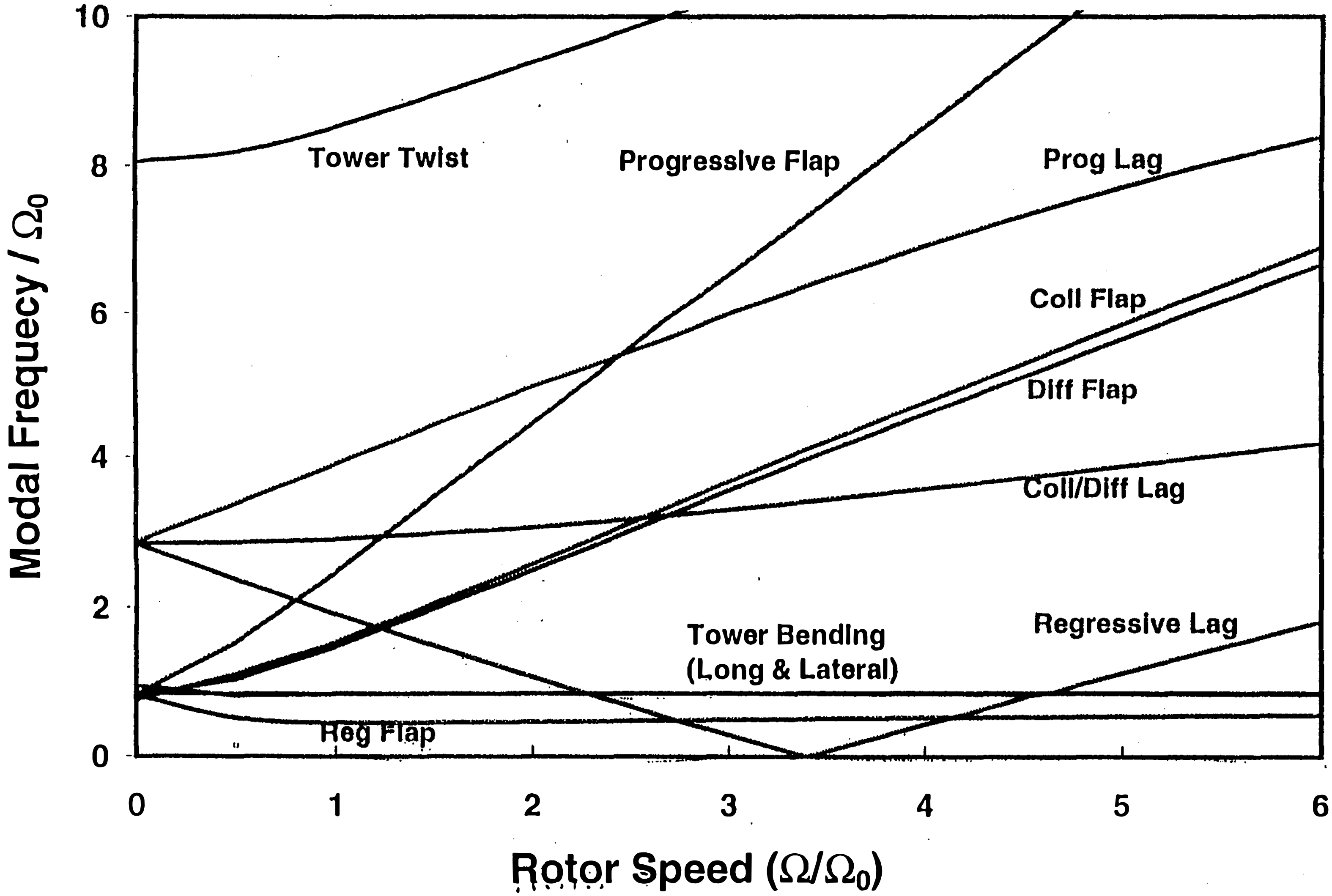
Approach: Transient Analysis

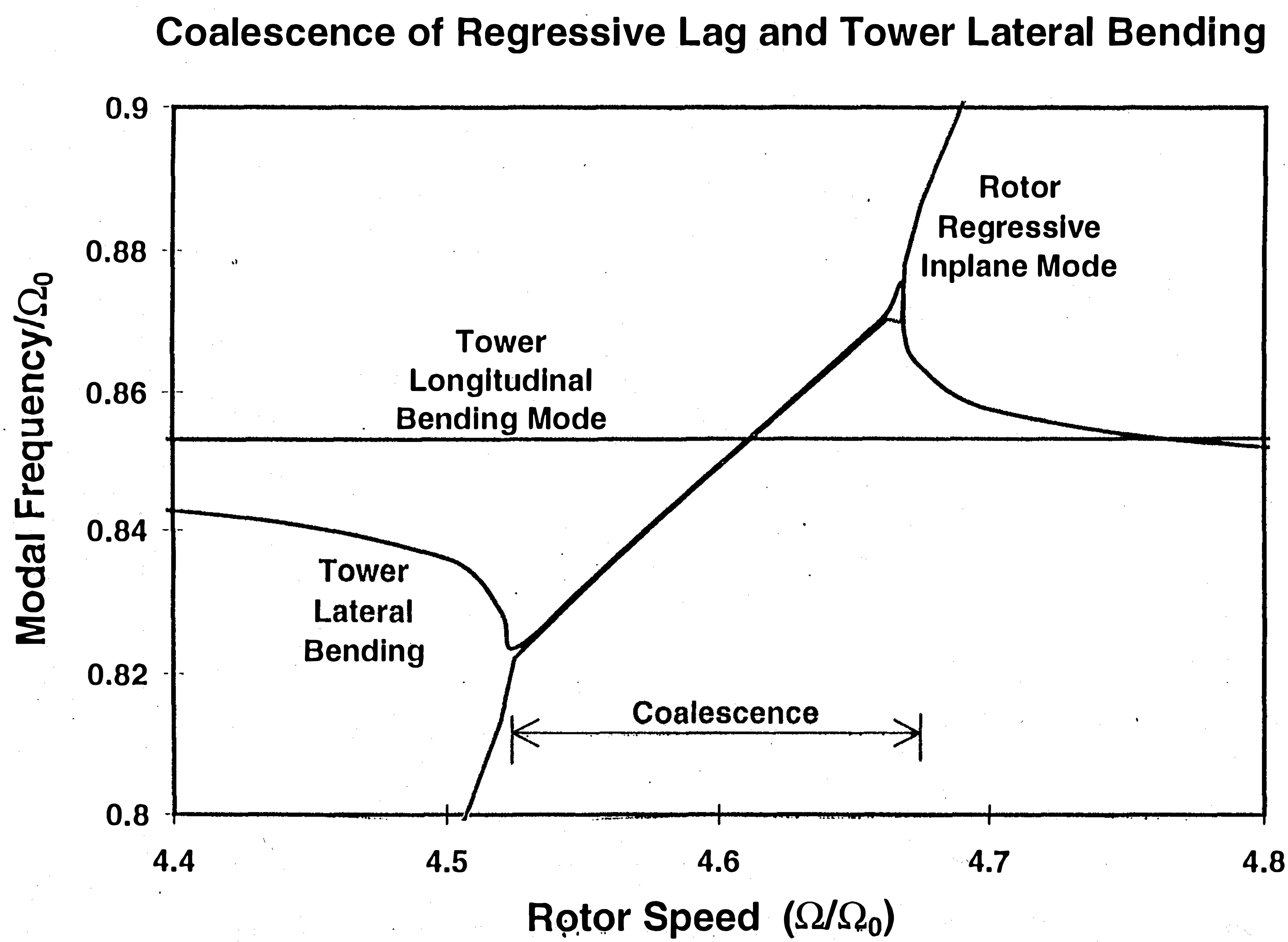


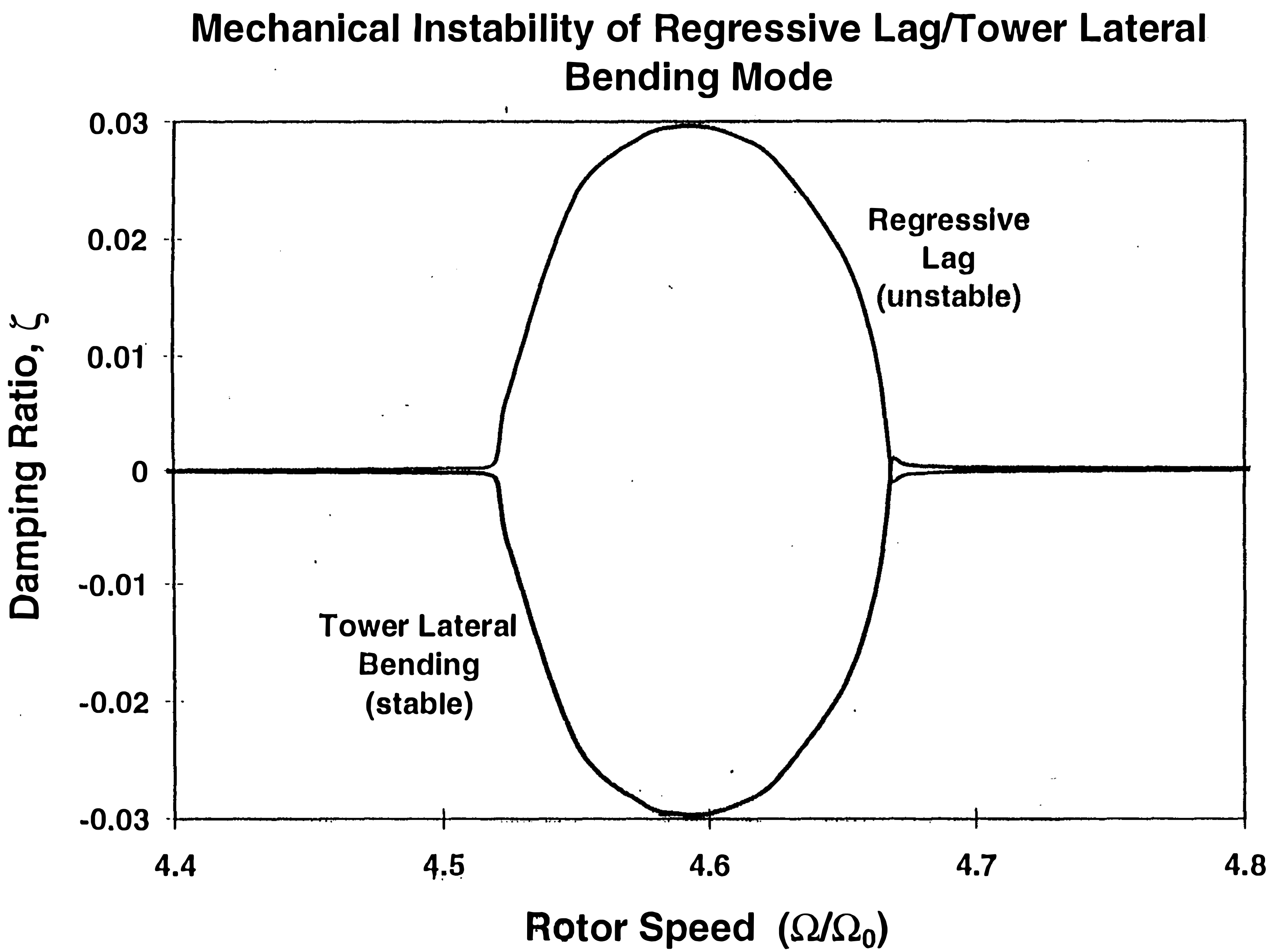
Isolated Blade Modal Frequencies



Coleman Diagram of the Coupled Rotor-Tower Modes




Coalescence of Regressive Lag and Tower Lateral Bending
0.9
0.88
0.86
0.84
0.82
0.8
Modal Frequency/Ω_0
Rotor
Regressive
Inplane Mode
Tower
Longitudinal
Bending Mode
Tower
Lateral
Bending
Coalescence
4.4
4.5
4.6
4.7
4.8
Rotor Speed (Ω/Ω_0)



Mechanical Instability of Regressive Lag/Tower Lateral Bending Mode
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
Damping Ratio, ζ
Regressive Lag (unstable)
Tower Lateral Bending (stable)
4.4
4.5
4.6
4.7
4.8
Rotor Speed (Ω/Ω0)

Future Work

- Work with MDI to troubleshoot ADAMS/Linear.
- Validate ADAMS direct eigenanalysis capability for the blade.
- Introduce specialized post-processors, e.g., Floquet analyzer.
- Extend the direct eigenanalysis validation effort to the full turbine system operating in vacuum.
- Develop dynamic inflow and linearized aero models.
- Perform aeroelastic stability analyses of representative turbine configurations.

Future Work (continued)

- Upgrade ADAMS to provide system matrices in the state-space and modal domains. These matrices are required for
  - design of modern efficient controllers & state estimators
  - experimental validation and analytical model updating
- Provide a general interface between ADAMS and different control algorithms.
- Develop/validate linearizer for FAST.
- Introduce aforementioned capabilities in FAST.

STEPS IN THE VALIDATION OF MODELS
or
Pitfalls I have known

by

D.J. Malcolm

Advanced Wind Turbines Inc.
Seattle, Washington

Code validation workshop, NWTC, 8-9 August 1996

background

* All comments are based on experience with AWT-type machines (2-bladed, teetered, free-yaw, downwind)

* Initial codes used: FLAP, YAWDYN. Results were compared with field data with mixed results. Use as design tools was not promising.

* ADAMS was adopted in 1993 and pursued with assistance from NREL

* Only recently has some confidence been achieved in the use of this code

* This may have more to do with the type of machine than the choice of code. This type of machine is extremely "active" and can be very sensitive to dynamic tuning.

* Design Loads have been based mainly on field data from prototypes

Questions to ask

* Material properties: where have they come from? Are they from handbooks or from actual tests? Under what conditions were tests carried out?

* Mass and center of mass (blades, nacelle, complete assembly): estimates or actual measurements? where is the original data?

* Airfoil data: 3-D effects? roughness effects? Reynolds no. effects? Tip effects?

* Turbulence simulation: what atmospheric stability conditions does it correspond to? (not just turbulence intensity)

* Tower shadow: is model correct? shedding of vortices?

* Beam representation (blades, tower): from FE model? inclusion of shear? axial/bending coupling? principal axes orientation?

* Nonlinear effects: gravity? mean aero loads?

* What kind of test runs for confirming aerodynamics? How to control aero input in the field?

Code validation workshop, NWTC, 8-9 Aug. 1996

AWT experience

* Blade static tests:
  Sometimes overlooked in favor of modal tests only.
  Self weight of blade
  Flap bending only?
  How to estimate edge stiffness? Flap/edge coupling
  AWT model within 5% of flap bending stiffness

* Blade modal tests:
  Are you testing the production blade?
  Are the boundary conditions known?
  Confidence with C of G and static tests?
  Difficult to get good agreement with both first flap and first edge modes. Inconsistent results with and without tip mass.

* System static modal tests:
  Wind excitation and standard instrumentation, or "full" modal test?
  Identifying higher modes requires full, sophisticated test.
  Check boundary conditions. Yaw and teeter free? Blade orientation
  Most modes agreed within 3%, but difficulty with blades vertical case (more active involvement of teeter and yaw)

* Performance curves
  OK but what other tests are possible for aeroelastic confirmation?

Primary problems

* Operating natural frequencies:
  - Can be extracted from field data under some conditions.
  - Can be extracted from model using HAWTMODE or from running model with turbulence and low damping.
  - Agreement is good with modes not affected by periodic supports (flap symmetric, drive train, etc.)
  - For other modes (edge symmetric, flap asymmetric, etc.), the model results are consistently higher than field indications by about 0.3P. This can be critical in avoiding operating resonant conditions.
  - What tools are used elsewhere?
  - Participation of aero loads in the natural modes?

* Transient response to gusts:
  - Does turbulence simulation really contain what happens in the field?
  - Response is sensitive to properties of teeter damper (very non-linear)
  - Can 2-D airfoil properties represent highly transient conditions?
  - Need large data base of field and model results
  - How to extrapolate data when response is so nonlinear?
  - How to describe overall loading of turbulence on rotor and to correlate it to turbulence characteristics?

Some golden rules

* "Never ask a computer something that you don't already know the answer to" (always have a way of checking the model's credibility)

* "You can be sure of death, taxes and errors" (quality assurance in the generation and transmittal of data is your responsibility)

* "If results are good, be doubly suspicious" (we tend to skip checks when we like the initial results)

* Keep careful track of all model versions, runs and parameters

* Never stop asking: "how do I know it's right?"

Conclusions

* ADAMS cpu time is acceptable with use of a Pentium and Windows NT

* ADAMS convergence is still a black art

* The use of modal coordinates would add "feel" to solutions

* Inclusion of all nonlinear effects by ADAMS is an advantage.

* Confirmation of all component properties is a common requirement for all models

* The system dynamics are equally affected by rotor, drivetrain, and tower

* We are closer to generating complete load spectra from models

* Adequacy of aerodynamic algorithms under transient conditions is questionable.

THE FAST CODE

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ABSTRACT

The FAST Code which is capable of determining structural loads of a flexible, teetering, horizontal axis wind turbine is described and comparisons of calculated loads with test data are given at two wind speeds for the ESI-80. The FAST Code models a two-bladed HAWT with degrees of freedom for blade bending, teeter, drive train flexibility, yaw, and windwise and crosswind tower motion. The code allows blade dimensions, stiffnesses, and weights to differ and models tower shadow, wind shear, and turbulence. Additionally, dynamic stall is included as are delta-3 and an underslung rotor. Load comparisons are made with ESI-80 test data in the form of power spectral density, rainflow counting, occurrence histograms, and azimuth averaged bin plots. It is concluded that agreement between the FAST Code and test results is good.

SCOPE

A current topic of considerable interest relates to the improvement of the accuracy and the reduction of time and effort needed to determine stochastic loads is, "how simple or complex must the structural dynamics model be?" This study compares calculated loads to measured loads for a contemporary lightweight teetered wind turbine using a structural model that has been incorporated into a computer code, FAST (Fatigue, Aerodynamics, Structure, Turbulence).

Before the accuracy associated with different levels of structural model can be ascertained, any model or code must first be validated. The FAST code results will be compared to test data from a horizontal axis wind turbine.

The ESI-80 test results (Musial, 1985) represent a valuable data set based on the current existence of both the data tapes and the original test machine. Additionally, personnel associated with the tests are still active in the wind energy field. The original machine was at the University of Massachusetts during much of 1992 and 1993 where measurements were made on the rotor to determine the actual parameters of the test machine (Bywaters, 1992). By using the ESI-80 test data, the study relates most closely with ESI-80-like machines. The ESI-80 has a significant amount of excitation in the range from 6 per revolution to 8 per revolution. Most of the examples presented by European investigators do not exhibit large excitation energy at high frequencies.

FAST CODE

The dynamic response of a horizontal-axis wind turbine (HAWT) has been modeled using five rigid bodies and three flexible bodies. There are 14 degrees-of-freedom in the system. The model accounts for blade flexibility, tower flexibility, yaw motion of the nacelle, variations in both rotor and generator speed, blade teetering, and blade bending. By selecting various physical constants, a variety of different configurations may be simulated, including generator axis tilt, preconed blades, teetering with selected hinge locations, "delta-3" orientation, various restrictions on the teeter angle, selected drive-train flexibility and damping, and tower flexibility parameters.

The first four degrees-of-freedom arise from flapwise blade motion of each of the two blades. The model allows for full or partial blade pitch. The blade torsional degree of freedom is not modeled in this study.

The fifth degree-of-freedom accounts for teeter motion of the two blades about a pin located on the turbine hub. The intersection of the blades principal moment of inertia axes can be displaced by the teeter axis by an undersling length. Additionally, the model allows for blade precone and a delta-3 angle. A lumped hub mass can be included in the code at a specified distance from the teeter pin. Teeter motion can be unrestricted, restricted by teeter dampers or teeter springs, or a combination of both.

The sixth degree-of-freedom accounts for variations in rotor speed. This degree-of-freedom can model a motor for start-up, a brake for shutdown, an induction generator with slip, or a variable-speed generator.

The seventh degree-of-freedom models the drive train flexibility between the generator and the rotor. This flexibility was modeled using a lumped drive train torsional spring and a damper.

The eighth degree-of-freedom accounts for yaw motion of the nacelle and rotor. Yaw motion can be free or fixed with a torsional yaw spring. A yaw tracking control model can be implemented with the fixed yaw version. The rotor can be either upwind or downwind. Aerodynamic nacelle loads are not currently modeled.

The ninth and tenth degrees-of-freedom are first mode tower motions. The ninth and tenth degrees-of-freedom are perpendicular to each other so that tower whirl can be modeled. The eleventh and twelfth degrees-of-freedom are the second mode tower motions. The eleventh and twelfth tower degrees-of-freedom are in the same direction as the ninth and tenth, respectively. Aerodynamic tower loads are not included. The last two degrees-of-freedom, 13 and 14, are edgewise motion of the blades.

The aerodynamic loading on the blades is determined using modified strip theory with nonlinear lift and drag characteristics. The aerodynamics is driven by a wind model that consists of a deterministic portion made up of mean wind, shear, and tower interference and a stochastic portion consisting of an atmospheric turbulence model including time varying wind direction.

The major loading on the wind turbine blades is due to the aerodynamic forces of lift and drag. The local relative wind speed contains contributions from the local wind, the rigid body motion of the blade due to rotation about the drive shaft, teeter and yaw axes, the flexible body motion of the blades and tower, and a contribution due to induction. The induced velocity is determined using strip theory wherein the local force on the blades due to lift is equated to the momentum flux. The blade force is based on the flow relative to the blade and contains the induced velocity explicitly in the velocity squared term and also contains the induced velocity implicitly in the lift coefficient and in the various trigonometric functions that are used to obtain the component of the blade force in the direction of the momentum flux.

The momentum flux through a segment of the rotor disk is obtained using Glauert's Momentum Equation. Whereas the blade force involves the flow relative to the blade, the momentum flux is determined in an inertial reference frame. The induced velocity appears both explicitly and implicitly in the momentum flux as well as in the blade force so that the induction must be solved for using iteration. A significant amount of computing time is used to determine the local induction at each time step.

The iteration process neglects the effects of the tangential component of the induced velocity, as well as the effects of turbulence. The effects of turbulence are ignored during the iteration because it is assumed that turbulence does not have a fully developed wake and, therefore, does not contribute significantly to the induced velocity. Once the iteration process is completed, turbulence is used in determining the final aerodynamic coefficients.

The aerodynamic loads are calculated in the blade deformed position. The resulting nonlinear equations are solved in the time domain using a predictor-corrector method. Tower and blade loads are determined by integration along the blade.

Turbulence in the wind was accounted for by use of a turbulence model, the Sandia Three-Dimensional Wind Simulation (Veers, 1984). This gives a rotationally sampled longitudinal turbulence component for each blade at one point on the blade. Each value represents the change in wind velocity due to turbulence. These values are superimposed on the steady component of the wind which already includes the effects of tower shadow and wind shear.

The FAST Code was developed at Oregon State University under contract to the Wind Technology Branch of the National Renewable Energy Laboratory (NREL) (Wilson et al., 1994).

THE ESI-80 WIND TURBINE

The ESI-80 wind turbine was tested extensively (Musial et al., 1985) and has been selected to compare calculated results from the FAST Code to field data. The wind turbine, which has two 40-foot (12.19 m) teetering blades, is a fixed pitch, free yaw, downwind machine with wood epoxy composite blades. The rotor blades employ the NASA LS(1) airfoil section. The specifications for the ESI-80 are summarized in Table 1.

FIELD MEASUREMENTS

The ESI-80 test turbine was located in the Altamont Pass near Tracy, California. A 120 ft (37 m) meteorological tower was located 160 ft (50 m) to the west of the wind turbine in the prevailing wind direction.

Table 2 lists the items that were measured during the test program and subsequently digitized at 50 Hz by the Solar Energy Research Institute (now NREL).

Table 1. ESI-80 Turbine Specifications

Rated Power	250 kW
Rated Wind Speed	20.3 ms (45 mph)
Rotor Diameter	24.2 m (80 feet)
Rotor Type	Teetered — Underslung
Rotor Orientation	Downwind
Blade Construction	Wood-Epoxy
Rotor Airfoil	NASA LS(1) 04xx
Tip Speed	77.9 m/s (173 mph)
Cut-In Wind Speed	5.9 m/s (13 mph)
Rotor rpm	60 rpm
Generator Type	300 kW, Induction
Gearbox	Planetary, 30:1
Hub Height	24.9 m (81.5 feet)
Tower	Open — Truss
Pitch	Fixed
Yaw	Passive
Overspeed Control	Tip Vanes
Total System Weight	9750 kg (21,500 lb)
Coning	7°
Natural Frequencies	
Teeter	1 Hz
Tower	1.31 Hz
First Flapwise	2.05 Hz
Second Flapwise	6.91 Hz
Edgewise	7.70 Hz

Table 2. Measured Parameters for the ESI-80 Test Turbine

Channel	Description
1	Wind Speed @ 31.5 m (120 ft)
2	Wind Direction @ 31.5 m (120 ft)
3	Wind Speed @ 24.5 m (80 ft)
4	Wind Direction @ 24.5 m (80 ft)
5	Wind Speed @ 12.2 m (40 ft)
6	Wind Direction @ 12.2 m (40 ft)
7	Rotor Azimuth Position
8	Teeter Angle
9	Yaw Angle
10	Blade Root Flap Bending
11	Blade Flap Bending @ 60% R
12	Low-Speed Shaft Torque

FAST RESULTS

Turbulence induced loads on the ESI-80 were examined using 10 minute records of wind conditions and loads measurements as reported by Wright and Butterfield (1992). The mean wind speed for Case 1 was 36.14 mph and turbulence intensity was 12.1%. For Case 2, the mean wind speed was 22.6 mph and the turbulence intensity was 9.7%.

The Sandia Three-Dimensional Wind Simulation (Veers, 1984), developed by Veers, was used for turbulent wind simulation. This code simulates the longitudinal component of the turbulence perpendicular to the rotor disk in non-yawed flow. A full three-component field of turbulence was not calculated.

The simulation method determines the "rotationally sampled" wind speed, although nonrotating wind speed can also be obtained from the model with minor modifications. The approach of this method is to simulate wind speed time series in a plane perpendicular to the mean wind direction and to propagate the time series in the mean wind direction at the mean wind speed. These signals are then rotationally sampled to prepare an input time series for the FAST Code.

In order to facilitate the calculation of blade loads, the FAST Code was run at constant rotor angular velocity. Further, the tower motion was limited to the first tower mode. Thus, ten degrees-of-freedom were employed; six degrees-of-freedom for the blade, teeter, yaw, and tower motion in two directions. Data on the configuration of the ESI-80 used for the tests was facilitated by measurements made at the University of Massachusetts. Of particular note is the presence of both teeter springs and teeter dampers.

COMPARISONS, 36.1 MPH

Histograms of test data and code calculations are shown below. Figure 1 shows a histogram for the 36.1 mph case for the blade root flatwise bending moment. Agreement between test data and code is good with a similar shape to both distributions. The test data mean was 26.34 kNm, while the FAST Code mean was 3.6 kNm lower. Figure 2 shows the flapwise bending moment histogram at a station 60% of the rotor radius. Again the data is higher than the code results, the mean for the data being 4.49 kNm and the mean for the code was 0.4 kNm lower. Since the mean acceleration of the blade in the flatwise direction is zero, the difference between test data and code must be from the mean aerodynamic loads, the mean centrifugal loads, or due to the data. Calculation of the mean blade root bending moment and comparison to test data shown in Figure 3 suggest that the calibration of the strain gages drift from test run to test run so that the code results shown in Figures 1 and 2 are felt to be within the range of experiment test error.

Figure 4 shows the teeter occurrence histogram at 36.1 mph. Several items may be mentioned concerning the data. First, the mean teeter angle from the test data is not zero being 0.24°. Second, the effects of the teeter springs/dampers can be seen in the data; the plateau above +2° and a similar plateau at about -1°. While the FAST Code results also exhibit "plateaus" in the region of ±2°, the code has a mean teeter angle of zero and the calculations are more or less symmetrical about the origin. Third, shape of the distribution of teeter angle was found to be a result of including the yaw degree-of-freedom. McCoy (1992) had modeled the ESI-80 using a code without a yaw degree-of-freedom and obtained a teeter occurrence histogram similar to the distribution that would be obtained from a harmonic oscillator. Further improvement to the teeter histogram was obtained by use of the variable speed degree-of-freedom.

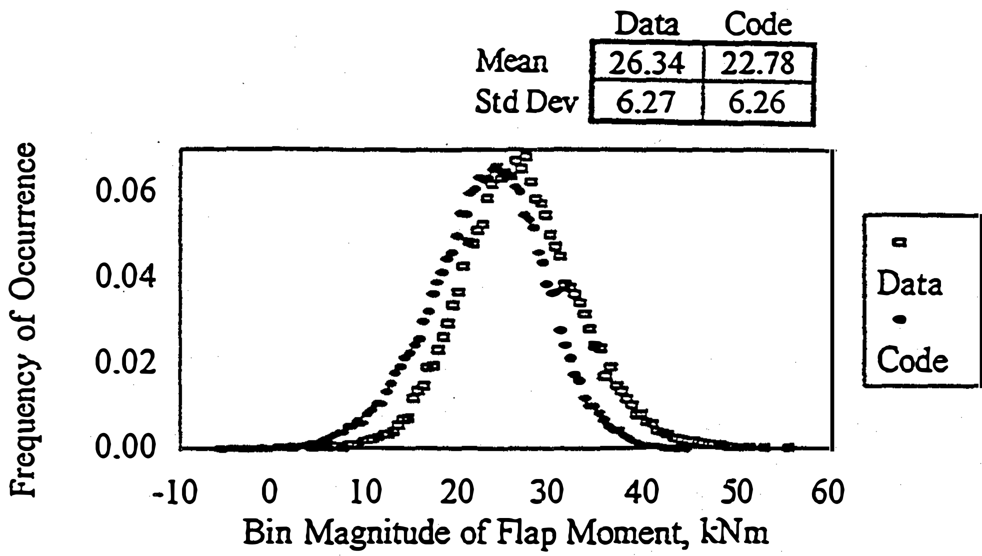

Figure 1. Occurrence Histogram of Blade Flap Moment at Root for ESI-80 Machine at 36 mph Wind Speed

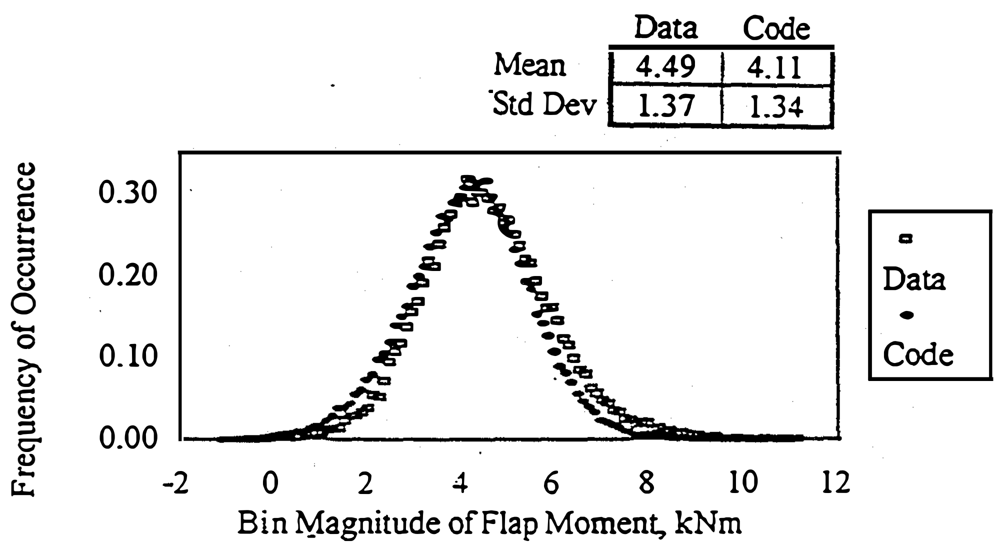

Figure 2. Occurrence Histogram of Blade Flap Moment at 60% Blade Station for ESI-80 Machine at 36 mph Wind Speed

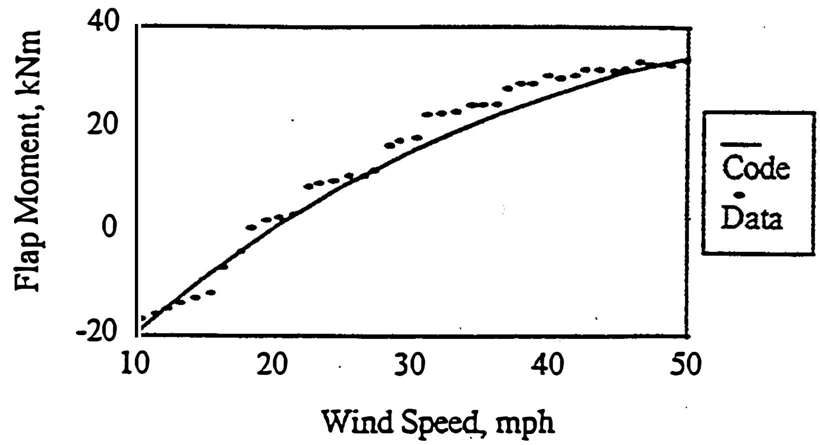

Figure 3. Mean Blade Flap Moment versus Mean Wind Speeds for the ESI-80 Machine

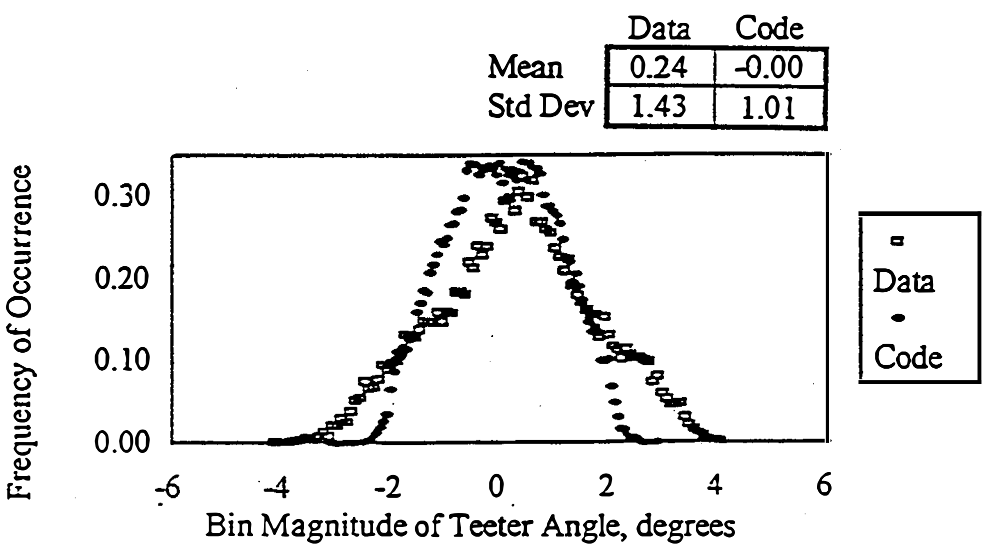

Figure 4. Occurrence Histogram of Teeter Angle for ESI-80 Machine at 36 mph Wind Speed

Azimuth averaged load plots are the second form of comparison between test data and FAST calculations. Figure 5 shows the azimuth binned blade root flatwise bending moment at 36.1 mph. Note that the load scale covers the range from 10 to 40 kNm. Agreement between FAST calculations is good as all fluctuations shown by the data are present in the calculations. The magnitude of the calculated moment between 90° and 135° (post tower shadow region) and between 270° and 315° has a maximum difference of 9 kNm below the test data.

Power Spectral Density of the root flatwise bending moment is shown in Figure 6 for a wind speed of 36.1 mph. Agreement between code and test data is good including the broadening in the region of 2 Hertz. The code failed to predict the broad plateau between 2 and 3 Hertz that appears in the test until the edgewise degrees-of-freedom were incorporated into the code.

Rainflow cycle counting is shown in Figure 7 for the 36.1 mph case. Agreement between FAST calculations and test data is good over the entire range. Code calculations shown in Figures 1 through 7 were made without dynamic stall. Calculations made with dynamic stall produced similar results to those produced without dynamic stall except for the low magnitude cycles.

COMPARISONS, 22.6 MPH

A histogram of the blade root flatwise bending moment is shown in Figure 8. Agreement between FAST2 calculation is very good as the mean, standard deviation, and distribution are all very close. The azimuth averaged flatwise blade bending moment shown in Figure 9 also shows good agreement between test data and calculations in magnitude, phase angle, and representation of major fluctuations. The power spectral density of the root flap moment is illustrated in Figure 10. While agreement between the test data and code is good, there appears to be a scale shift in the frequency, the data peaks occurring at slightly lower than integer values of the rotor angular velocity while the code peaks occur at values slightly above integer values of the rotor angular velocity. With the rotor angular velocity of

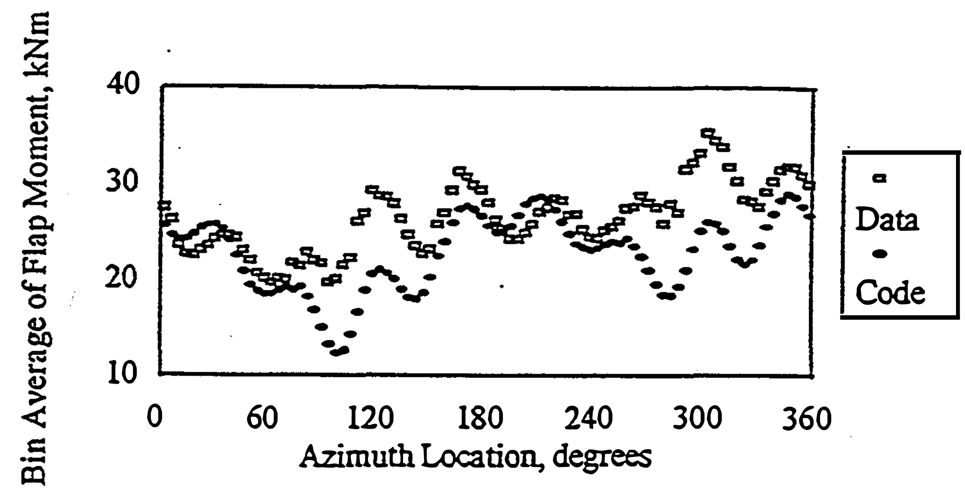

Figure 5. Azimuth Binning of Blade Flap Moment at Root for ESI-80 Machine at 36 mph Wind Speed

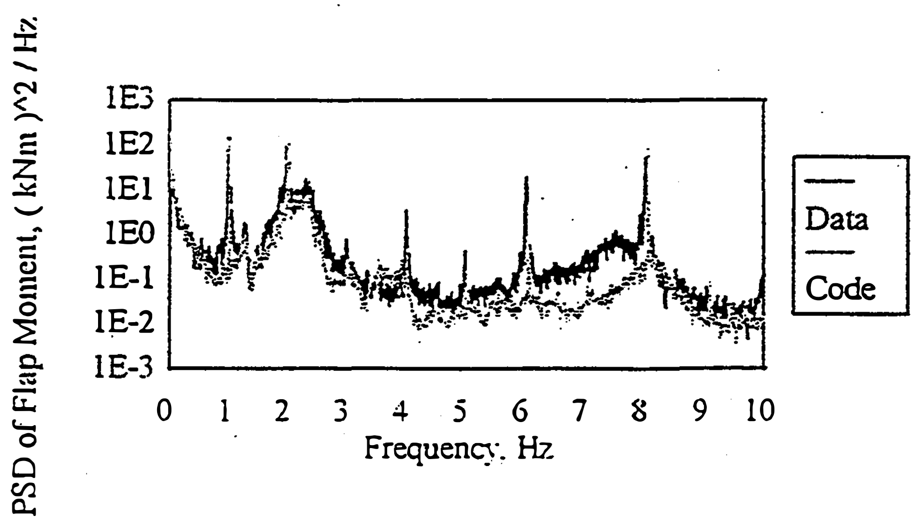

Figure 6. Power Spectral Density of Blade Flap Moment at Root for ESI-80 Machine at 36 mph Wind Speed

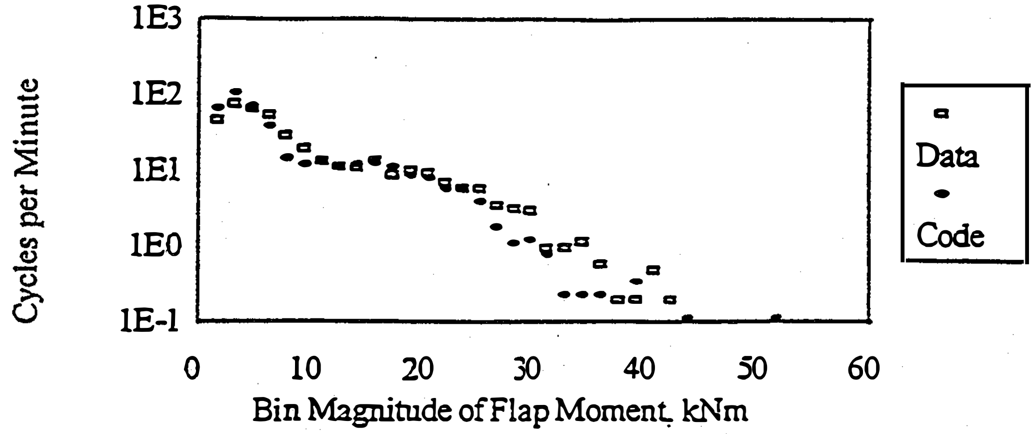

Figure 7. Rainflow Cycle Counting for the Blade Root Flap Moment for ESI-80 Machine at 36 mph Wind Speed

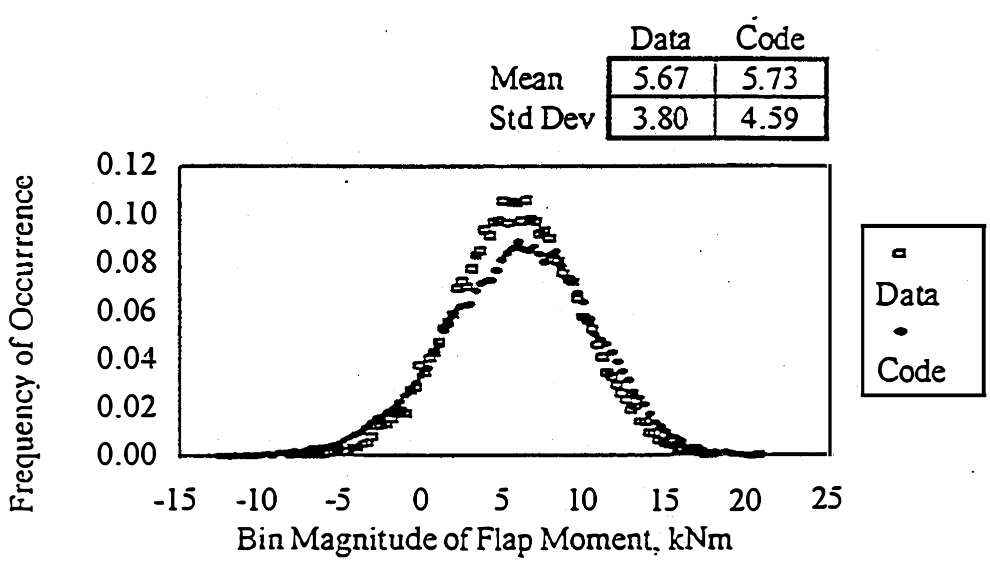

Figure 8. Occurrence Histogram of Blade Flap Moment at Root for ESI-80 Machine at 23 mph Wind Speed

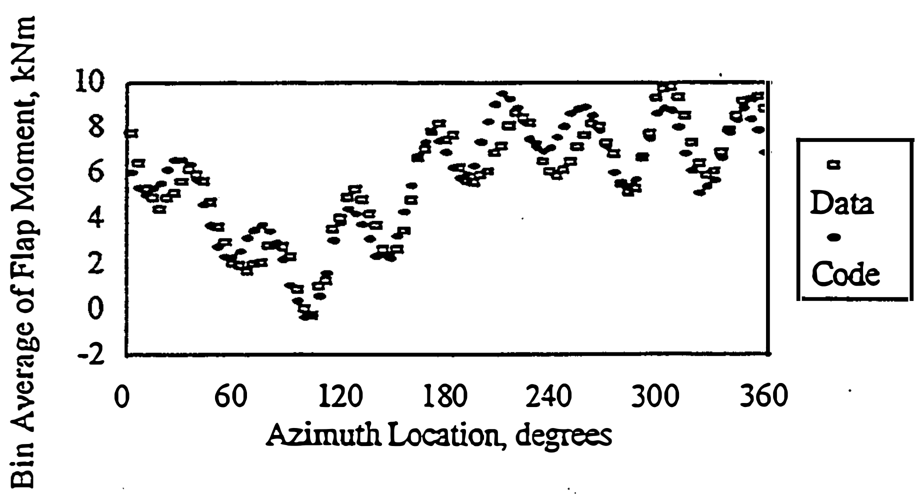

Figure 9. Azimuth Binning of Blade Flap Moment at Root for ESI-80 Machine at 23 mph Wind Speed

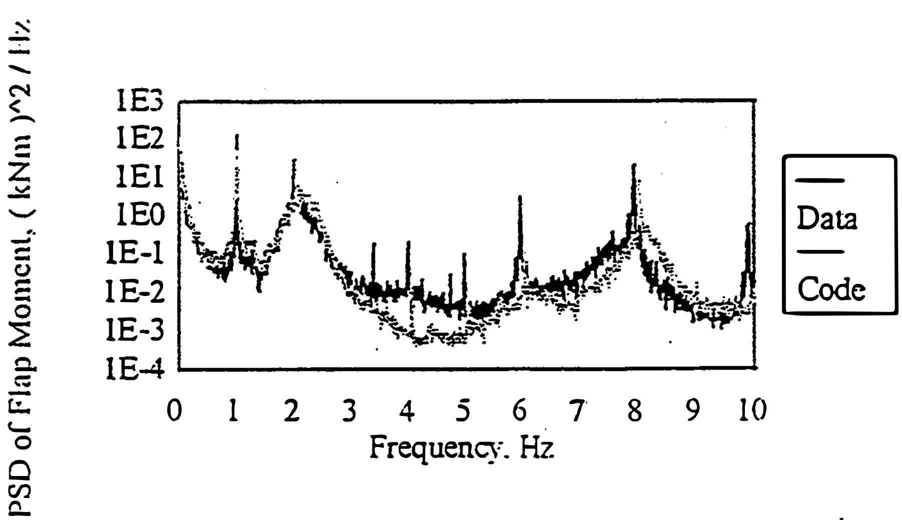

Figure 10. Power Spectral Density of Blade Flap Moment at Root for ESI-80 Machine at 23 mph Wind Speed

1.005 Hertz, the differences are believed to be associated with the digitization of the data from the analog tape (Wright, 1991).

Rainflow cycle counting is shown in Figure 11 where root flap cyclic moment count is shown at 22.6 mph. The results shown in this figure show as good agreement with the test data as the previous figures. The 60% blade station cyclic count is shown in Figure 12. Agreement between the code and test data is again good.

OTHER OUTPUT

In addition to the quantities previously illustrated, there are a number of variables of interest for which ESI-80 test data is not available. Paramount of these quantities is the blade edgewise bending moment. Figure 13 shows the blade root edgewise bending moment at 36.1 mph. Shown in Figure 13 are the rainflow cycle count for fixed speed operation. The code was run using both fixed and variable speed operation and the difference in calculated loads was found to be minor. The rainflow cycle count shows the characteristic behavior of a bi-modal distribution, the large number of low amplitude cycles being due to the gravity loads that occur once per rotor revolution. Figure 14 shows the distribution of the calculated angle-of-attack near the blade tip for both wind speeds. While comparison data is not available, such plots may be useful in determining the magnitude and the frequency of large angle-of-attack excursions.

Finally, Figures 15 and 16 show the calculated blade tip deflection, including the effects of blade teeter and elastic flatwise bending, at a wind speed of 36.1 mph. Again, while test data is not available for the tip deflection, such calculations would be of use to a wind turbine designer. Figure 15 shows the occurrence distribution of the tip deflection while Figure 16 shows the azimuth-binned distribution of tip deflection.

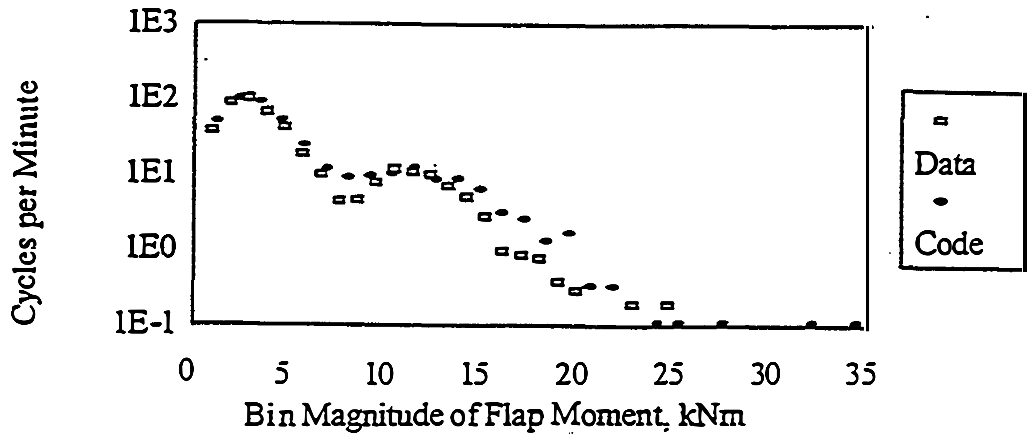

Figure 11. Rainflow Cycle Count of Blade Flap Moment at Root for ESI-80 Machine at 23 mph Wind Speed

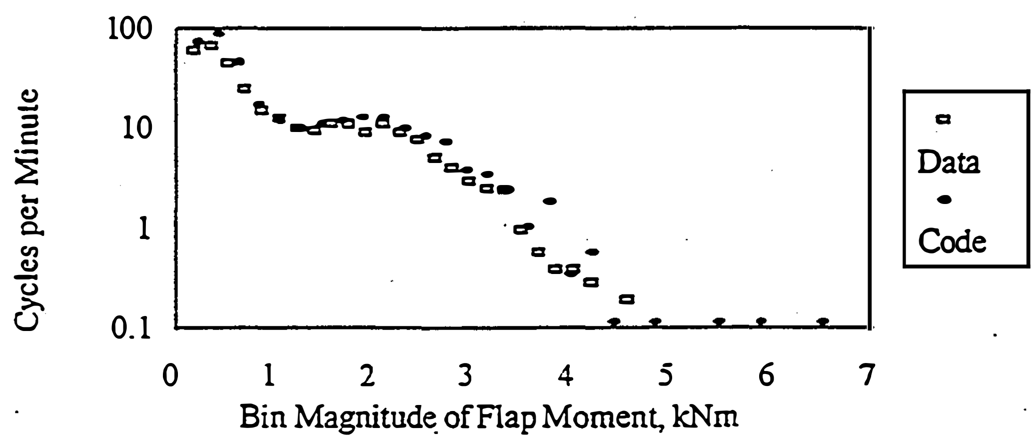

Figure 12. Rainflow Cycle Count of Blade Flap Moment at 60% Blade Station for ESI-80 Machine at 23 mph Wind Speed

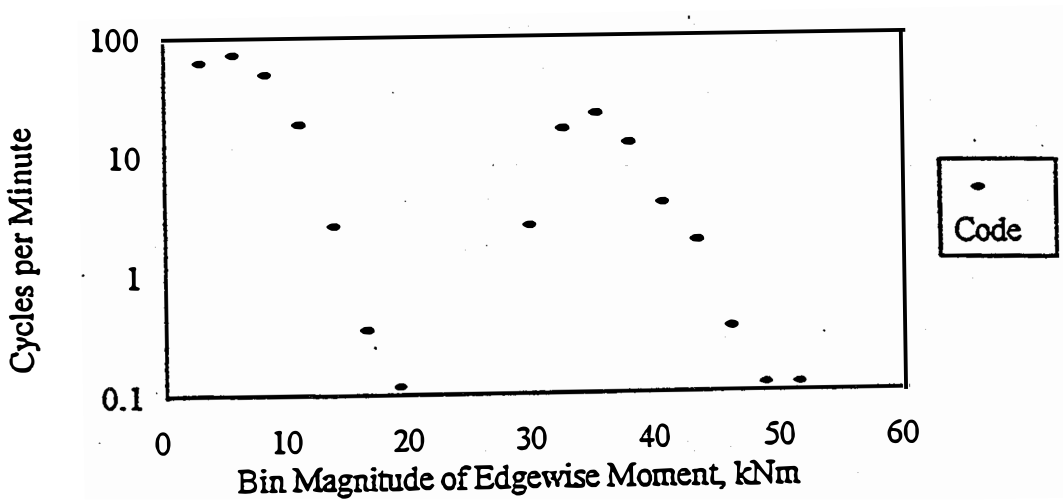

Figure 13. Calculated Rainflow Cycle Count for the Blade Root Edgewise Bending Moment at 36.1 mph

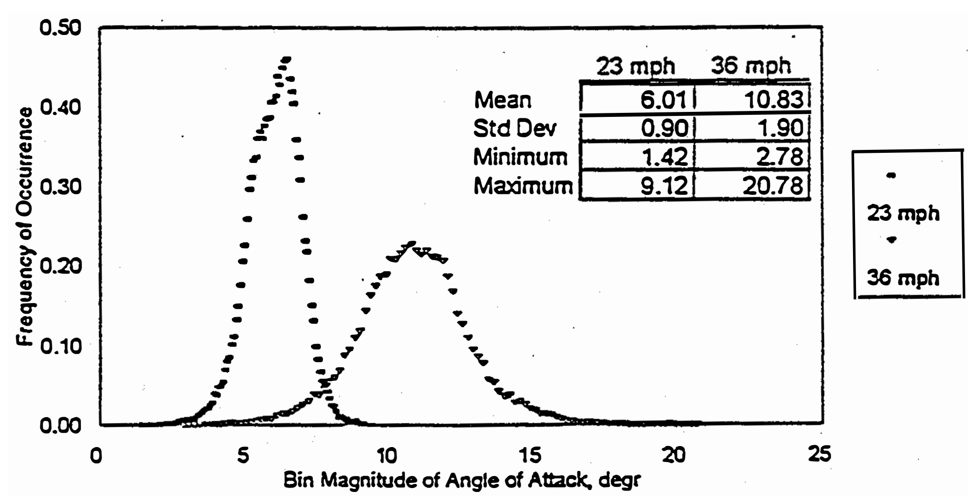

Figure 14. Calculated Frequency Distribution of the Angle-of-Attack Near the Blade Tip for the ESI-80

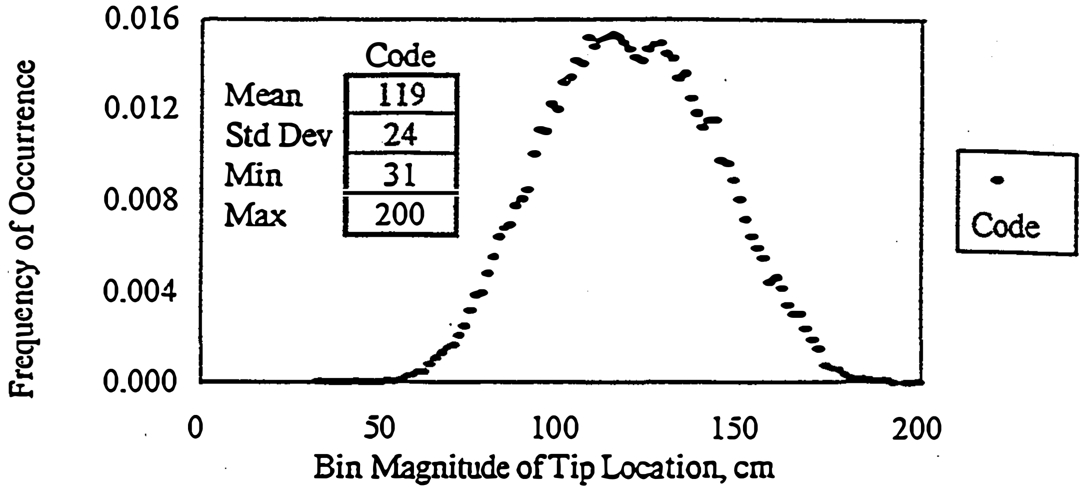

Figure 15. Calculation Frequency Distribution of the Blade Tip Deflection of the ESI-80 Operating at 36.1 mph

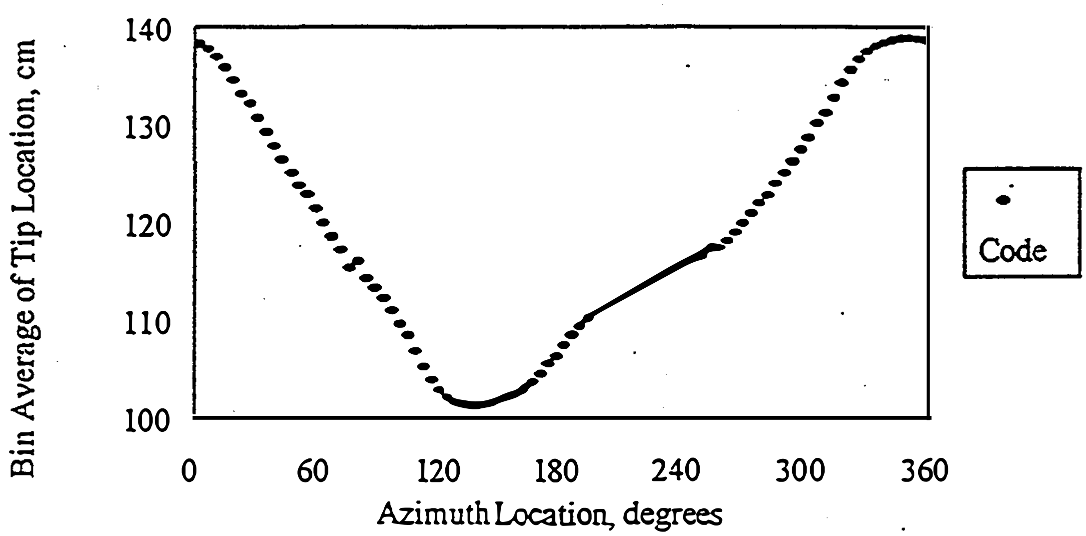

Figure 16. Calculated Azimuth-Binned Blade Tip Deflection of the ESI-80 Operating at 36.1 mph

CONCLUSIONS

Comparison of ESI-80 test results for the root flapwise bending moment have been made with calculations from the FAST Code. The comparisons have been made at mean wind speeds of 22.6 and 36.1 mph and cover occurrence histograms, azimuth averaged bin plots, power spectral density distributions, and rainflow counting. Based on the results shown in Figures 1 through 12 it is our opinion that the FAST Code is capable of good accuracy in the determination of stochastic blade bending loads on the ESI-80 wind turbine. Calculations have been made using both fixed and variable rotor angular velocity and it is concluded that the blade flatwise loads and teeter motion are adequately determined for the ESI-80 using a constant rotor angular velocity.

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Validation of the YawDyn and AeroDyn Codes

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Outline:

- List of publications
- Results for tilting, variable-speed rotor
- Combined Experiment Phase 3 Results
- Variable-Speed Testbed Results
- Conclusions

U. of Utah Publications in this Area

- Rigid Rotors
  - Combined Experiment, Phase 2
  - Micon 65
- Teetering Rotors
  - ESI-80
- Tilting Rotors (Rigid, Variable Speed)
  - Synergy Power Corp S-20000, S-50000 and SL Systems
- Wind-tunnel data for dynamic stall validation
- Comparison with other models and analytic solutions
- List of publications included in handouts

List of Publications Containing Code Validation and Related Results

University of Utah Wind Energy Research Team
August 1, 1996

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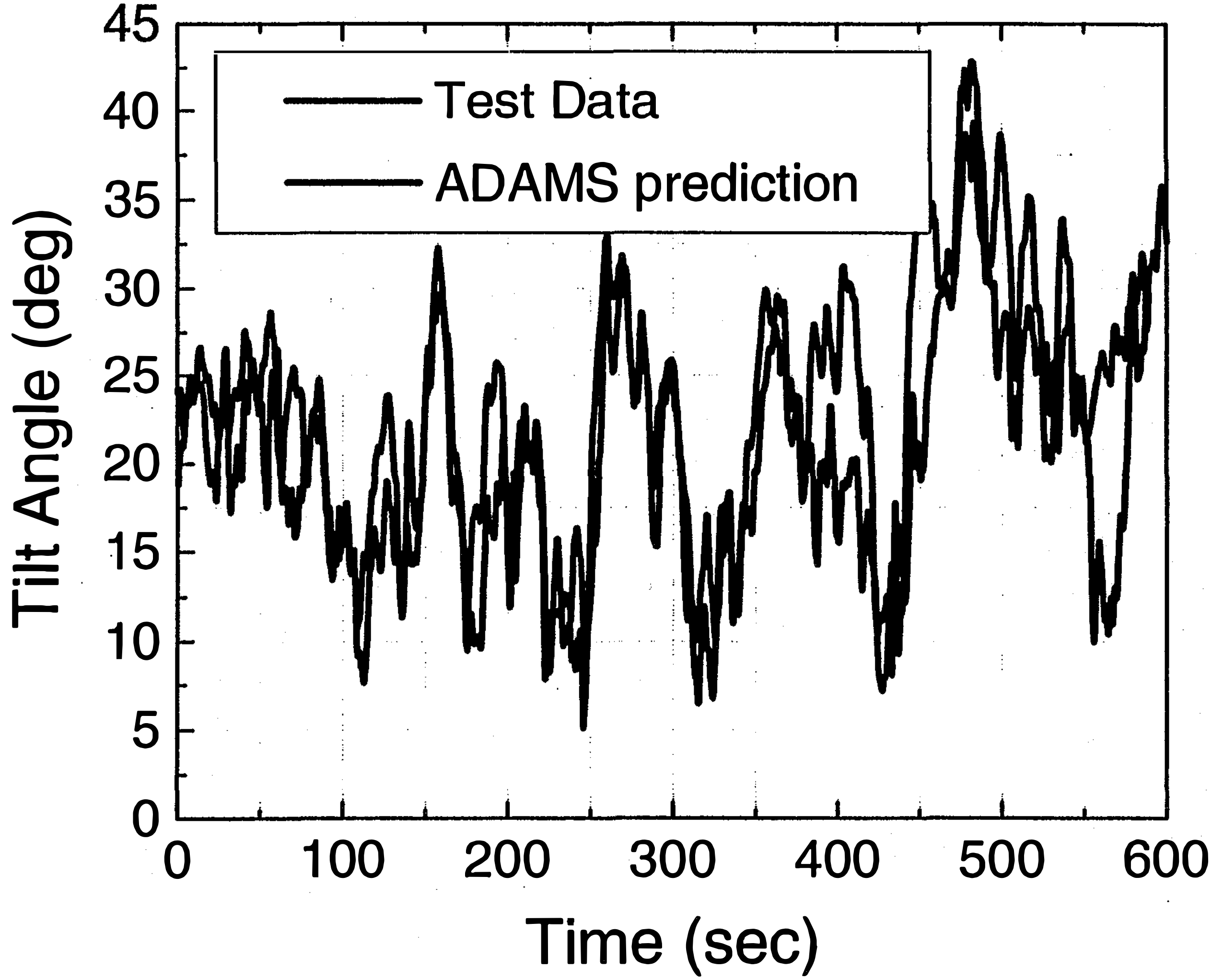
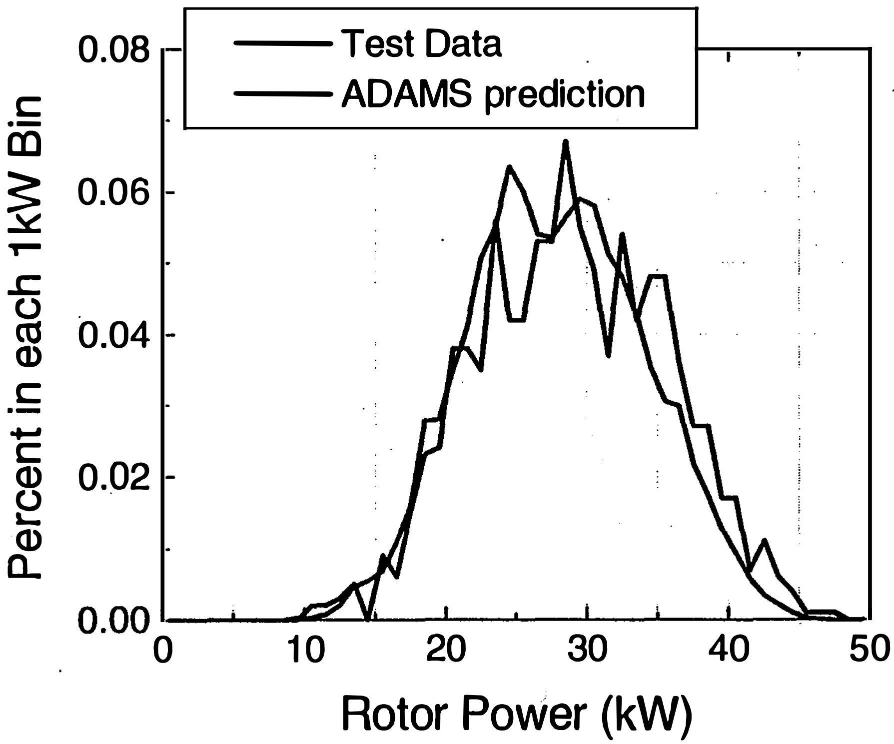
Pierce, K. G. and D. J. Laino (1996). Modeling the Effects of Control Systems on Wind Turbine Fatigue Life. Windpower '96, Denver, CO, American Wind Energy Association.

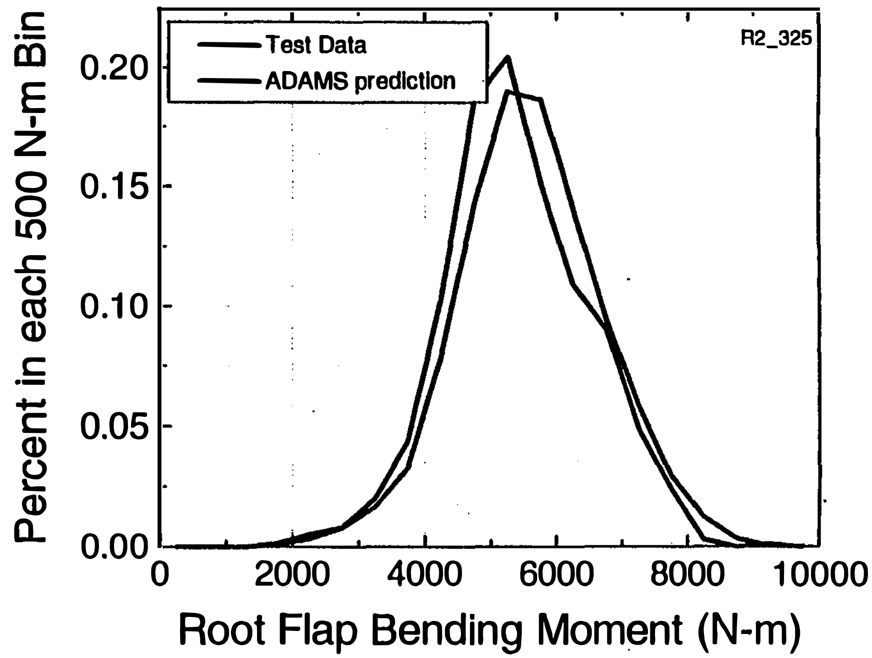
Tilt Angle Prediction for Synergy S-50000 System



Power and Blade Load Comparison



Synergy SL Turbine (Constant speed, tilting rotor)



Validation Using CER Phase 3 Data

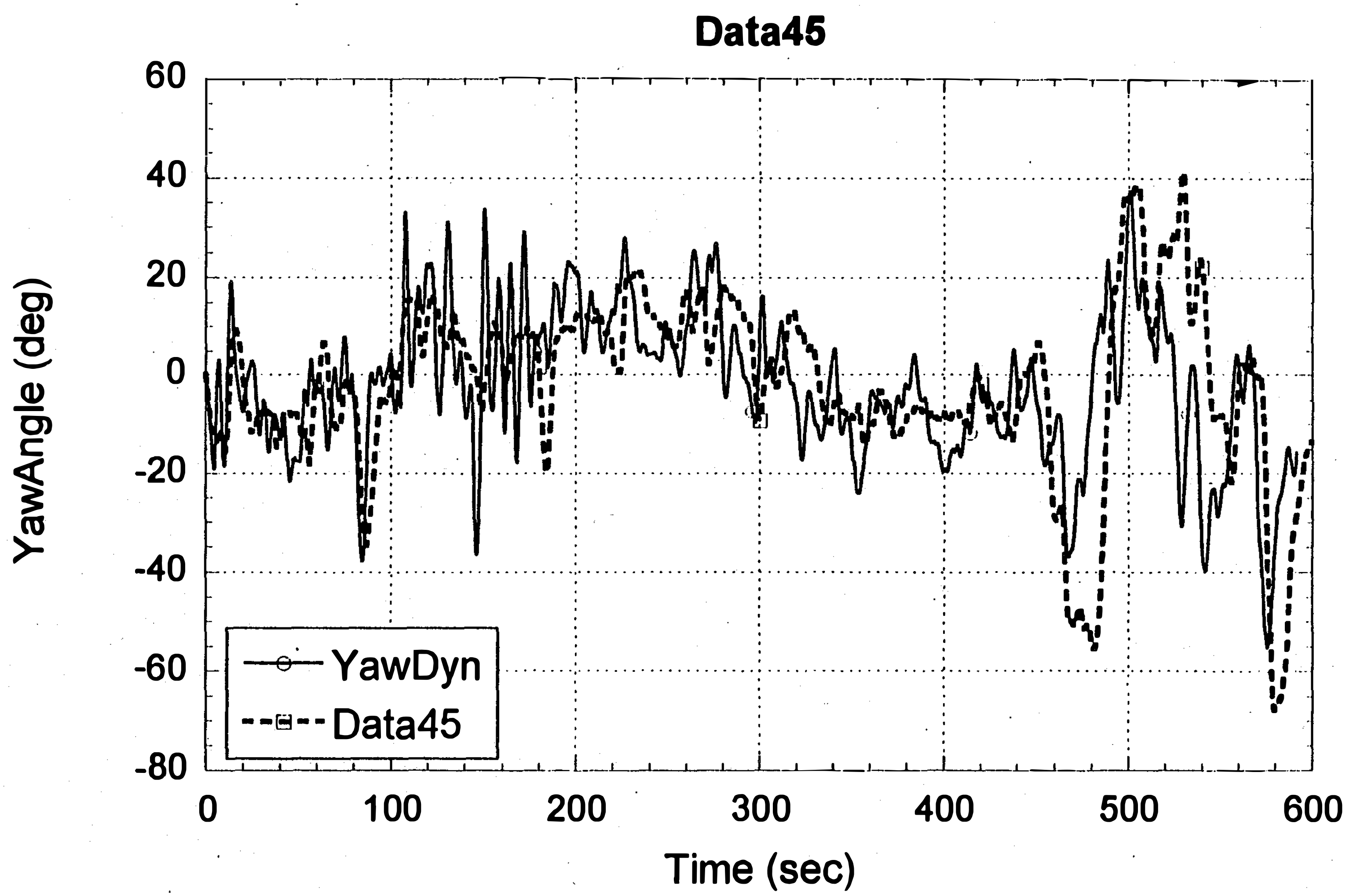
- Attempted to conduct "blind test" for results I will show today
  - No tweaking
  - Used OSU airfoil data for S809 (steady, Re=0.75E6, Clean, processed using Foilchk program for high angle of attack)
  - No added damping
  - Judgment still required to develop inputs, different analysts would get slightly different results
- One exception to the "no tweaking rule": ADAMS structural model was "tuned" after seeing the data. The purpose was to see if other structural compliance could be the cause of the high cyclic flap loads

Five Data Sets Selected

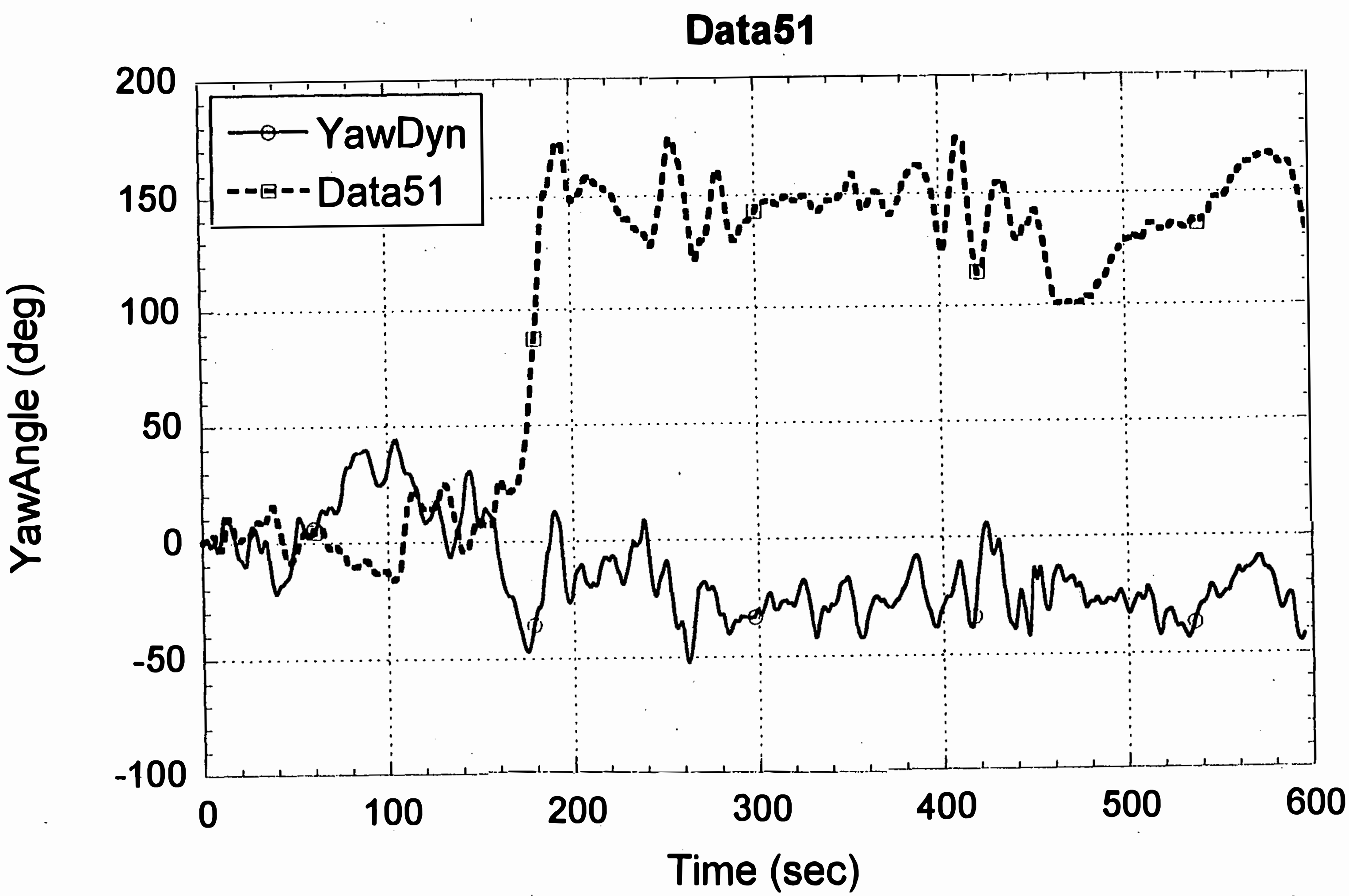
Each data set is ten minutes long, selected sets had all necessary data channels working--except angle of attack in free-yaw cases

Data set	Mean Wind Speed (m/s)	Yaw	Notes
data45	9.0	Free	
data51	5.6	Free	Yawed upwind
data74	9.0	Locked	First 240 s deleted (yaw not locked)
data79	8.6	Locked	
data94	9.2	Free	Yawed upwind

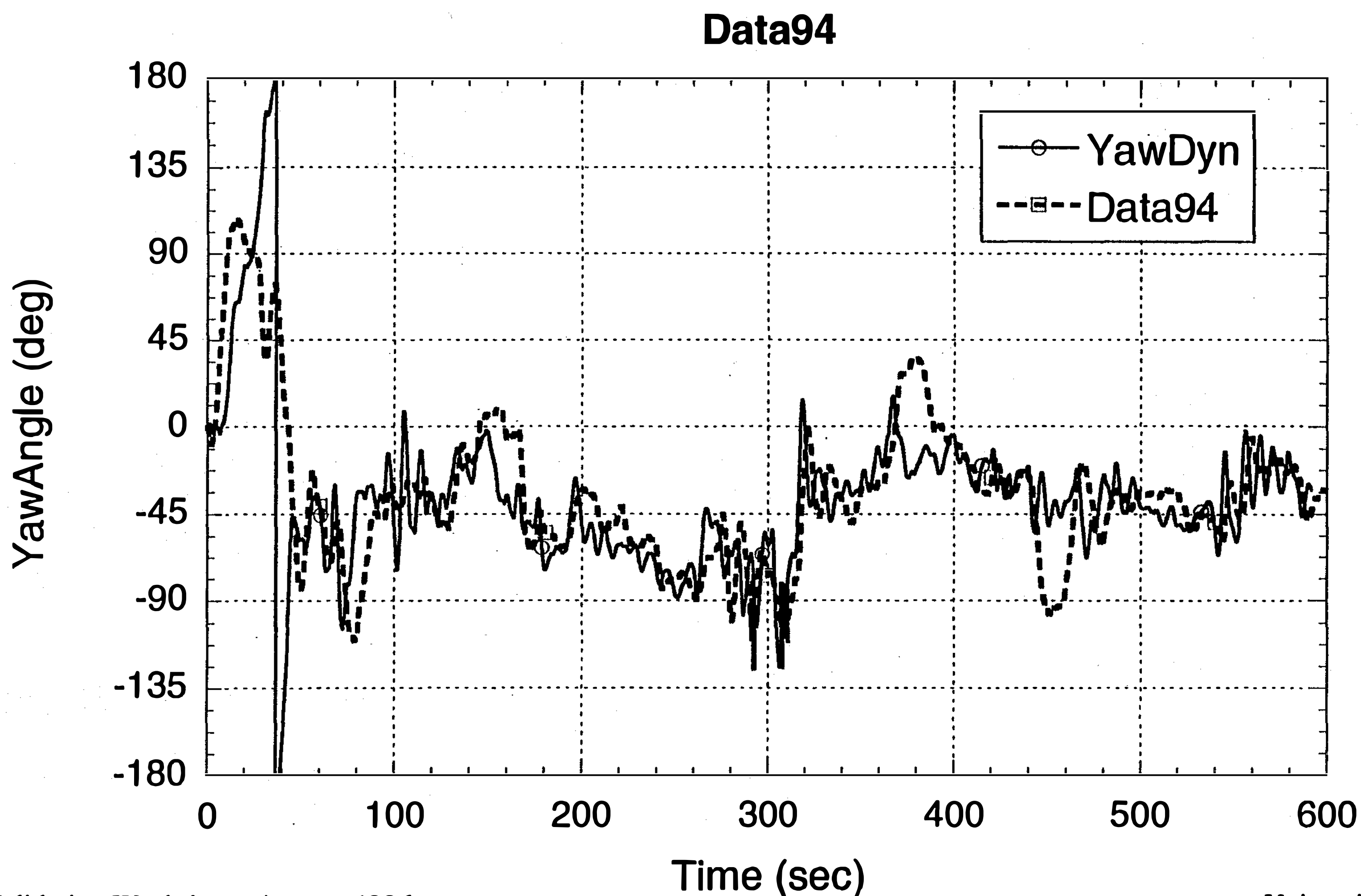
CER3 Yaw Motion



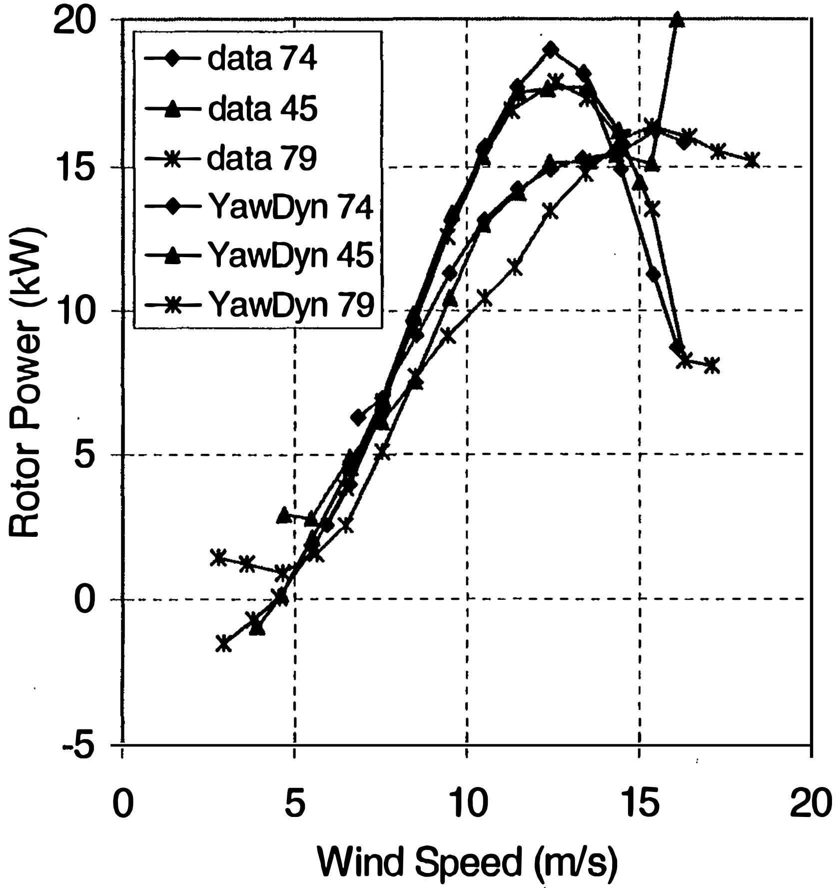
CER3 Yaw Motion

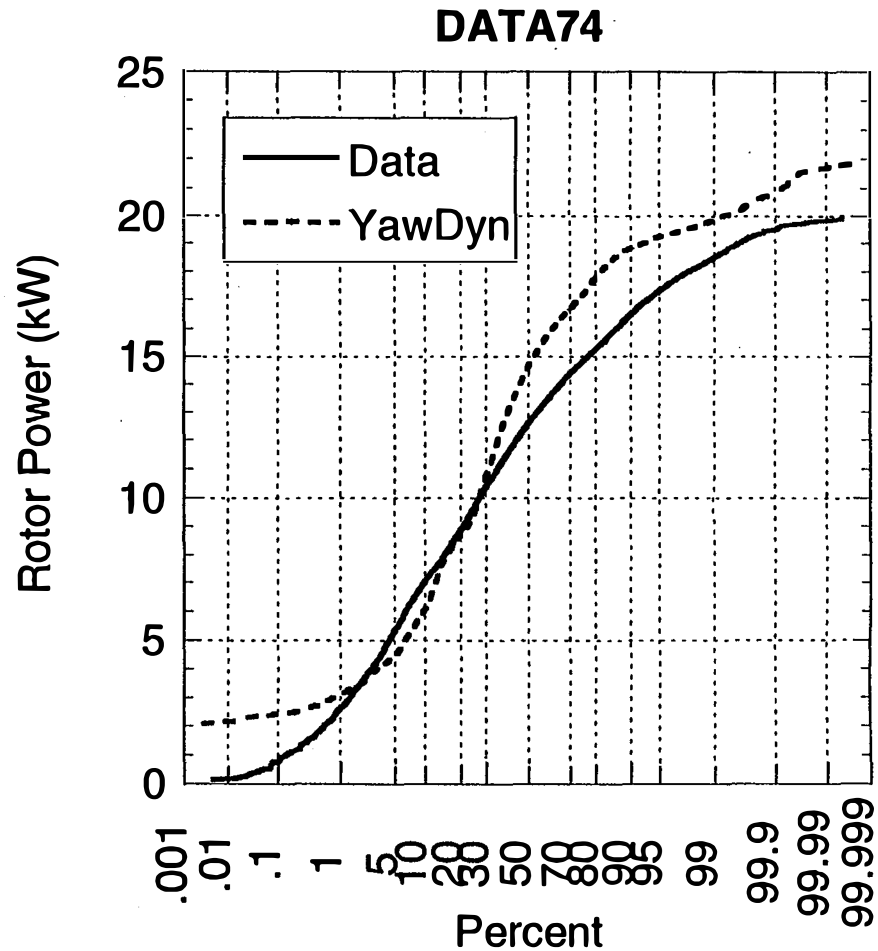


CER3 Yaw Motion



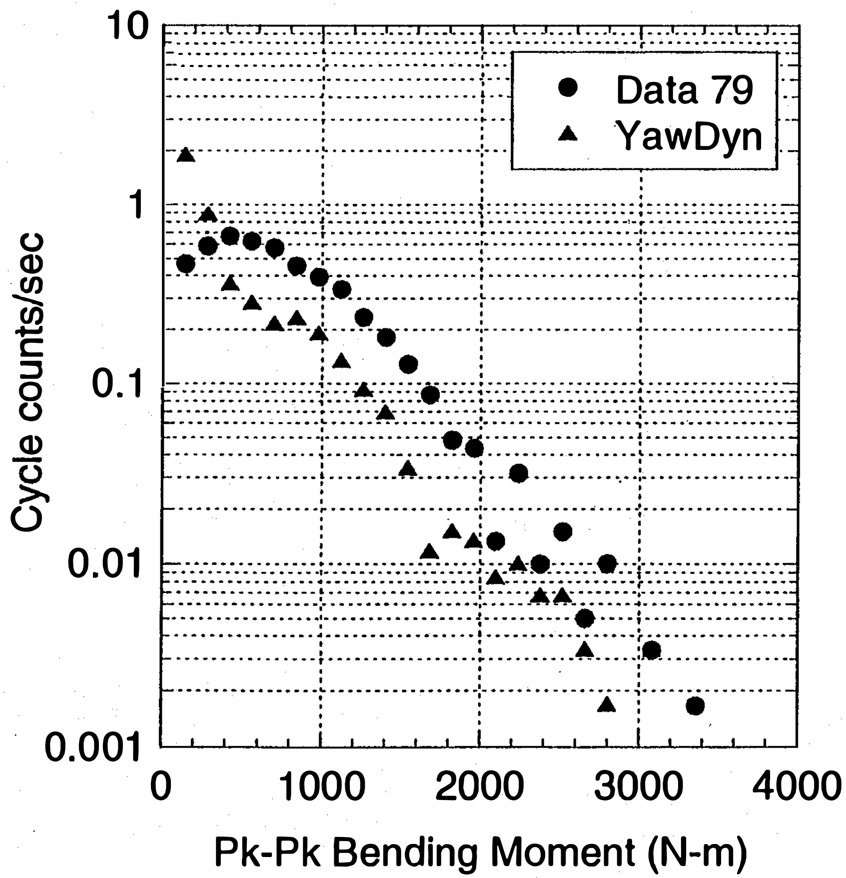
CER3 Rotor Power



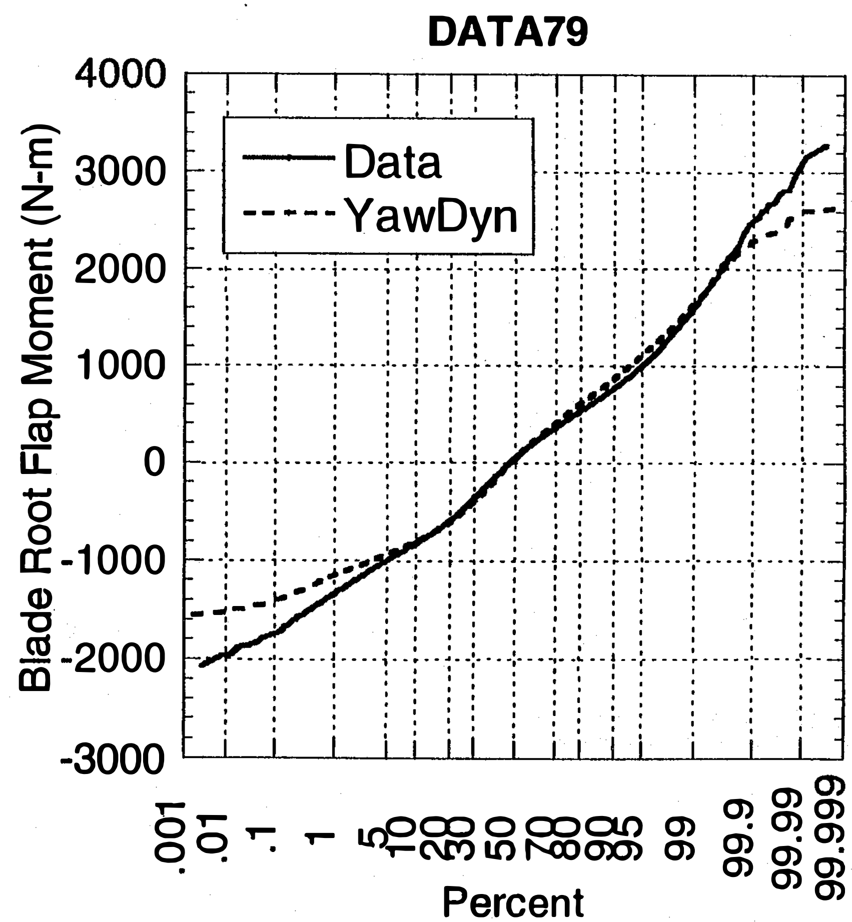


CER3 Blade Root Bending Moment

Rainflow Counts

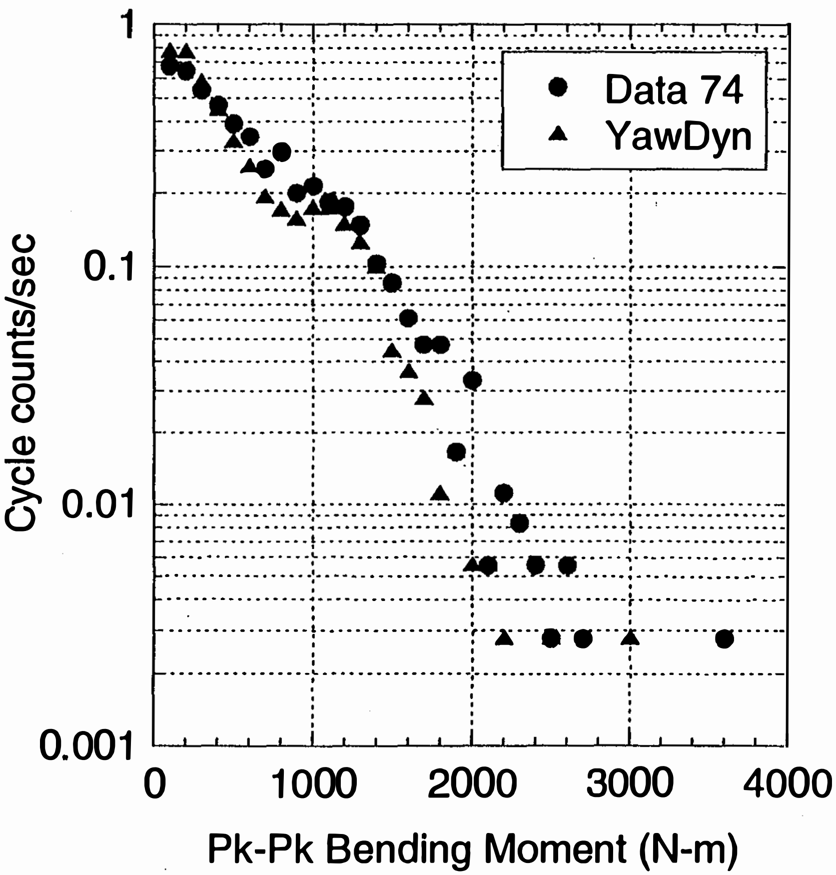


Probability Plot

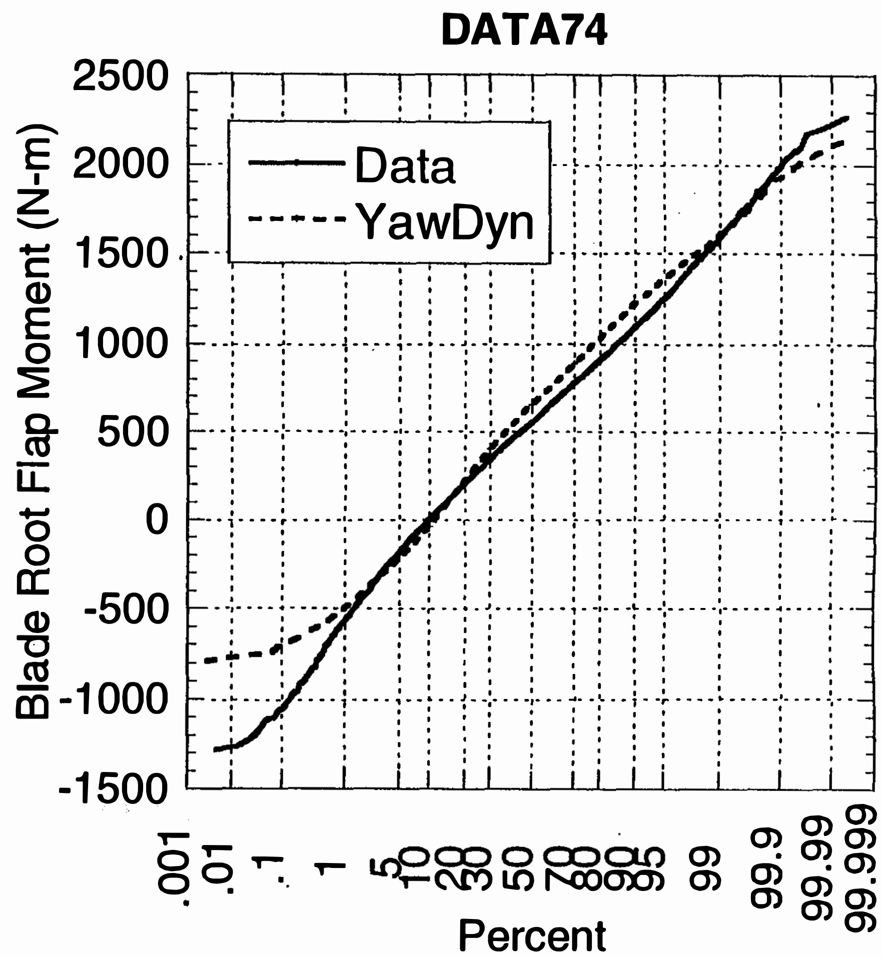


CER3 Blade Root Bending Moment

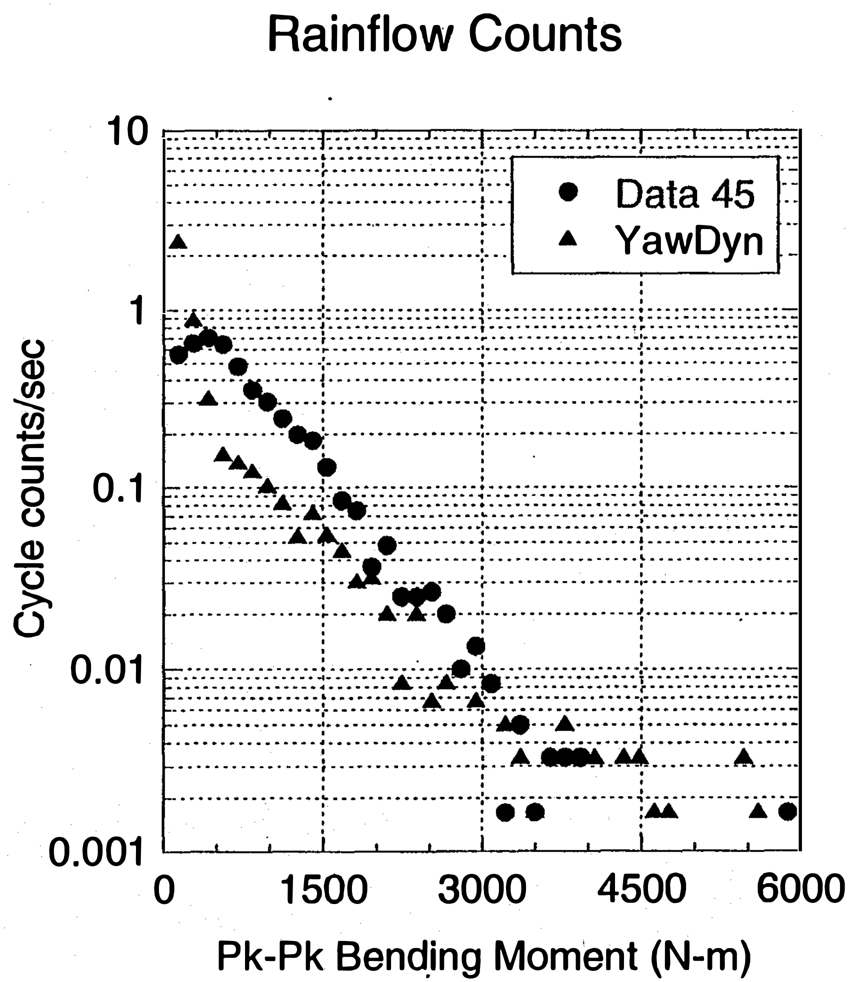
Rainflow Counts

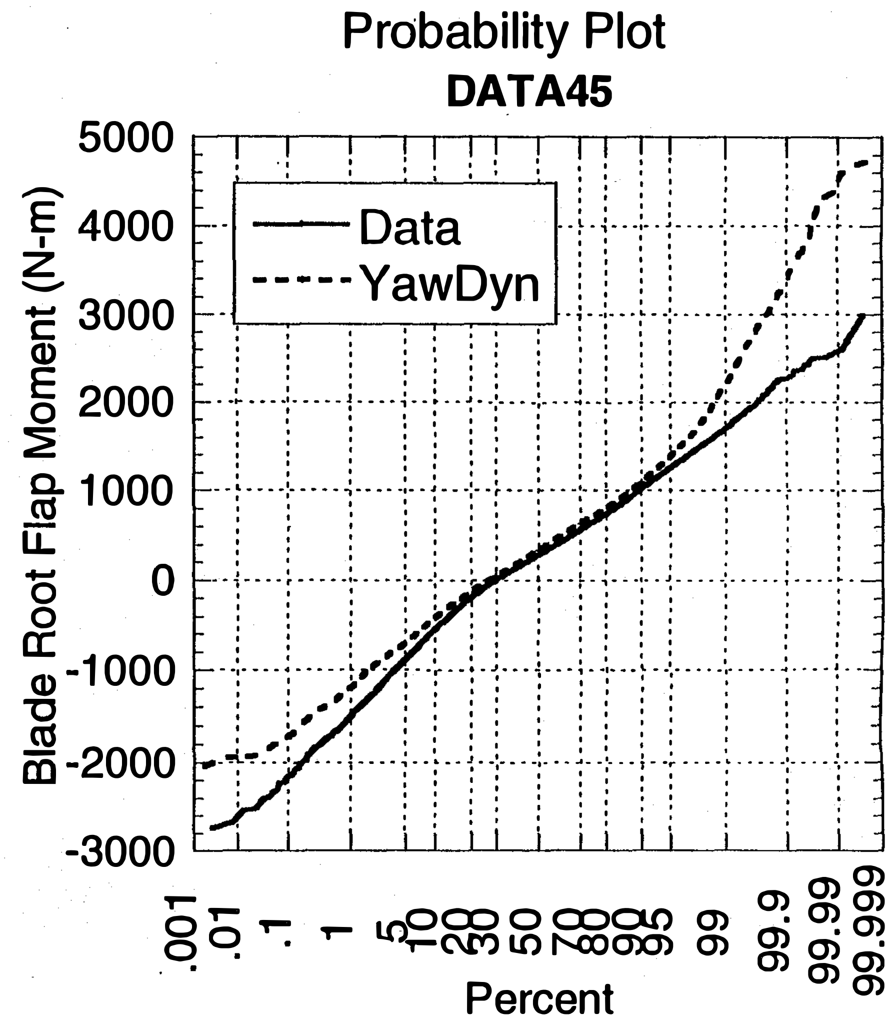


Probability Plot

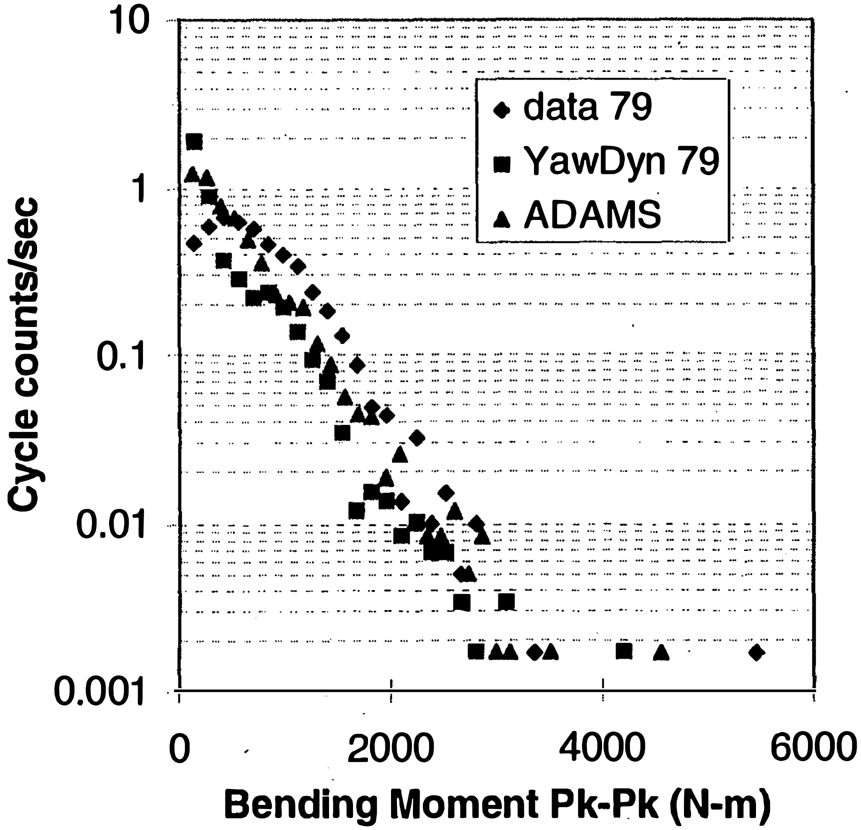


CER3 Blade Root Bending Moment



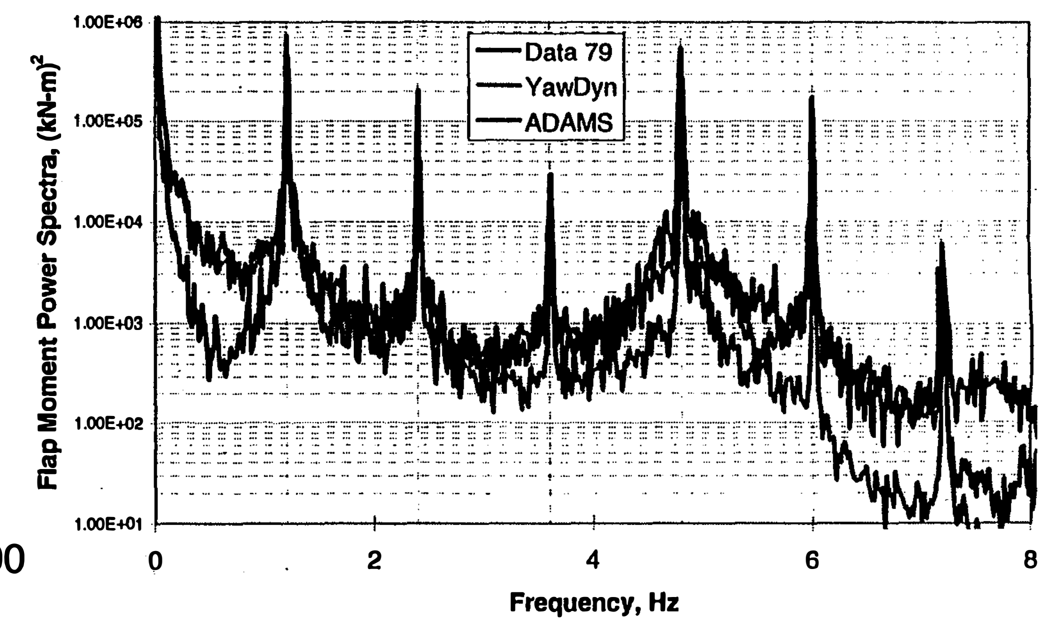


CER3 Root Flap Bending in ADAMS

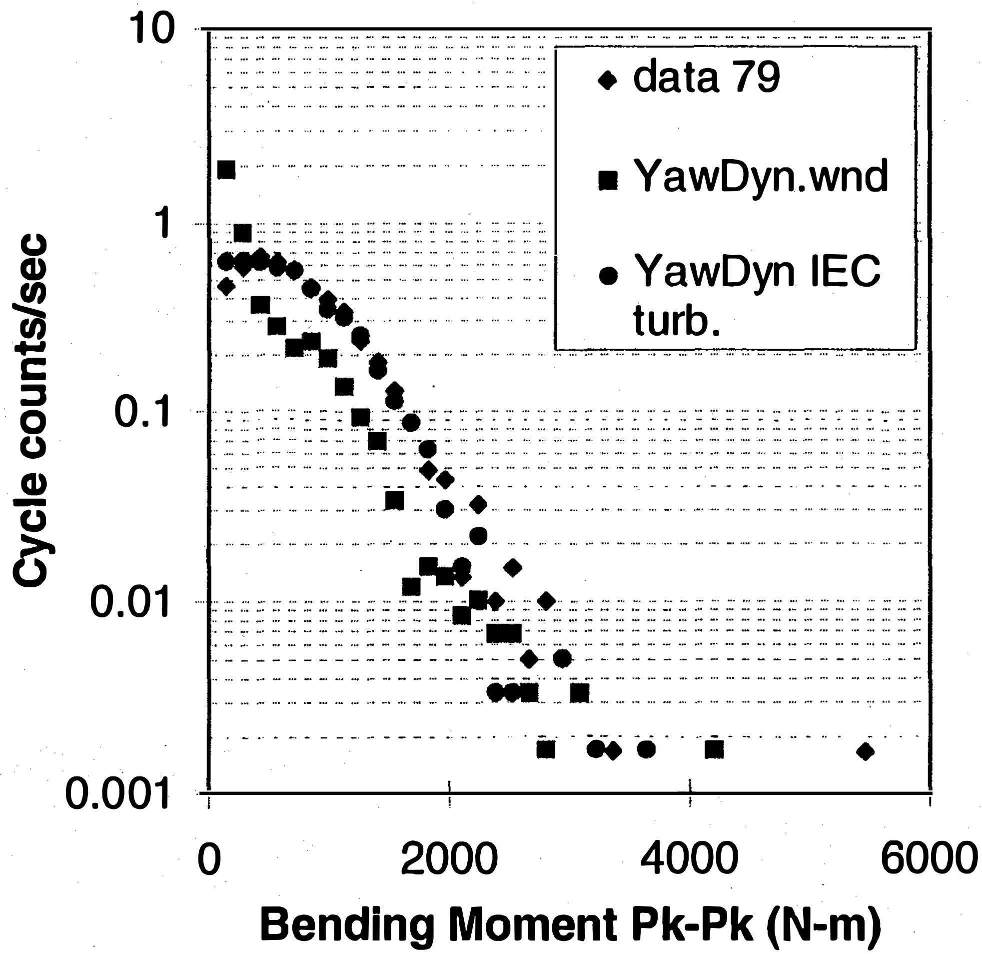


ADAMS was used to add nacelle roll and pitch degrees of freedom (with stiffness) at the tower-top

No other changes were made from the YawDyn model



Turbulence vs. "YawDyn .wnd Files"

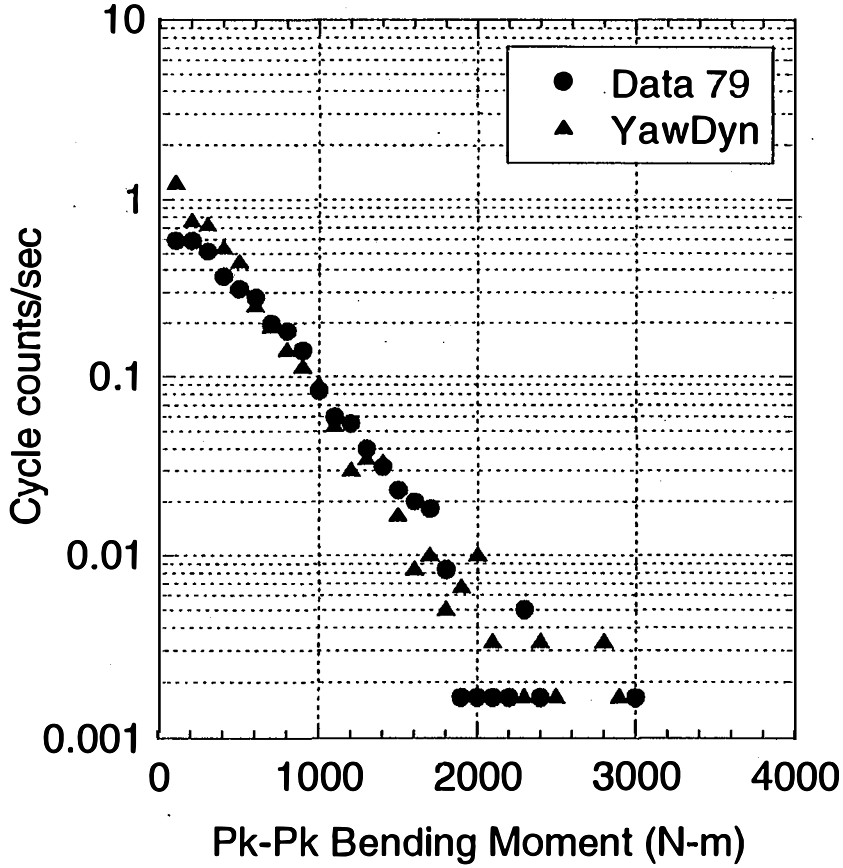


Case 79 was run with 3-D turbulence (IEC Kaimal) instead of the YawDyn wind data file

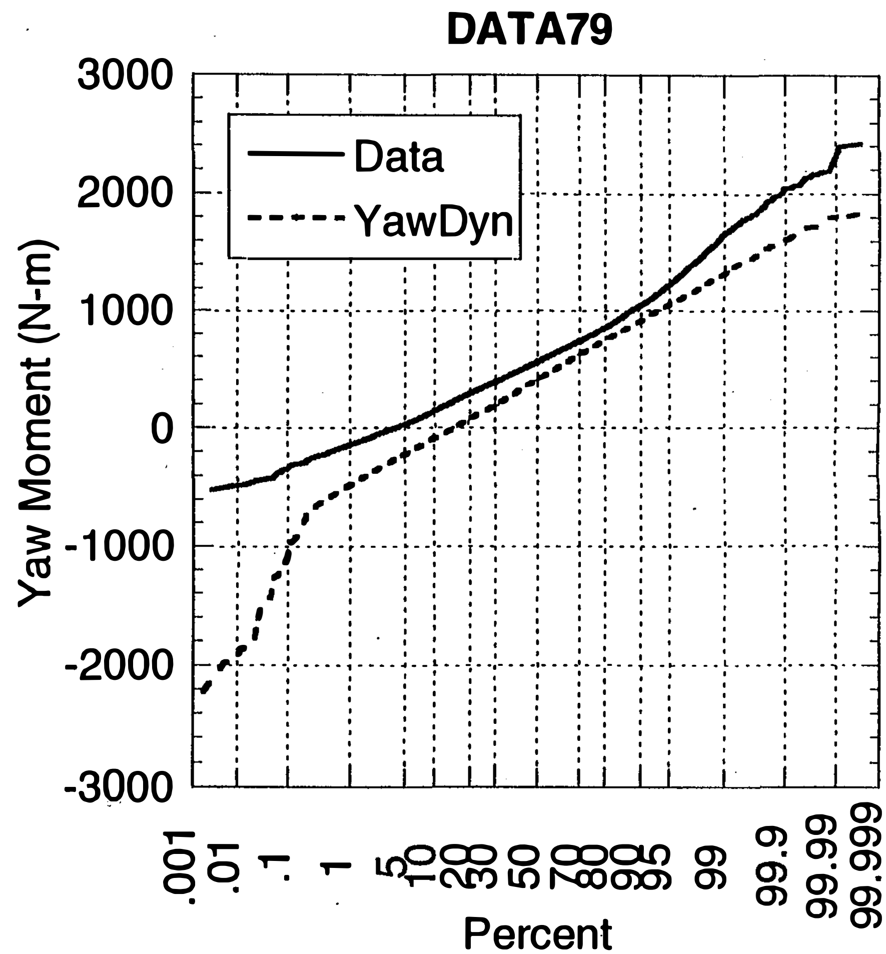
The mean velocities at hub height match in all cases, but the turbulence characteristics do not

CER3 Yaw Moments (Data 79)

Rainflow Counts

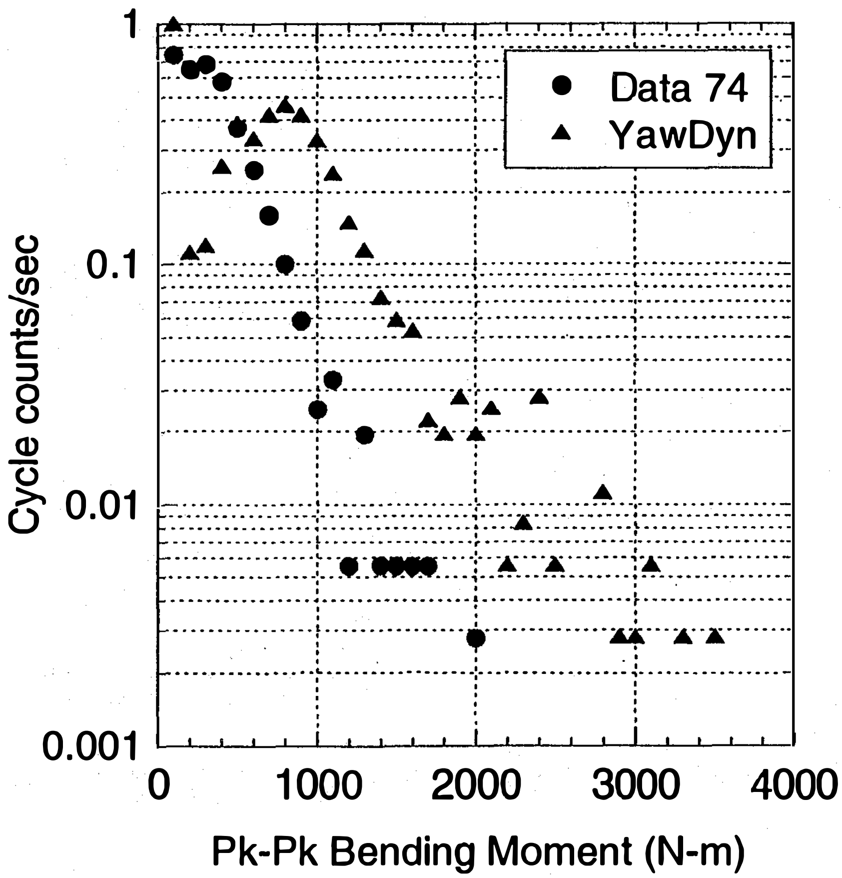


Probability Plot

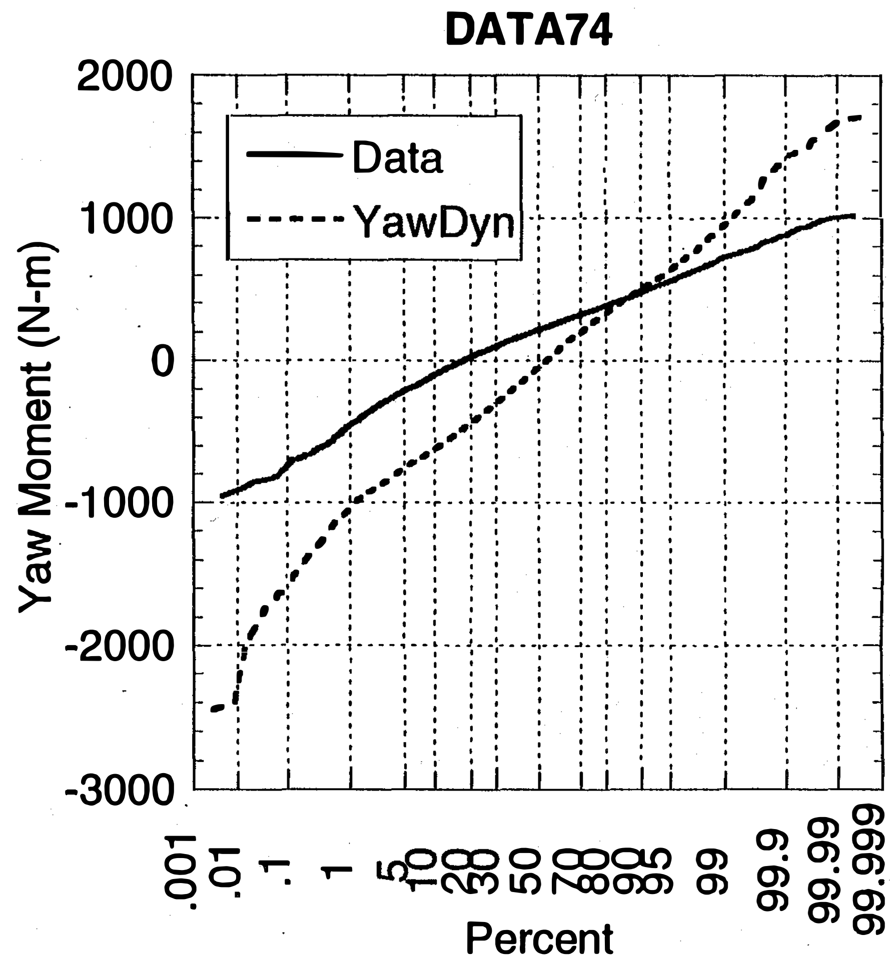


CER3 Yaw Moments (Data 74)

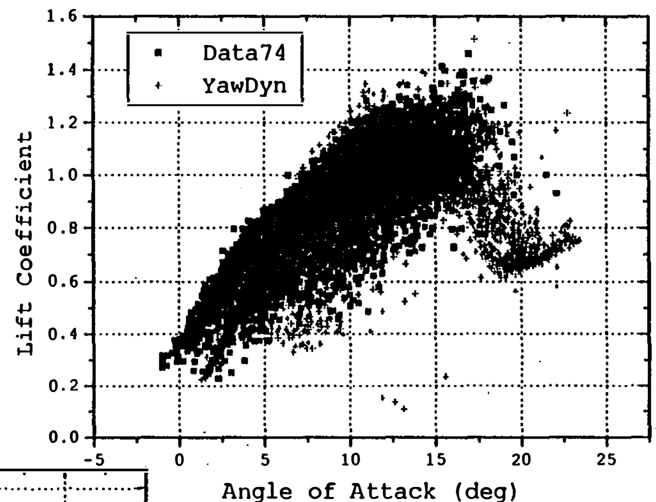
Rainflow Counts



Probability Plot

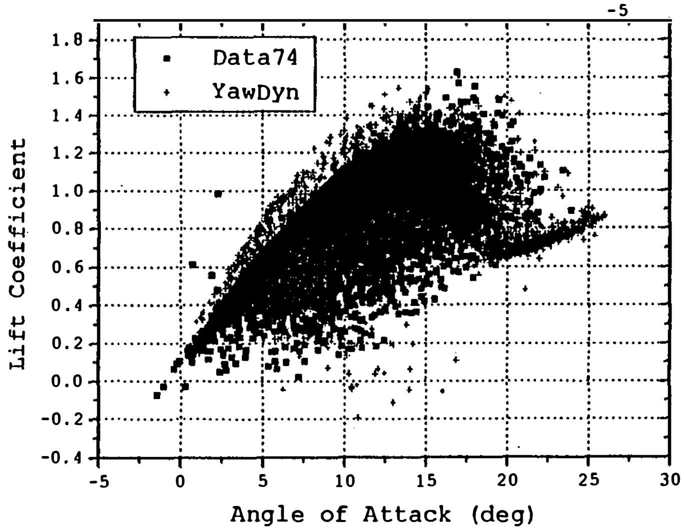


Lift Coefficient and Angle of Attack (data 74)

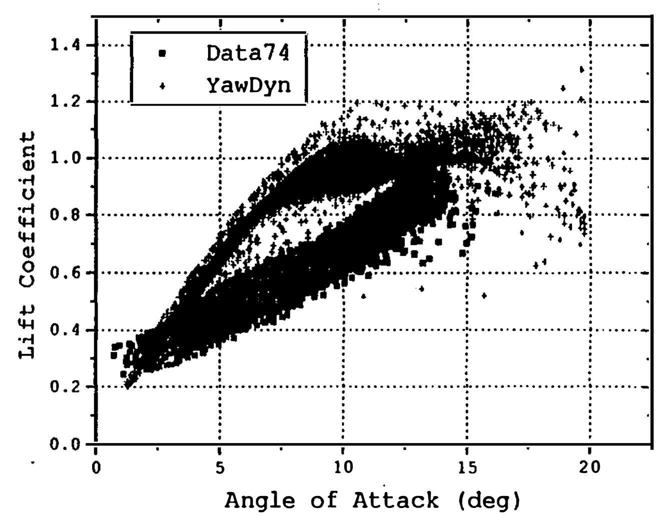


63% station

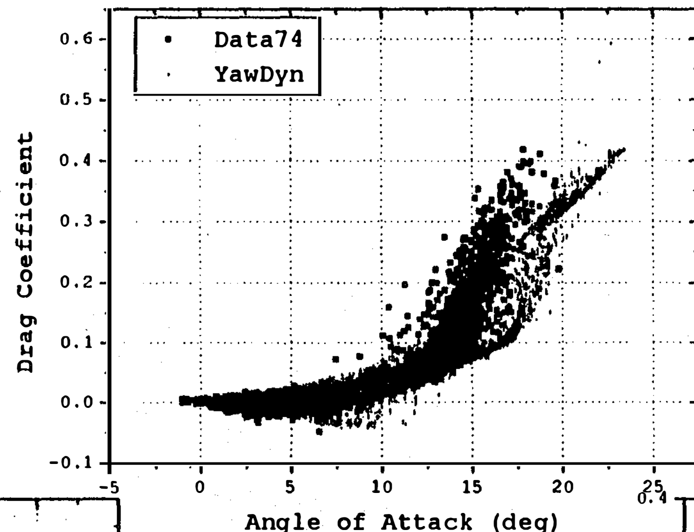
47% station



95% station

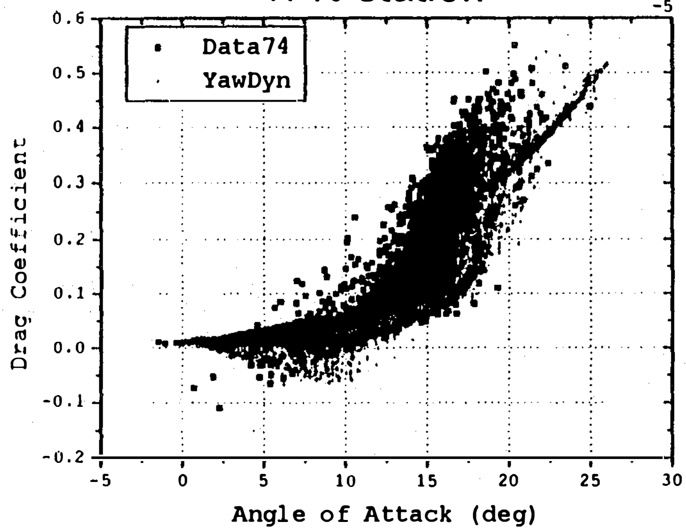


Drag Coefficient and Angle of Attack (data 74)

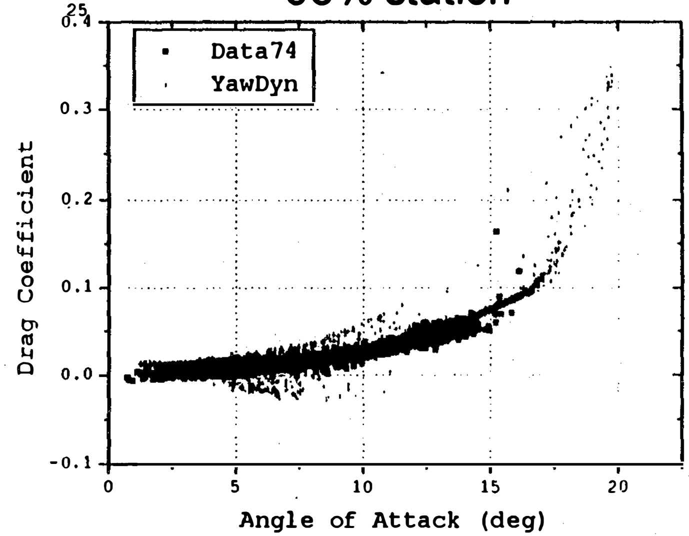


63% station

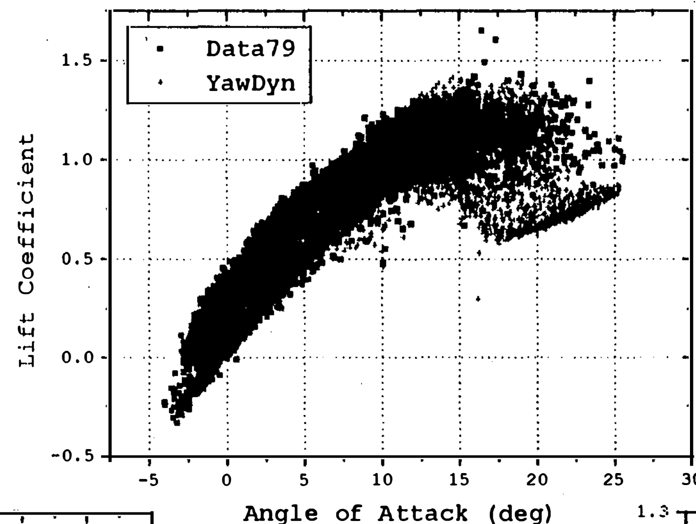
47% station



95% station



Lift Coefficient and Angle of Attack (data 79)



63% station

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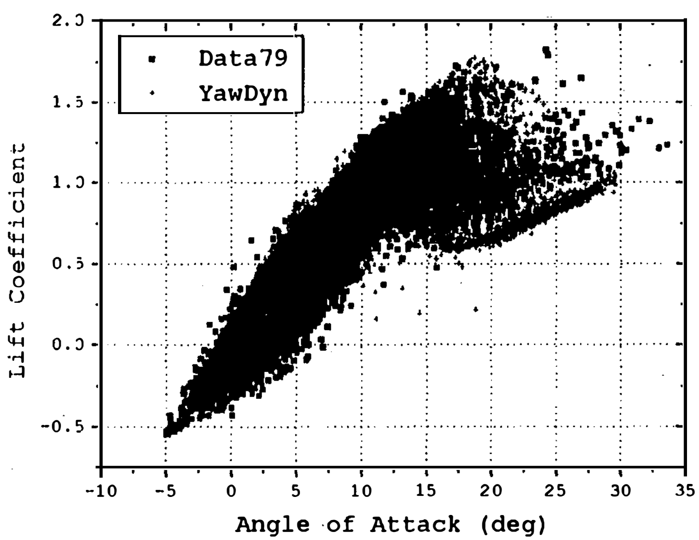
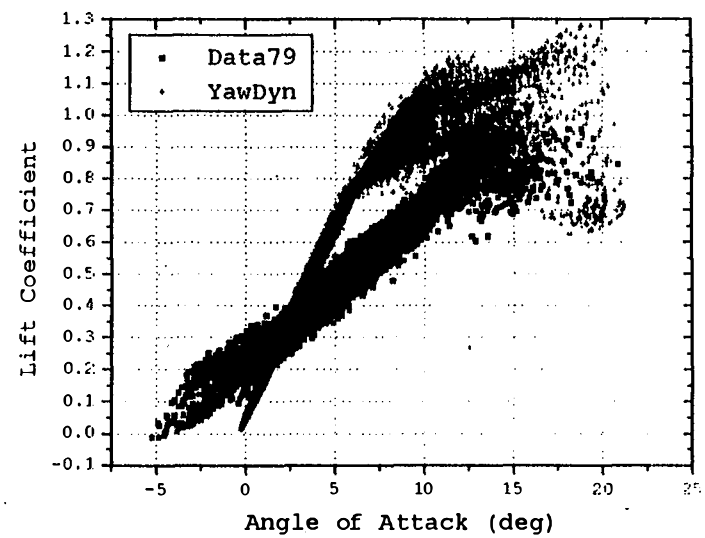
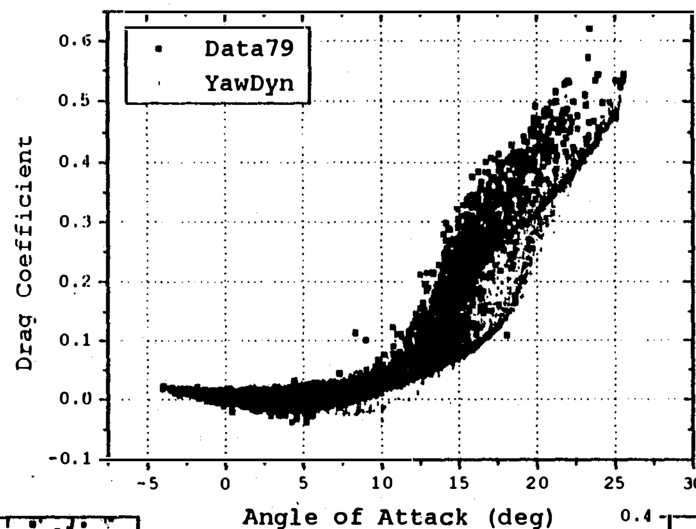


95% station

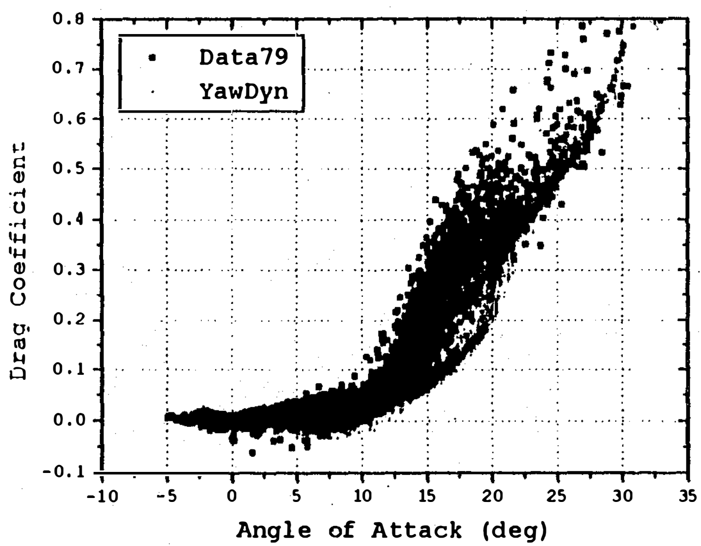


Drag Coefficient and Angle of Attack (data 79)

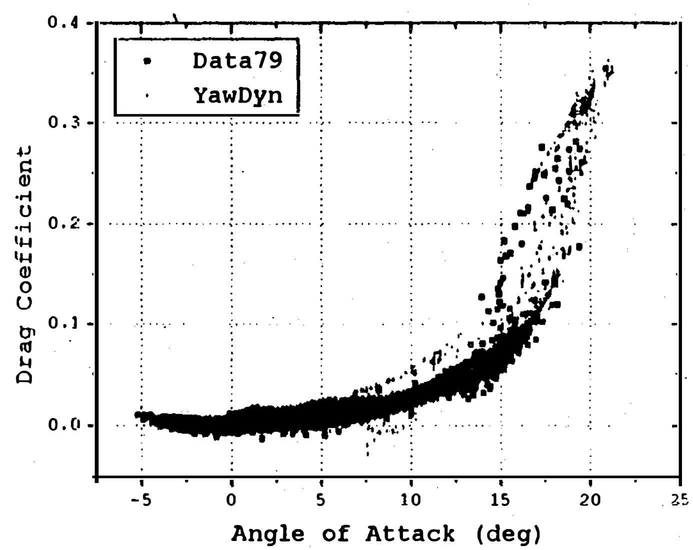


63% station

47% station

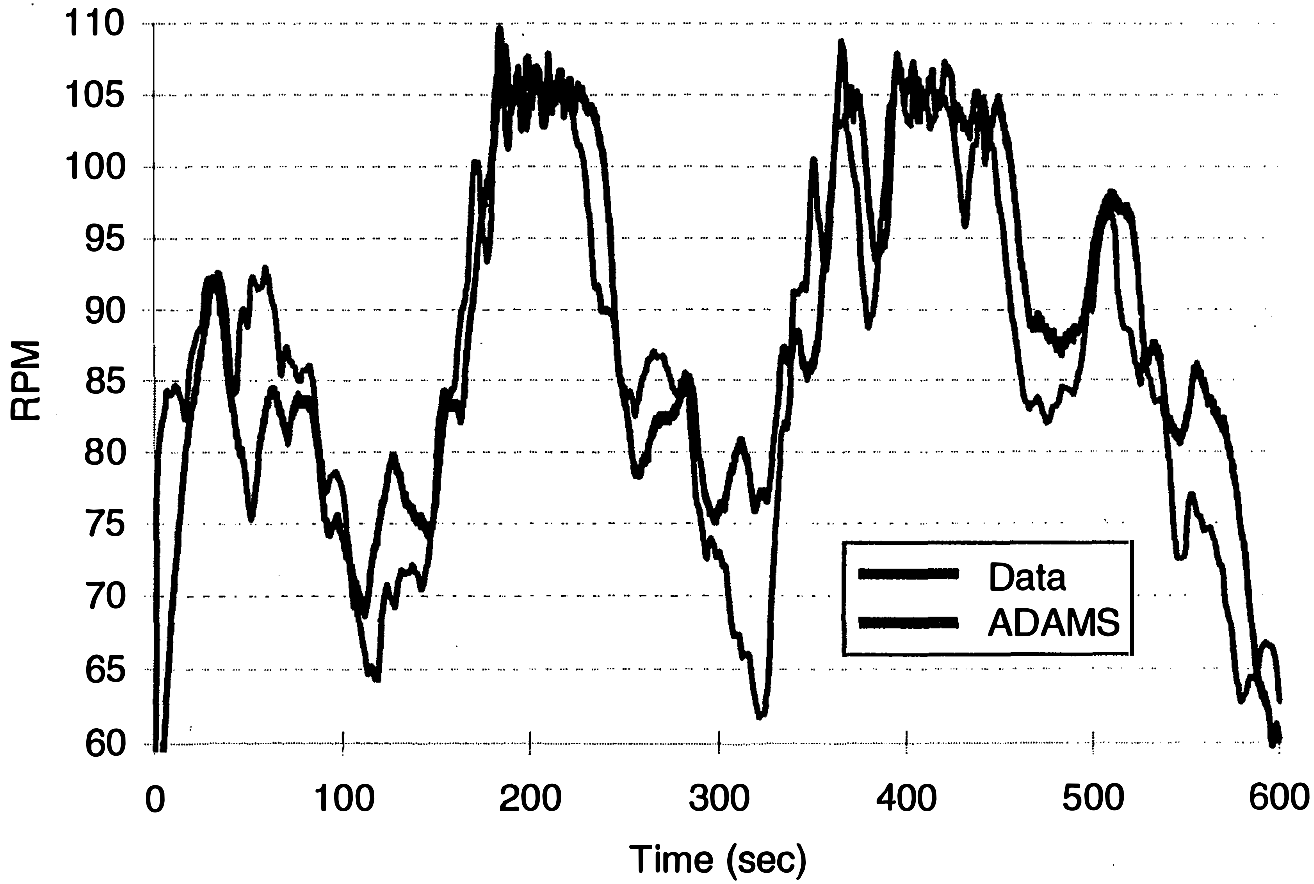


95% station



Variable-Speed Control Modelling

- ADAMS model of the NREL variable-speed test bed
- Load (torque) control below 105 rpm (Torque is polynomial function of rpm <100, constant above 100)
- PID pitch control to maintain 105 rpm
- Wind inputs via yawdyn.wnd file



Simulation Results for a Micon 65

- Simulate operation in fixed yaw with mean yaw errors allowed by the controller
- YawDyn simulations with 3-D turbulence isolate yaw error parameter
- Trend seen in test data analysis confirmed
- Significant fatigue damage attributable to yaw error

Mean Hub-Height Wind Speed	Large Mean Yaw Error	Small Mean Yaw Error	5° Mean Yaw Error	0° Mean Yaw Error
7.6 m/s	13.84°	11.47°	5°	0°
11.5 m/s	23.91°	2.54°	5°	0°
14.5 m/s	21.07°	11.86°	5°	0°
Normalized LIFE2 Estimate for Simulation	3.3	5.9	5.7	14.6
Normalized LIFE2 Estimate for test data	11	35	NA	NA

Pierce and Laino, Windpower '96

Conclusions

- CER3 cyclic 4p flap moment underpredicted by YawDyn
  - ADAMS gives better results when tower-top compliance is modeled--similar observations have been noted for other turbines
  - Turbulence inputs give better results than YawDyn.wnd inputs for the low amplitude, high frequency cycles
- Predicted yaw Motion of CER3 is generally accurate over time scales greater than several seconds, but too active at high frequency--slight amount of yaw damping in the model solves this problem
- Aerodynamic data reasonably well matched except at 95% station

Conclusions (continued)

- The models do quite well when the input data is accurate
  - (But we've never used inputs accurate on the first try--time must be invested)
  - Airfoil data remains one of the biggest problems--A database?
  - Detailed structural data difficult to obtain, FEA or modal test results very helpful
  - Friction and damping characteristics of bearings and other joints very difficult (sometimes, but not always important)
- Largest void in validation studies is for teetering rotors
  - Teetering CER will help tremendously
  - Is other data available?

Turbulent Models: Are They Correct?

Neil Kelley
NREL/NWTC

Code Validation Workshop - August 8-9, 1996

Status of Turbulence Simulation

- SNLWIND-3D has been developed from Veers' original stochastic wind code.
- Provides spatial mapping of the three components of the wind vector in Cartesian or polar coordinates as well as rotationally-sampled.
- Has not been formally validated in conjunction with an operating wind turbine.

Code Validation Workshop

SNLWIND-3D Attributes

- Cartesian version simulates the wind vector within a plane at an even number of grid points; i.e., 6x6, 8x8, ..., 12x12, etc. with a time resolution of 0.05 seconds.
- Optimized for generating a 10-minute record.
- A 6x6 grid can be generated in 10-20 minutes on a PC and less than 5 min on a Unix workstation.

Code Validation Workshop

SNLWIND-3D Attributes - *cont'd*

- Inflow conditions can be simulated representative of
  - smooth, homogenous terrain
  - multi-row wind park environments
    - upwind of a park with a smooth fetch but located within complex surrounding terrain
    - within the park with turbine row-to-row spacings of 7 or 14 rotor diameters
  - IEC Kaimal or von Karman spectral models.

Code Validation Workshop

SNLWIND-3D Attributes - *cont'd*

- Will generate complex, three dimensional patches of organized turbulence or coherent structures which have been shown to be responsible for damaging loading events.
- Based on accepted surface layer scaling which adjusts frequency (spatial) characteristics of the simulated turbulent field as a function of height, wind speed distribution, and vertical stability.

Code Validation Workshop

"Backhanded" Validation Approach

- Use well-validated numerical simulations of specific turbine designs to compare the predicted alternating load distributions with observed ones for a similar ranges of inflow scaling conditions.
- Have applied this technique to a three-bladed, rigid hub turbine (Micon 65) and a two-bladed, teetered turbine (AWT-26).
- Recently have simulated a complete diurnal cycle (144 10-min records) at locations upwind and downwind of a multi-row, San Gorgonio wind park for both turbine designs.

Code Validation Workshop

Experiment Overview

- Derived representative diurnal variation of boundary layer scaling parameters from extensive measurements from 50-meter met towers upwind (Row 1) and downwind (Row 41, 14D spacing) of San Gorgonio wind park.
- Simulated a single 24-hour variation of 10-minute records for each location and scaled for each turbine.
- Compared predicted alternating blade flapwise load spectra with those observed at Row 37 (7D spacing) in San Gorgonio for Micon 65 and at a Tehachapi windfarm for AWT-26.
- Used ADAMS and YawDyn codes for the Micon 65 and ADAMS and FAST for the AWT-26.

Code Validation Workshop

Questions We Wish to Answer ...

- Do the predicted alternating loading distributions exhibit shapes equivalent to those observed; *i.e., do they follow a decaying exponential distribution in the critical high loading tail or low-cycle, high amplitude (LCHA) load range?*
- Are the observed magnitudes similar to those that are observed?
- How does the fatigue damage accumulation (lifetime) compare with that calculated from the observed load distributions?

Code Validation Workshop

Some Initial Results ...

- Spectral shape for Micon 65
- ADAMS/YawDyn comparisons for Micon 65
- ADAMS/FAST comparisons for AWT-26
- A new distribution model?
- Effect of row-to-row spacing
  - LCHA slope
  - Instantaneous Reynolds stress distributions
- A "terrible turb" simulation

Code Validation Workshop

Conclusions

- The combination of a representative turbulent inflow simulation and a good turbine model produces realistic results.
- The character of the inflow is very important in assessing simulation results.
- Much can be learned from using the turbine and inflow simulations.
- We desparately need corroborating data to totally confirm what now we can only hypothesize.

Code Validation Workshop

CODE VALIDATION AND CERTIFICATION

Presented at the
Code Validation Workshop
Sponsored by
National Wind Wind Technology Center, NREL

by William E. Holley, Consultant
August 8, 1996

What is Certification?

- Formal Certification

  Design review by an accredited body (called the "certification agent") according to established criteria.

- Informal Certification

  Engineering "due diligence" review and self certification

Examples of Formal Certification

- Germanischer Lloyd - Germany
  - GL Rules and Regulations
- CIWI (ECN and KEMA) - Netherlands
  - Dutch National Criteria or others
- Risoe and DNV- Denmark
  - Danish Standards or others

Examples of Informal Certification

- Project Financing Reviews
  Known as “engineering due diligence” review
- Self Certification
  European CE mark

What is Code Validation?

- Basically it is convincing the certifying agent that your code gives "correct" results
- All agents require a review of input parameters and some comparison with measured data under controlled tests

very much

- There is no standard body of evidence which will be accepted as "proof"

Code Validation is a Common Element of all Certification Processes

- Validation process depends on the agent and the criteria for certification
- All require comparison of code predictions and measured field data
- Some also require comparison between codes (often certifying agent's "favorite" code)

Different Views of Validation

- Design Engineer

  Who cares?

- Code Developer

  "Garbage in - garbage out"

- Lawyer

  Whose fault is it if it's wrong?

- Cynic

  Validation = $$

Minimum Code Requirements for Wind Turbines

IEC 1400-1 (new revision)

"Calculations shall be performed using appropriate methods. Descriptions of the calculation methods shall be provided in the design documentation. The description shall include evidence of the validity of the calculation methods or references to suitable verification studies.

"Where relevant, the following shall also be taken into account in the calculations:

IEC 1400-1 (new revision - cont.)

- “wind field perturbations due to the WTGS itself (wake induced velocities, tower shadow, etc.);
- “the influence of three dimensional flow on the blade aerodynamic characteristics (e.g. tiploss);
- “unsteady aerodynamic effects;
- “structural dynamics and the coupling of vibrational modes;
- “aeroelastic effects;
- “the behavior of the control and protection system of the WTGS.”

Common Additional Requirements

- The code must be able to calculate all load cases (combinations of external conditions and design situations)
- IEC 1400-1 provides a detailed prescription of external conditions but little guidance on details of dynamic computations
- Certification agents each have their own requirements for code validation which are outside of the current IEC or other international standards (IEC TC88 WG9 is working to provide common criteria)

Conclusions

- Use of validated codes is a requirement (albeit vague) for certification
- Proof of validation is akin to convincing a jury in a court of law
- There are no standards for code validation only general guidlines
- The most expedient strategy may be to use codes developed by a member of the “club”

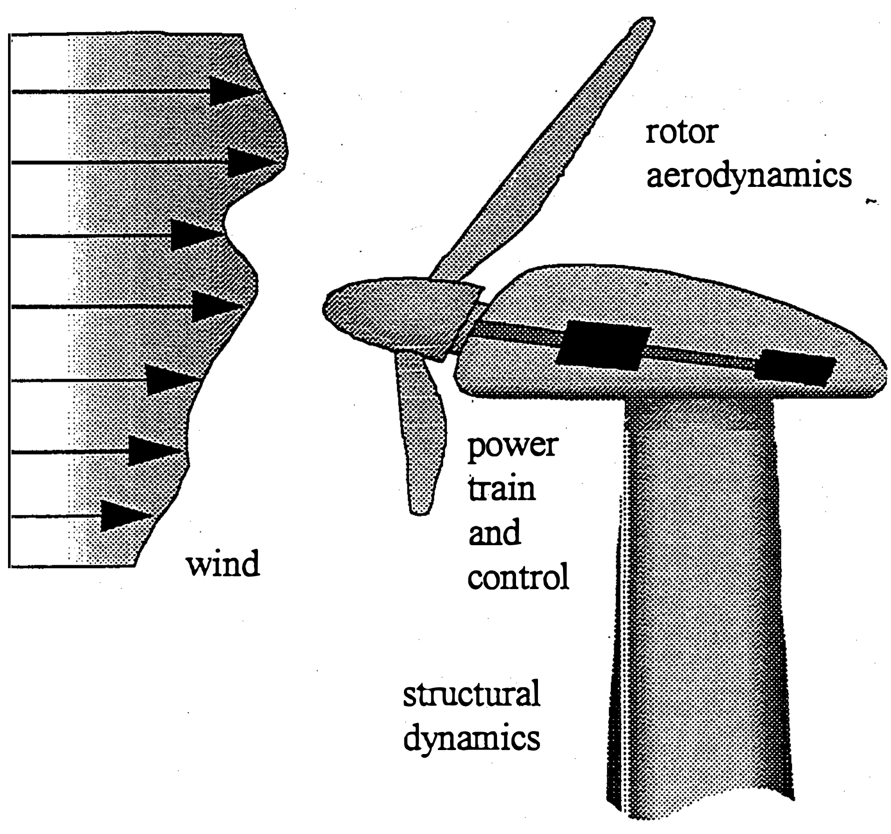
VALIDATION OF THE BLADED CODE

David Quarton
Garrad Hassan and Partners Ltd

Presented at the Code Validation Workshop
NWTC, 8-9 August 1996

Wind turbine modelling for design purposes
Key elements of the model

- Wind modelling
- Rotor aerodynamics
- Structural dynamics
- Power train and control



Wind turbine modelling for design purposes
What are the deliverables?

- Prediction of performance
- Prediction of dynamic characteristics
- Prediction of controller behaviour
- Prediction of fatigue loads
- Prediction of extreme loads

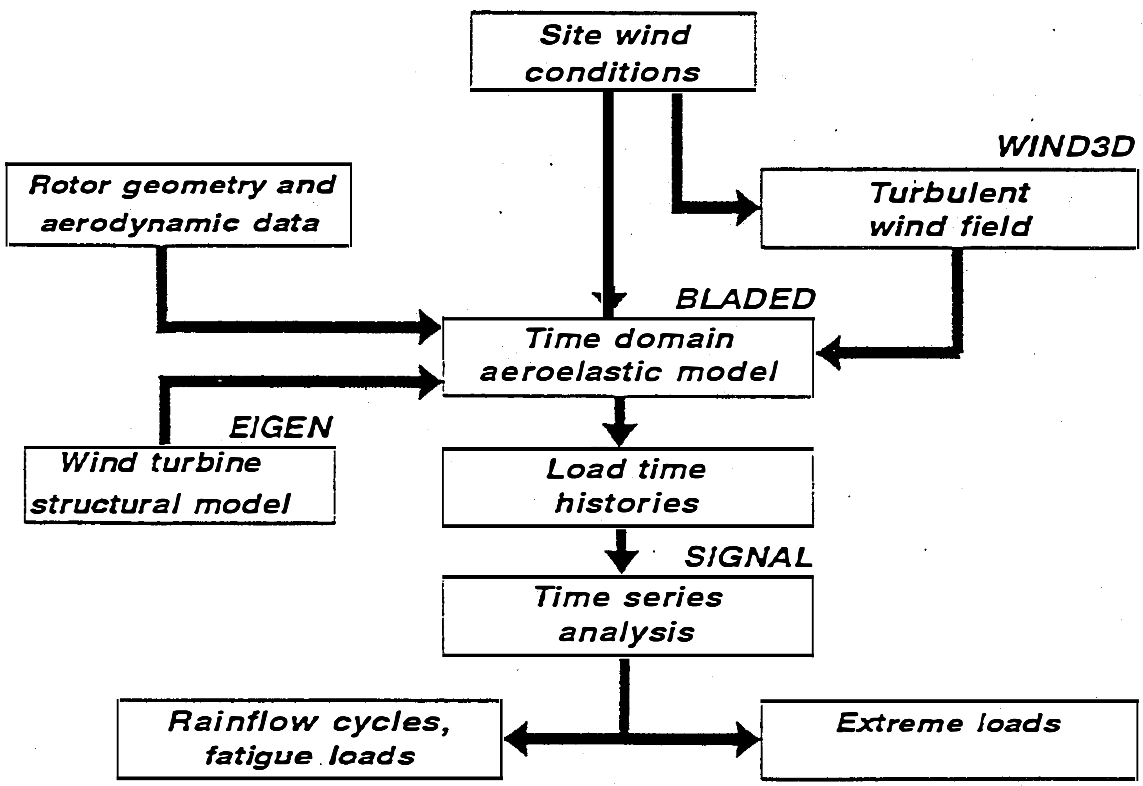


Figure 4.1.1 Garrad Hassan Analysis of Wind Turbine Loads

Basis of Calculation Method
Wind Modelling

- *Wind shear*
  - *power law*
  - *logarithmic*
  - *user specified*
- *Wake flow*
  - *gaussian profile*
  - *user specified wake width, deficit, c/line*
- *Tower shadow*
  - *potential flow dipole model*
  - *user specified based on cosine profile*

Basis of Calculation Method
Wind Modelling

- *Turbulence*
    - *simulation based on Veers*
    - *single or three component model based on von Karman*
    - *user specified no. of time histories over the rotor disk*
    - *user specified hub height wind speed history coherent over the rotor disk*
    - *user specified hub height wind speed history with von Karman spatial coherence*
    - *user specified wind direction history*
    - *upflow*
- *Deterministic transients in wind speed, wind direction, vertical and horizontal shear*

Basis of Calculation Method
Aerodynamics

- *Blade element theory*
- *Options for inflow calculation*
  - *equilibrium wake*
  - *frozen wake*
  - *dynamic wake based on Pitt and Peters*
- *Dynamic stall representation based on Beddoes*

Basis of Calculation Method
Structural dynamics

- *Modal analysis of rotor blades and tower*
- *Coupling of the component modes through the equations of motion*
- *Structural degrees of freedom*
  - *blade flapwise bending*
  - *blade edgewise bending*
  - *rotor teeter*
  - *nacelle yaw*
  - *tower fore-aft*
  - *tower lateral*
- *Solution of modal equations of motion through time marching integration (Runge Kutta)*
- *Aeroelastic coupling of structural motion with aerodynamic forcing*

Basis of Calculation Method
Power train dynamics

- *Torsional stiffness and damping of low and high speed shafts*
- *Torsional dynamics of gearbox neglected*
- *Torsional dynamics of drive train mounting*
  - *stiffness and damping of gearbox support*
  - *stiffness and damping of pallet support*
- *User specified location of brake*
- *Electrical system dynamics*
  - *Asynchronous generator: electrical torque related to slip speed by first order lag*
  - *Variable speed: reaction torque related to demand by first order lag*

Basis of Calculation Method
Control system

- Control system options
  - fixed speed, fixed pitch
  - fixed speed, variable pitch
  - variable speed, fixed pitch
  - variable speed, variable pitch
- Aerodynamic control surfaces
  - full span blade pitch
  - partial span pitch
  - ailerons
  - spoilers
- Closed loop control based on PI or user specified algorithms with gain scheduling
- Representation of actuator and transducer dynamics
- Supervisory control representation

Validation
What are the requirements?

- Comprehensive data base of measurements
  - ambient conditions and turbine signals
  - operational, non-operational and transients
  - long term statistics
  - time series data
  - high quality

- Reliable turbine description for modelling

- Process measured data and perform calculations for comparison in terms of:
  - steady state performance and loading
  - resonant frequencies
  - dynamic performance and loading
  - fatigue load spectra
  - *extreme loads*

- Assess quality of agreement between measured and calculated data
  - enhancement of model where appropriate

Validation of BLADED

- WEG MS-1, UK, 1991
- Howden HWP300 and HWP330, USA,1993
- ECN 25m HAT, Netherlands, 1993
- Newinco 500kW, Netherlands, 1993
- Nordex 26m, Denmark, 1993
- Nibe A, Denmark, 1993
- Holec WPS30, Netherlands, 1993
- Nordtank 300kW, Denmark, 1994
- Riva Calzoni M30, Italy, 1993
- Tjaerbourg 2MW, Denmark, 1994
- WindMaster 750kW, Netherlands, 1994
- Zond Z-40, USA, 1994
- Nordtank 500kW, UK, 1995
- Vestas V27, Greece, 1995
- Danwin 200kW, Sweden, 1995
- Carter 300kW, UK, 1995
- NedWind 1MW, Netherlands, 1996
- WEST Medit 320kW, Italy, 1996-97
- Nordtank 600kW, UK, 1996-97

Validation of BLADED

Turbine	Number of Blades	Rotor Diameter	Rated Power	Aero Control	Rotor Speed	Site
WEG MS1	2	20m	250kW	tip pitch	fixed and variable	simple
Howden HWP330	3	33m	330kW	tip pitch	fixed	complex
ECN HAT	2	21 - 25m	200 - 250kW	pitch and stall	fixed and variable	simple
Newinco	2	34m	500kW	stall	fixed	simple
Nordex	3	26m	250kW	stall	fixed	simple
Nibe A	3	40m	600kW	stall	fixed	simple
Holec WPS30	3	30m	300kW	pitch	variable	simple
Nordtank	3	28m	300kW	stall	fixed	simple
Riva M30	1	33m	200kW	pitch	fixed	simple
Tjaereborg	3	61m	2000kW	pitch	fixed	simple
WindMaster	2	40m	750kW	pitch	fixed	simple
Zond Z40	3	40m	550kW	aileron	fixed	complex
Nordtank	3	37m	500kW	stall	fixed	complex
Vestas V27	3	27m	225kW	pitch	fixed	complex
Danwin	3	23m	180kW	stall	fixed	simple
Carter	2	24m	300kW	stall	fixed	simple
NedWind	2	53m	1000kW	ac. stall	fixed	simple
WEST Medit	2	33m	320kW	pitch	fixed	complex
Nordtank	3	37m	600kW	stall	fixed	complex

Validation of BLADED - Reports

Howden HWP300 and HWP330, US
Jamieson P M, "Further analysis of Howden data", final report for UK Department of Trade and Industry project W/24/00198, GH:198/GR/1, January 1993.

ECN 25m HAT, Netherlands
Newinco 500kW, Netherlands
Nordex 26m, Denmark
Nibe A, Denmark
Rasmussen F, Petersen J T, Winkelaar D and Rawlinson-Smith R, "Response of stall regulated wind turbines - stall induced vibrations", final report for CEC project JOUR-0076 and UK Department of Trade and Industry project E/5A/6049/2378, Riso-R-R-691, June 1993.

WEG MS1, Orkney, UK
van Grol H J, Snel H and Schepers J G, "Wind turbine benchmark exercise on mechanical loads", final report for CEC project EN3 W/C1/151/NL, ECN-C--91-030, May 1991.

Quarton D C et al, "Further analysis of Orkney MS1 data", final report for UK Department of Energy project E/5A/5131/2033, GH:181/R/9, February 1992.

Tjaerborg 2MW, Denmark
van Grol H J and Bulder B H, "Reference procedure to establish fatigue stresses for large size wind turbines", final report for CEC project JOUR-0085, ECN-C--94-013, February 1994.

Holec WPS-30, Netherlands
Nordtank 300kW, Norrekaer Enge, Denmark
Tindal A J, "Dynamic loads in wind farms", final report for CEC project JOUR-0084 and UK Department of Trade and Industry project E/5A/605/2476, GH:205/R/12, August 1993.

Riva Calzoni M30, Italy
Stork C, "Theoretical and experimental investigations on a one bladed medium size wind turbine to improve the design criteria for bigger units", final report for CEC project JOUR-0089, 1993.

WindMaster 750kW, Netherlands
Bossanyi E A, "A design tool for wind turbine loading and fatigue", final report for CEC project JOU2-CT92-0198, GH:282/R/8, July 1995.

Nordtank 500kW, Wales
Vestas V27, Greece
Danwin 200kW, Alsvik, Sweden
Adams B M, "Dynamic loads in wind farms II", final report for CEC project JOU2-CT92-0094 and UK Department of Trade and Industry project W/43/00370, GH:286/R/1, March 1996.

Zond Z-40, US
Quarton D C, "Zond Z-40 wind turbine - computer modelling and validation", report for Zond Systems Inc., GH:378/R/1, December 1994.

NedWind 50, Netherlands
Drost L and Visser B, "NedWind 50 monitoring - data interpretation and evaluation", report for CEC project JOU2-CT92-0066, SPE96-016, March 1996.

Carter 300, UK
Quarton D C, " Monitoring and analysis of a Carter 200/300 wind turbine", draft final report for UK Department of Trade and Industry project W/24/00350, GH:321/BR/08, February 1996.

An example validation study: WindMaster 750P

- WindMaster 750P
  - two-bladed, rigid hub
  - 40m diameter
  - 750kW rated power
  - fixed speed at 35rpm
  - active pitch control
  - "soft-soft" tower
  - 51m hub height

- Monitoring programme
  - Halsteren, The Netherlands
  - GH measurement system
  - 1993/1994
  - objectives: turbine design verification
    : computer code validation

- Measurements
  - blade bending loads at two radii
  - pitch system loads
  - shaft torque
  - power, pitch angle, nacelle direction
  - rotor speed and position
  - tower bending and torsion loads
  - wind speed at five heights
  - wind direction

Data base of measurements

- Summary data
  - Mean, standard deviation, maximum and minimum of each channel over 10 minutes
  - Continuous data collection

- Campaign data
  - Time history of each channel recorded at 50Hz over 10 minutes
  - Automatic or manual triggering of data capture

Steady state performance and loading

- Analysis of summary data

- Calculations include the effect of turbulence

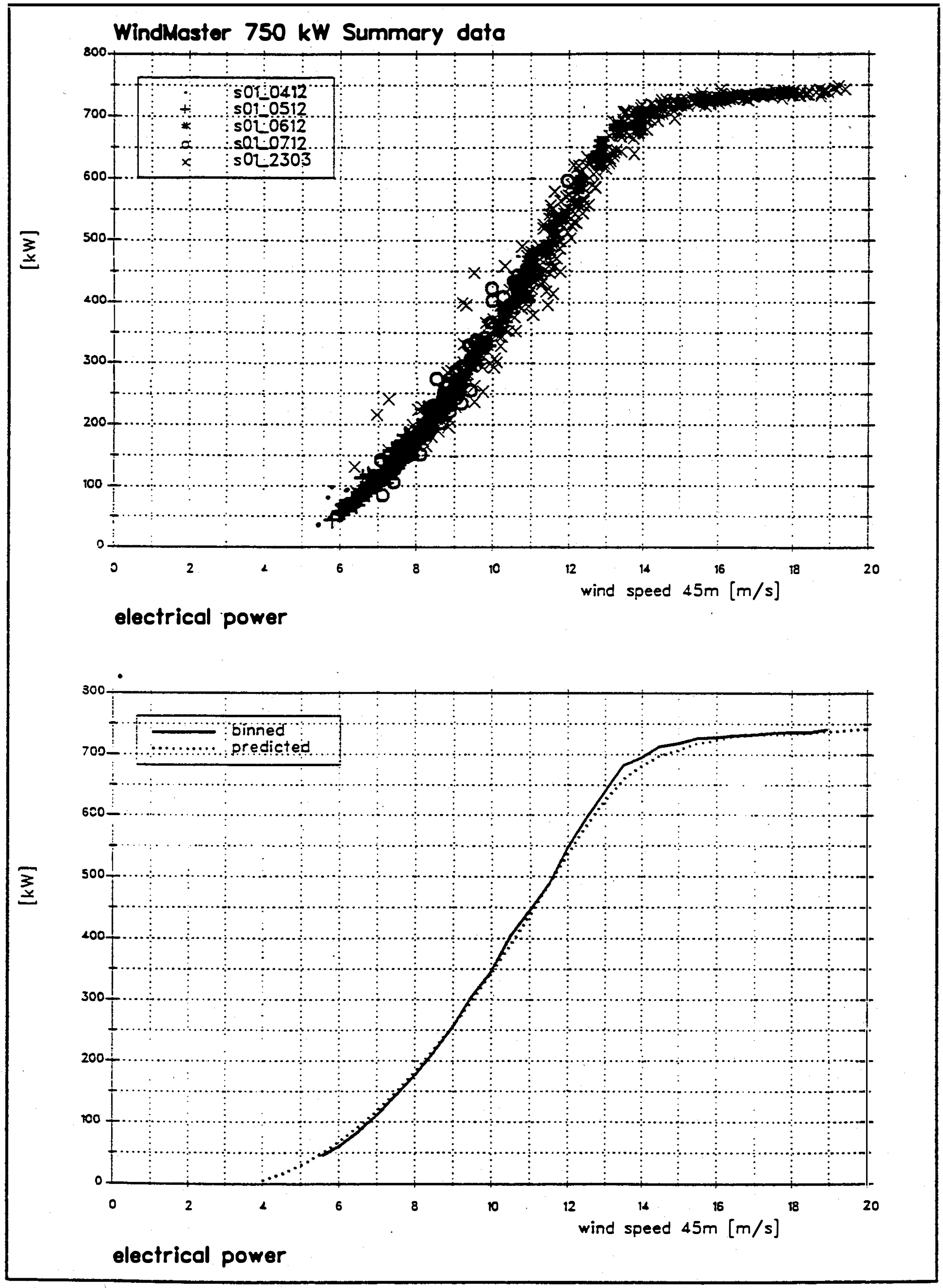


Figure 4.1.1 Electrical power

19

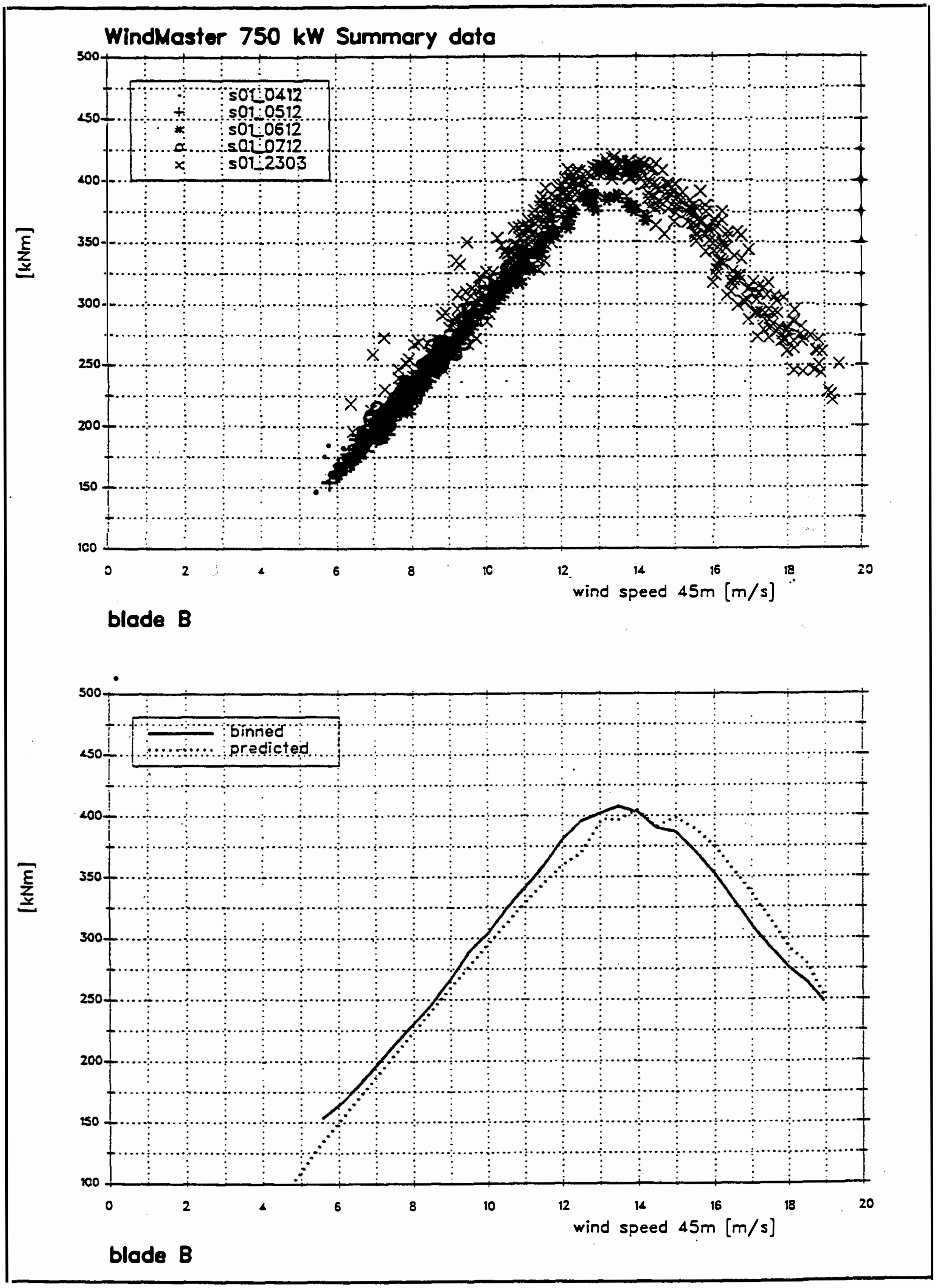


Figure 4.1.6 Out of plane bending moment at 2m

Resonant frequencies

- In the absence of a full modal survey, resonant frequencies may be identified from analysis of auto spectra of strain signals.

- Use of non-operational measurements better due to absence of nP harmonic content

- Calculations based on finite element analysis of the turbine structure

Dynamic loads

- Analysis of campaign data sets:
  - statistics of each channel
  - waveform of periodic component
  - auto spectrum of random component
  - auto spectrum of total component
  - probability density distribution

- Calculations based on BLADED simulation using turbulent wind field synthesised from measured wind speed data

- Detailed comparison for each channel
  - power production
  - start-up, normal and emergency shutdown
  - standby

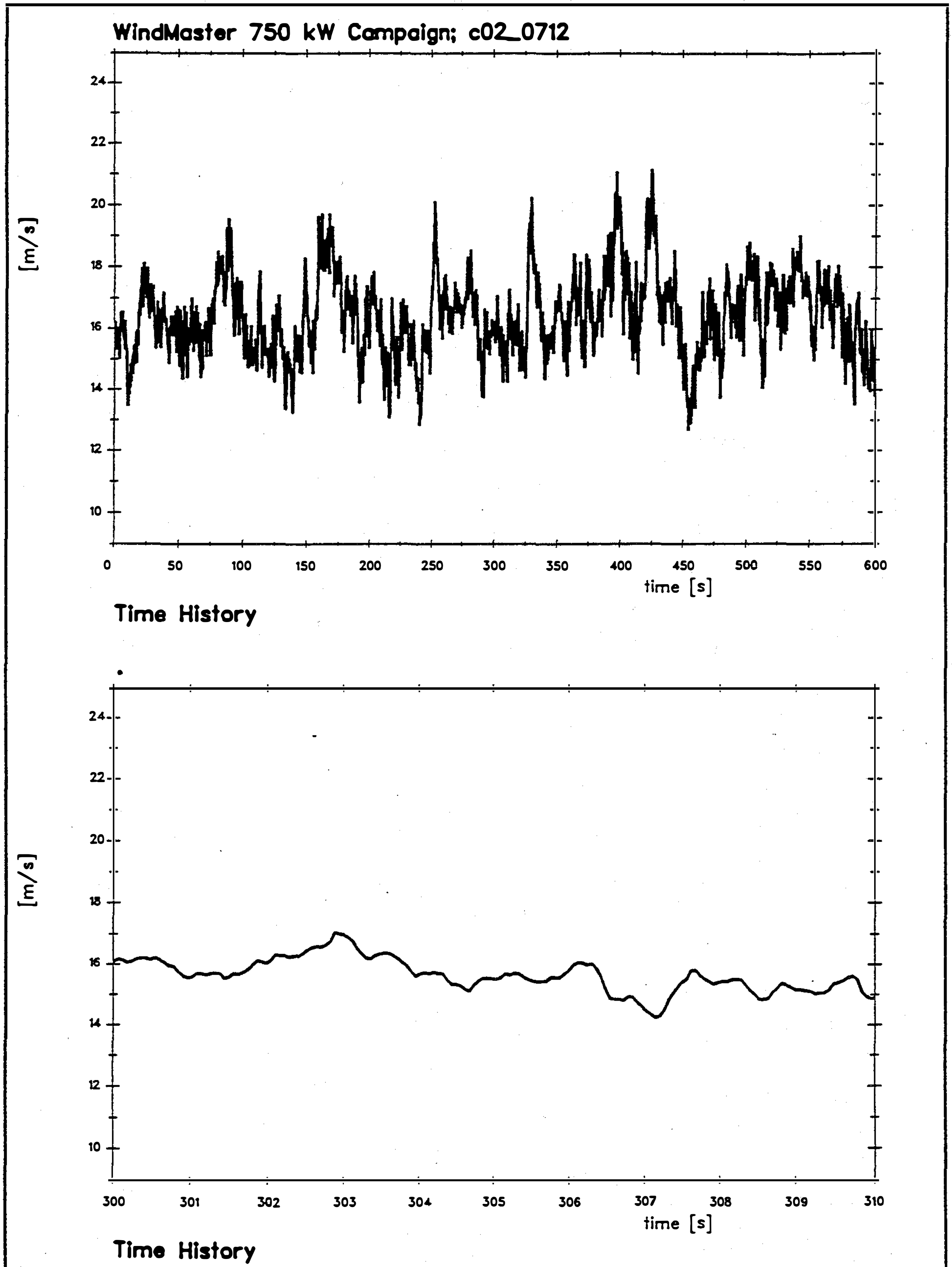


Figure 4.2.3.1 Wind speed at 45m operation above rated

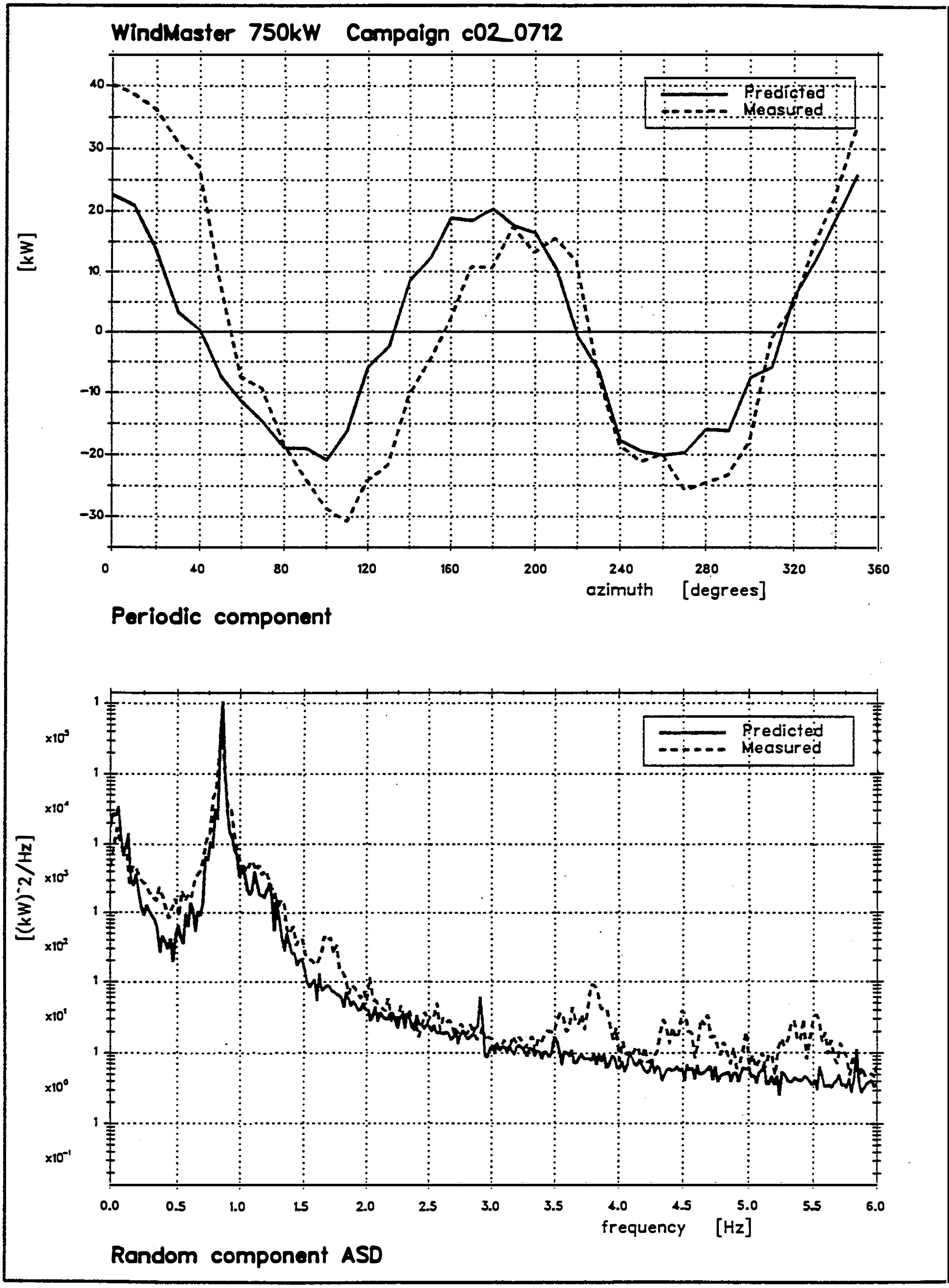


Figure 4.2.3.3b **Electrical power operation above rated**

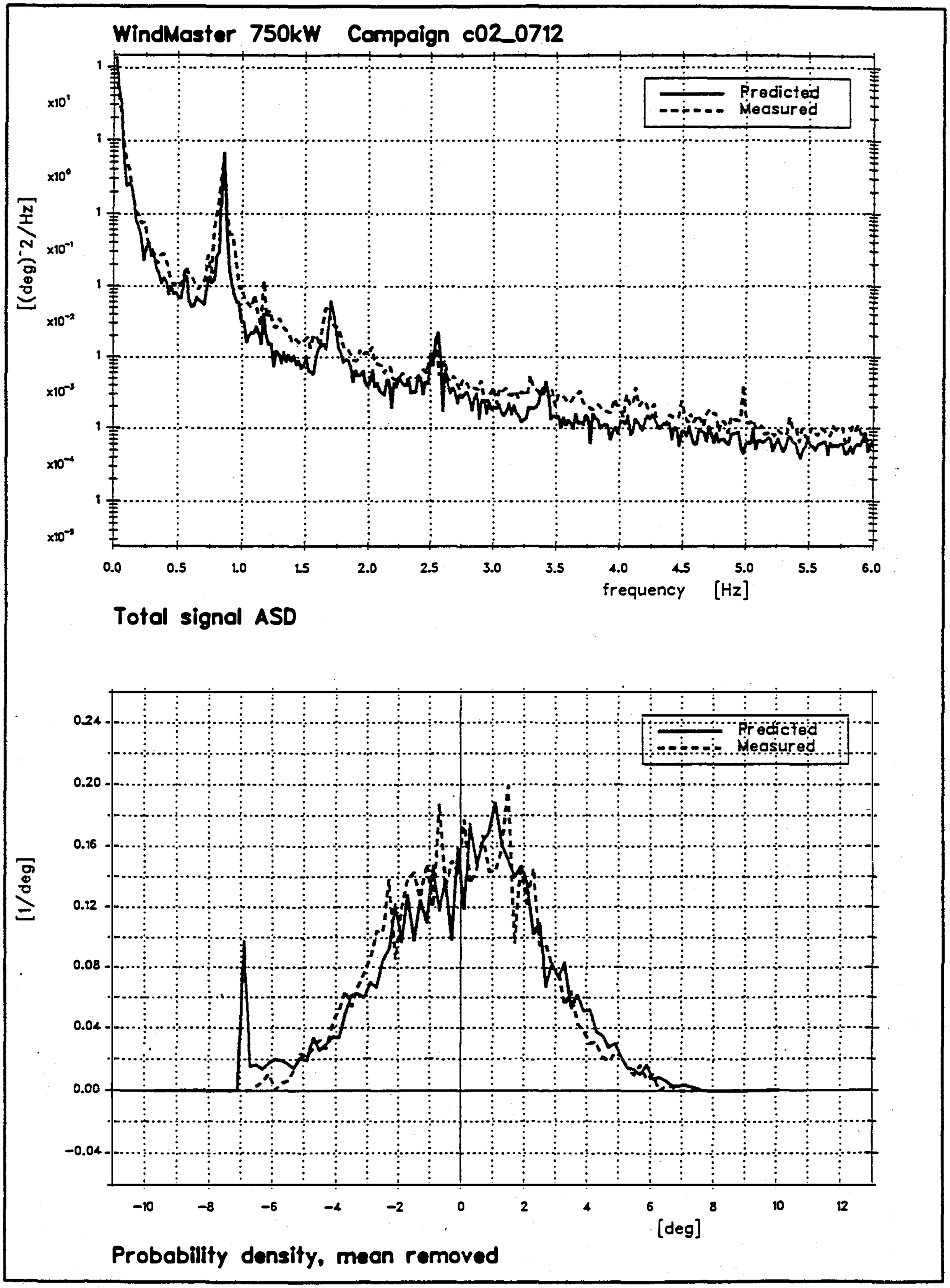


Figure 4.2.3.4c Pitch angle operation above rated

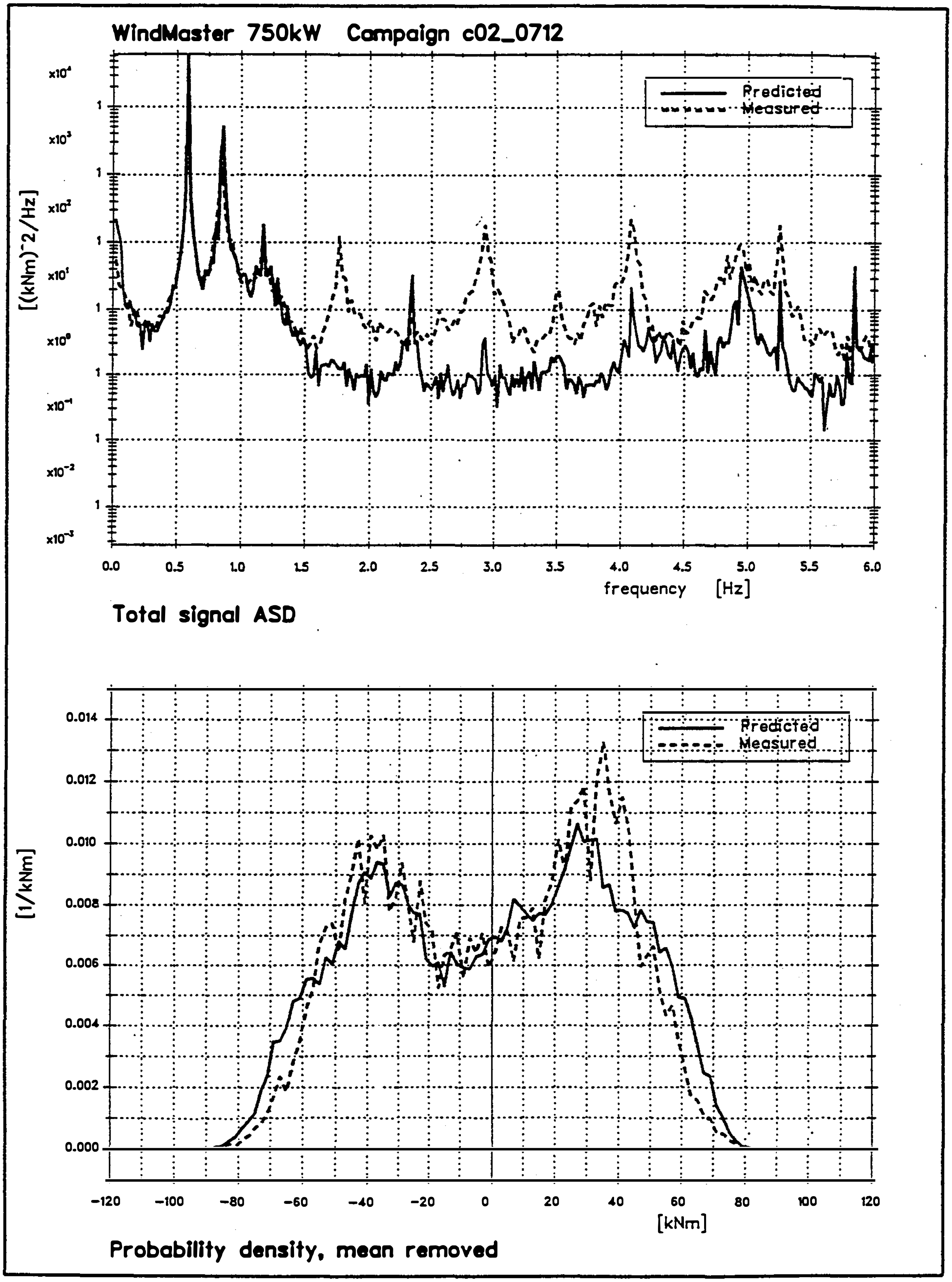


Figure 4.2.3.10c Edgewise bending moment at 6m operation .above rated

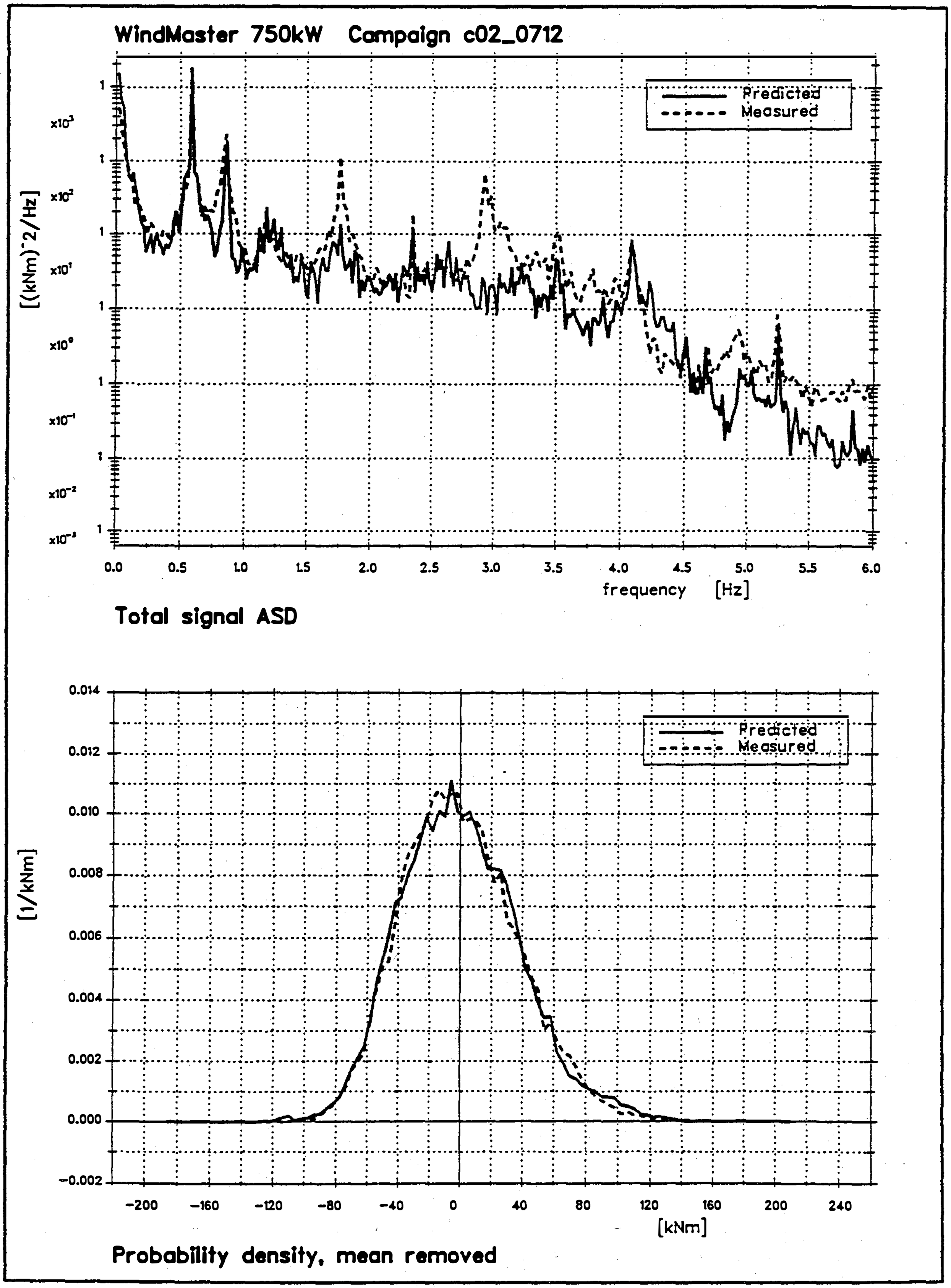


Figure 4.2.3.11c Flatwise bending moment at 6m operation.above rated

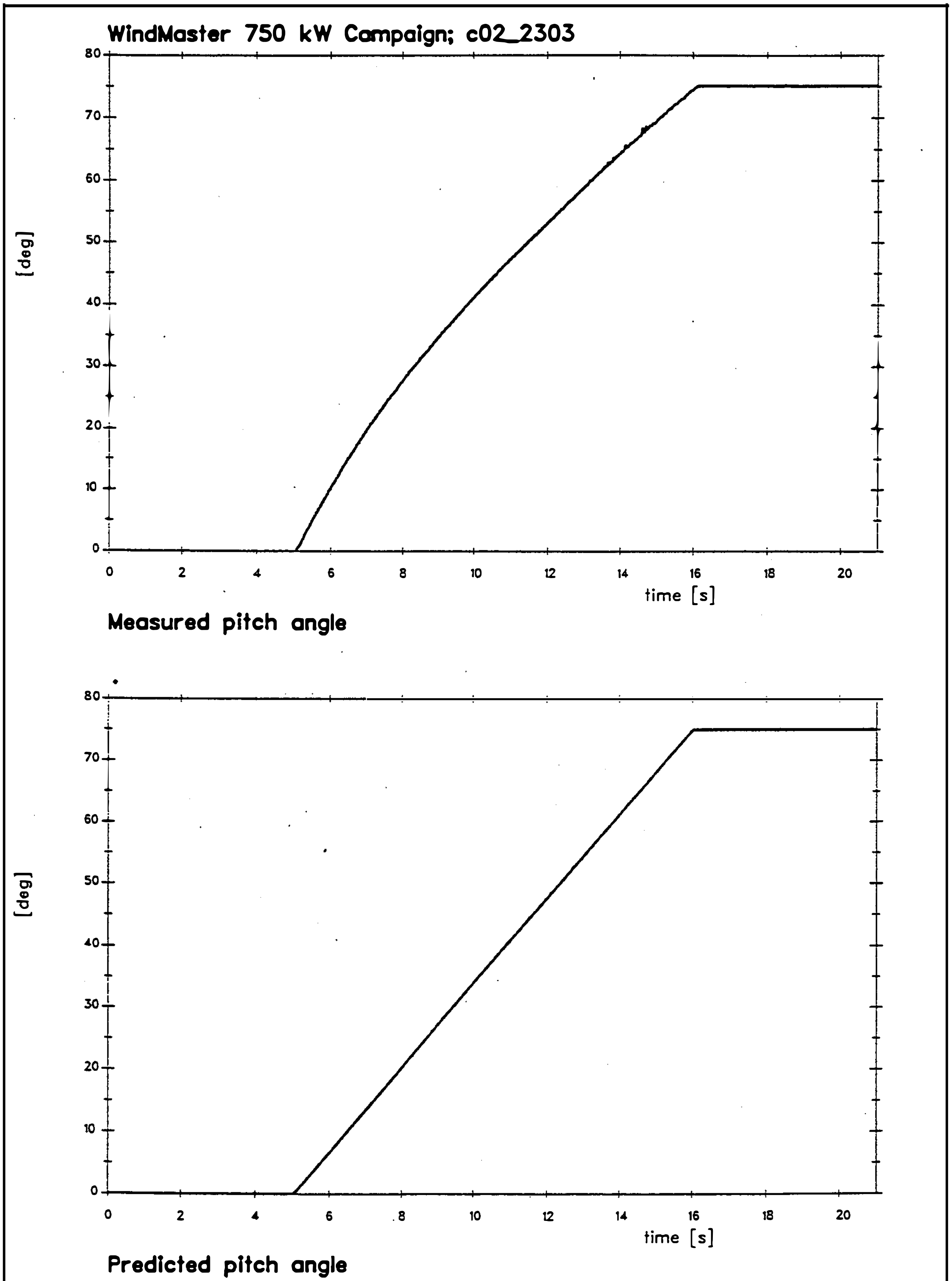


Figure 4.4.1.3 Normal shutdown below rated

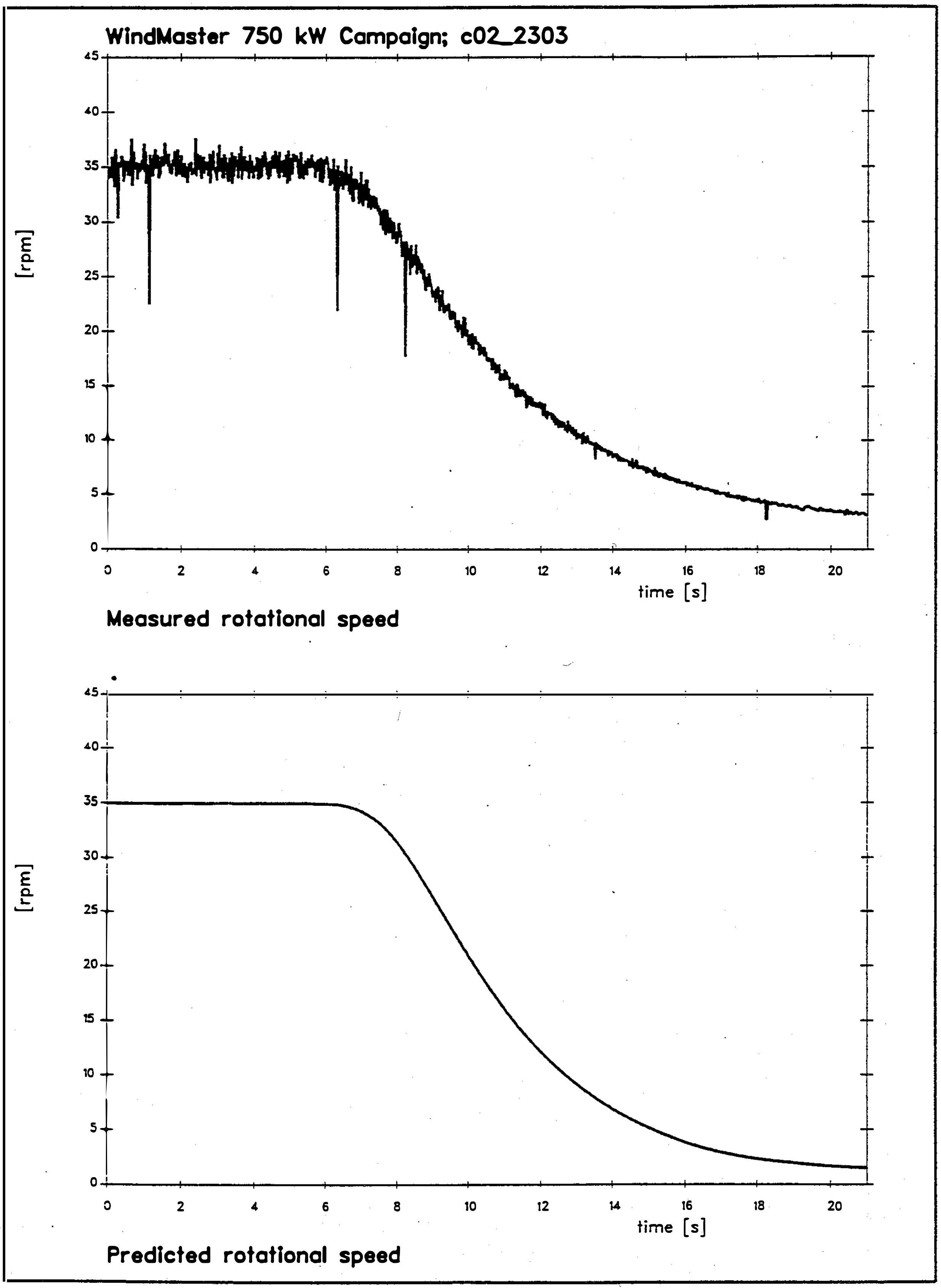


Figure 4.4.1.4 Normal shutdown below rated

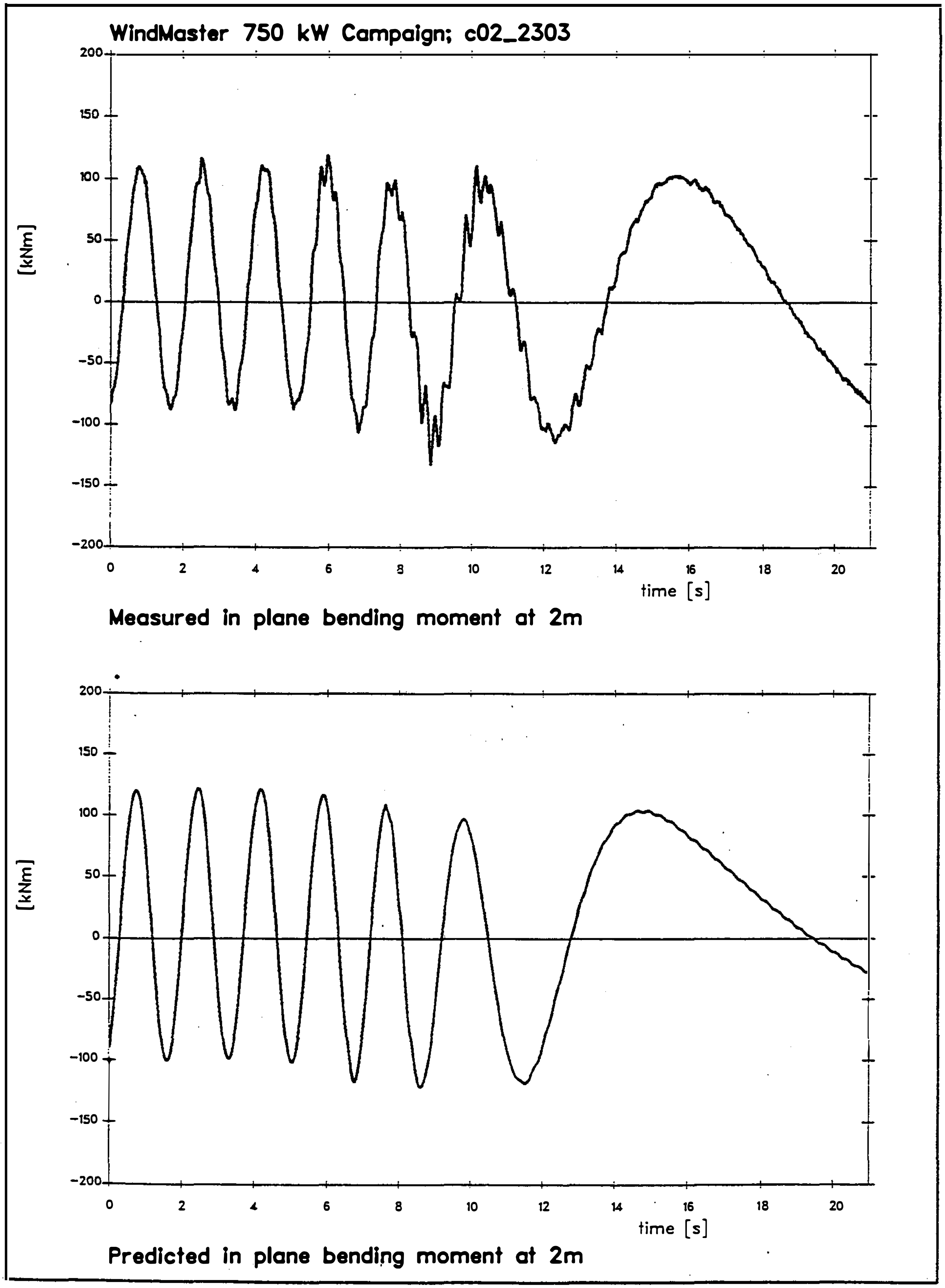


Figure 4.4.1.5 Normal shutdown below rated

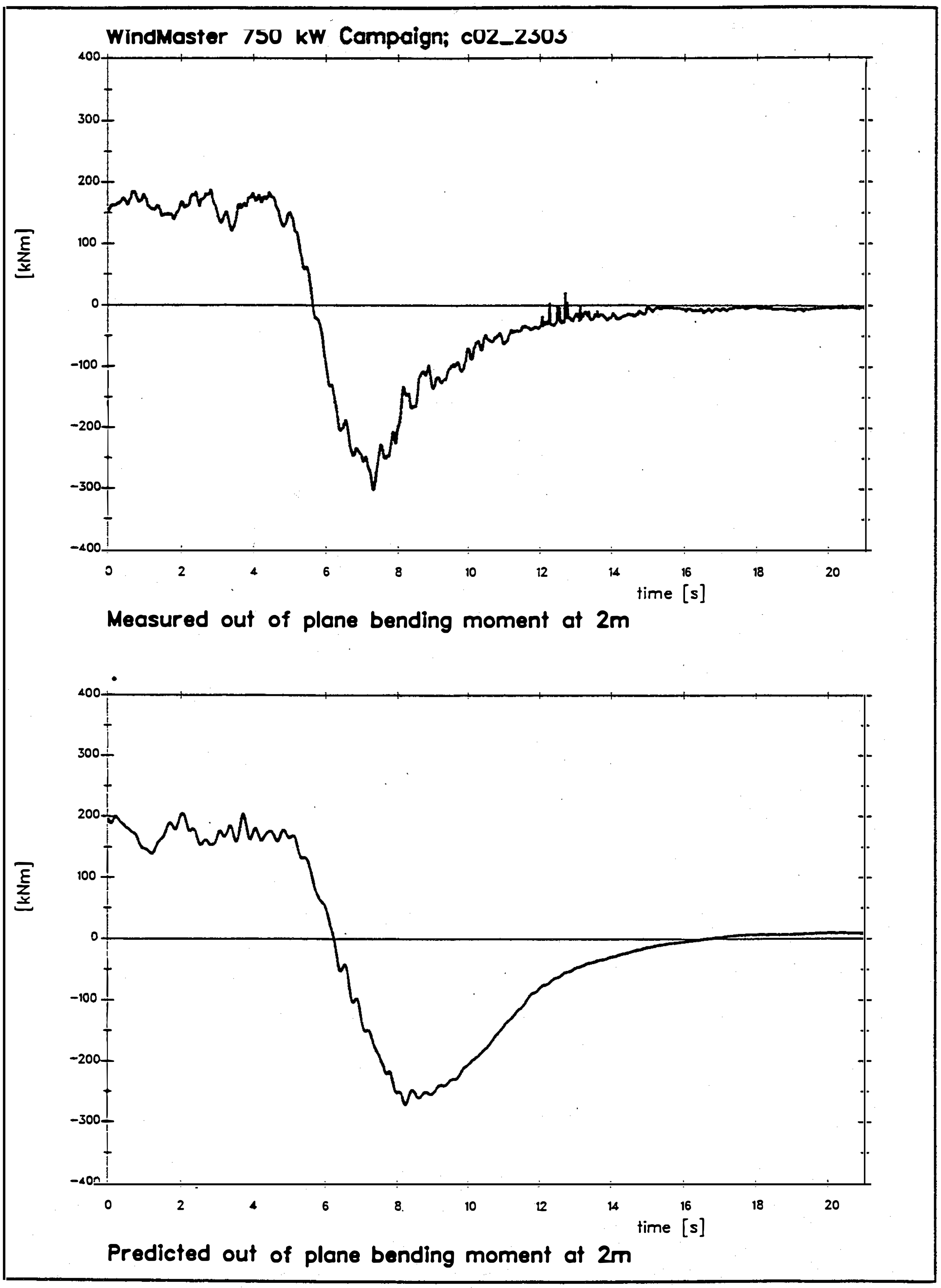


Figure 4.4.1.6 Normal shutdown below rated

Fatigue load spectra

- Fatigue load spectra derived from measured campaign data sets:
  - sufficient no. of power production cases between cut-in and cut-out
  - start-up and shut-down cases
  - standby
  - rainflow cycle counting
  - integration of cycle counts with assumed wind speed probability distribution and no. of transient events
- Calculations based on BLADED simulations and post-processing as for the measured data
- Comparison of measured and calculated fatigue load spectra

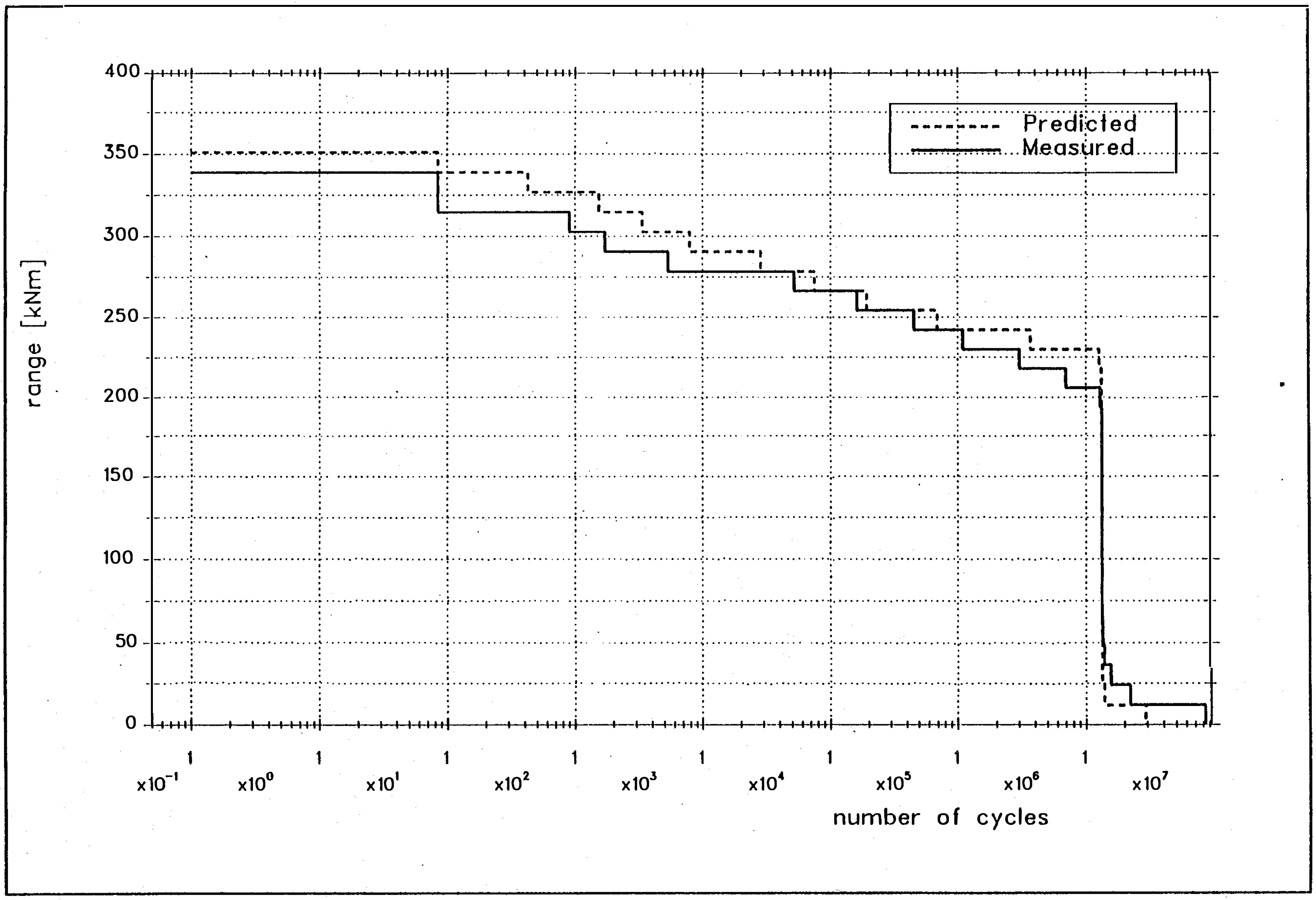


Figure 4.6.1.4 **Cumulative cycle counts for in plane bending moment at 2m, annual operation**

Extreme loads

- Measurement of extreme loads is difficult!
- Probabilistic analysis of measured time histories will allow estimation of extreme loads for comparison with equivalent calculated data [Madsen et al, 1984]
- Relationship between probabilistic estimates of extreme loads and those computed from "discrete event" design load cases is uncertain
- Further research required to verify codified extreme load cases and/or develop alternative probabilistic methods

Areas of greatest uncertainty

- Wind modelling
  - wake flow within wind farms
  - on complex terrain sites
  - atmospheric stability
  - extreme wind conditions

- Aerodynamics
  - steady and dynamic stall
  - highly deflected blades
  - yawed rotors

- Structural dynamics
  - modal properties, aeroelastic stability and dynamic loading of lightweight, flexible turbines

28th IEA Experts Meeting, april 11.-12. 1996, Lyngby, Denmark

State of the Art of Aeroelastic Codes for Wind Turbine Calculations

SUMMARY

prepared by

B.Maribo Pedersen, DTU

This Experts Meeting, the purpose of which is expressed in the introductory note, had gathered 23 participants from 6 different countries. 18 of the participants gave a presentation and although countries with a sizeable wind program, i.e. Italy, Greece and Spain were not present and also not the group at the University of Stuttgart, it is felt that the meeting gave a fair impression of the contemporary state of the art world wide.

6 of the participants came from universities, 7 from national laboratories, 6 from private consultancies, 2 from industry, 1 from a national funding agency and 1 from a certifying company.

10 "complete" codes or packages of codes were presented as well as 6 codes dealing with specific sections of the problem areas.

The "complete" codes all claim to have been validated and given "good" agreement with available experimental data, although few presented evidence to that effect. Details on methods as well as information on accuracy and computing time will in most cases have to be found in the cited references.

Almost all codes solve the equations of motion in the time domain and two codes are claimed to give adequate results with a ratio of computing time to real time of only 2 when run on an up-to-date desk top PC. This seems to indicate that the main draw-back for time domain calculations as compared to calculations carried out in the frequency domain now has been eliminated.

From the written papers in these proceedings one might get the impression that almost all problems have been solved and not much remains to be done. However during the lively discussions which took place during presentations and also from the round table discussion, that impression got tempered by more realistic statements from the authors to the effect that still a number of problem areas need to be better resolved.

These problem areas could be listed as follows:

- Wind Field Modelling

  - Turbulence characteristics in wind farms, in mountainous terrain and for unstable atmospheric conditions.
  - Extreme wind conditions, i.e. max. wind velocity, extreme rate of change of wind velocity and wind direction, extreme wind shear.

- Rotor Aerodynamics

  - better and validated engineering models of 3-D flows **and of 3-D "static" and dynamic stall in particular** is urgently needed.
  - operation under yawed conditions.
  - improvement to blade element theory by combination with wake modelling.

- Structural Dynamics

  - methods for predicting structural damping.
    With decreased aerodynamic damping when running in stalled condition, the amount of structural damping has turned out to be crucial for edgewise stability for some large machines.
  - improvement of codes in order to deal with large deflections (flexible turbines).
  - better information on material properties in fatigue.

- Validation

  - there still appears to be a need for more complete validations to be carried out. Available experimental data often do not cover the whole operational envelope for the turbine, and in particular it can be very difficult to cover extreme load cases which occur very rarely. Also validation for very flexible machines has only been carried out in a few cases.

With the number of issues as large as listed above, the need for some prioritisation arises. One attempt of putting together a structured and argued priority list was brought forward by Ian Fletcher from ETSU, (see page 169 - 171). The general opinion of the participants was however to give highest priority to a concerted attack on the dynamic stall problem.

David Quarton offered to draft a document which will specify projects most likely to ensure rapid progress towards more general and realistic modelling of this flow regime. When available the document will be circulated to all participants for comments and a final version produced. In this way a solid basis will be available for formulating applications to the relevant funding agencies, national and/or international.

For continued progress towards less conservative designs and hence in the end towards cheaper energy it is vital, that the funding agencies recognize and honour these needs for further research, and that the certification bodies will be willing to accept the results obtained by using the codes, so that current safety factors eventually will be reduced in accordance with the reduction of the uncertainty of the calculations.