WIND ENERGY SYSTEM TIME-DOMAIN (WEST) ANALYZERS

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ABSTRACT

Using the latest hybrid electronics technology, a portable analyzer which simulates in real time the complex nonlinear dynamics of horizontal axis wind energy systems has been constructed. Math models for an aeroelastic rotor featuring nonlinear aerodynamic and inertial terms have been implemented with high speed digital controllers and analog calculation; this rotor model is then combined with other math models of elastic supports, control systems, a power train and gimballed rotor kinematics. The analyzer also features a stroboscopic display system graphically depicting distributed blade loads, motion, and other aerodynamic functions on a cathode ray tube. The viewer sees a clear picture of rotor dynamics in the start-up, shut-down, and trim states, as well as operation in special transient conditions such as gust and emergency shutdown. Limited correlation efforts have shown good comparison between the results of this analyzer and other sophisticated digital simulations; the digital simulation results have been successfully correlated with test data.

INTRODUCTION

This paper describes the second generation Wind-Energy System Time-Domain (WEST) analyzer system developed by Paragon Pacific, Inc. under contract with the NASA-Lewis Research Center, Cleveland, Ohio.

WEST2 GENERAL DESCRIPTION

The WEST2 simulator is a complete coupled wind turbine dynamics analysis unit. The analyzer contains nonlinear dynamic math models for all components of a wind energy generator system, including the aeroelastic rotor, power train, tower, electrical machinery and control system elements. These models are executed in the time domain at speeds exceeding the capabilities of conventional digital computers by factors of 1000 or more, using the Special Purpose Hybrid Computer (SPHYC) technology developed by Paragon Pacific, Inc. Because of the high speed analysis capability of the SPHYC technology, the WEST2 simulator is able to perform critical analyses in real time; analyses that are totally impractical using other available methods.

The heart of the WEST2 simulator is the complex aeroelastic rotor analysis subsystem. Under contract with the U.S. Army Electronics Command (ECOM) Fort Monmouth, New Jersey, Paragon developed a Special Purpose Rotorcraft Simulator (SPURS). The most fundamental subsystem of SPURS, the rotor analysis, is used (with nominal extension for wind turbine analysis) in WEST2.

WEST2, including the aeroelastic rotor math models, is a special purpose analyzer containing both digital and analog components. Conventional strip theory is incorporated in the rotor analysis, including all nonlinear inertial and aerodynamic loading phenomena. The aerodynamic and inertial loads are integrated along the blade span at extremely high speeds, using an analog aerodynamics math model for a blade of infinitesimal radius.

The same loads package is switched from blade to blade by the digital controllers, and swept along the span of each blade to compute all loads which excite blade-mode and shaft motion. The high-speed capacity of the analog subsystems in WEST2 makes real time analysis practical.

WEST2 features a stroboscopic display system which enables convenient viewing of distributed loads and blade deflections during analyzer operation. When the rotor blade enters a narrow azimuthal sector defined by the WEST2 operator using the front panel controls, the distributed functions are "painted" on an oscilloscope for all blades in the rotor. the specific function presented is selectable using a front panel switch. The list of display radial functions includes in-plane and out-of-plane aerodynamic loading, flapping motion, angle of attack, lift coefficient, and drag coefficients due to stall.

In addition to the special-purpose portion of WEST2, a general purpose simulation unit (GPURS) is incorporated for modelling those components of the wind generator system which may vary from time to time, as the designs of wind energy devices evolve. Examples of such variable systems are the control and power management systems.

Applications for WEST Systems

Because of their unique power for fast nonlinear analysis, and because of their dedicated architecture, the WEST units are ideal for analysis where

- Large amounts of data (i.e., time histories of loads and motions under varying conditions) are required at low cost;
- Nonlinearities such as blade stall and mechanical hysteresis are significant to the analysis results;

- Stochastic processes are involved (e.g., predicting fatigue lives of critical components in a statistically varying environment);

- Real-time operation is required (e.g., operator training in failure modes);

- High speed operation is required so the WEST can be used in conjunction with complex simulations of electrical power network dynamics;

- A coupled simulation is performed involving many wind turbines operating in concert with one power network.

In these and many other areas, the WEST concept is technically superior and much lower in cost than the alternative methods associated largely with general-purpose digital computer simulation.

THE NEED FOR AND CAPABILITES OF A WEST2 ANALYZER

A wind energy generator is a very complex dynamic system, representing an assemblage of individual elements, each with its own special dynamic characteristics. When the system is operating, the dynamics of all the components of the system couple together: all elements of the system move at the same time, and the overall symphony of these motions determines the performance, safety and longevity of the complete wind generator unit. The following coupled dynamic phenomena, for example , represent critical aspects of wind generator performance:

- Dynamic loads in the various structural components of the system, which determine fatigue life, and therefore substantially impact on overall operational cycle costs;

- Overall system stability - the property that prevents certain motions from growing without bound and leading to the ultimate destruction of machine components;

- System control, wherein the rotor and power machinery are properly controlled for fruitful average yields of electrical power, with acceptable quality for use in existing utility networks.

The wind generator is a tuned dynamic system that must be operated in all kinds of weather. The system component loads, stability properties, and control quality and effectiveness will need to be evaluated not only in conditions with steady benign winds, but also in the random environments that characterize those periods when wind speeds and, hence, energy content are highest.

The WEST2 analyzer simulates the complete nonlinear dynamic characteristics of a wind energy system at speeds which make realistic environmental analysis practical. Because it represents a complete nonlinear simulation of the wind generator system, the WEST unit is able to perform virtually any of the standard analyses currently used in wind turbine development. Such analyses address performance, blade loads, control system stability, response characteristics, etc. Because of its unique high-speed capabilities, however, WEST2 is also able to perform examinations of wind generator operations that are not generally considered practical for standard analyses. A few examples of such unique capabilities are:

- Design Parametric Synthesis, wherein key design parameters in the wind generator system are input from front-panel or adjustable internal controls. Parameters such as blade chord, rotor tip speed, blade modal frequencies, power train critical stiffness, and control system gains are examples of such adjustable system properties. Time-history plots of dynamic blade and power train loads, vibrations, electrical signal purity, and control system response are examples of outputs that are revealed instantly by the operating WEST analyzer.

- Statistical Analyses, performed using internal random environment generators in the WEST2 unit. Wind speed and directional random properties are synthesized by filtering white noise. The key properties associated with the filter spectra, amplitude and bandwidth are adjusted from the front panel. Time-history responses are instantaneous outputs from the WEST simulator. Additionally, panel meters reveal general operating parameters such as shaft torque, power output, rotor speed, and rotor thrust.

- Real Time Control System Synthesis can be performed using the WEST2 analyzer/synthesizer system. Control laws synthesized using the WEST2 analysis could be switched over for direct control of research wind energy systems. This capability will enhance the safety of wind energy research programs, since control system stability and performance can be evaluated with a high-fidelity system math model before a set of control laws is used in a real system.

- On-Site Confirmation of Analytic Models can be performed using the real-time capability of the WEST analyzer. The WEST system can be operated during wind turbine test activities for immediate comparison of test and analytic results. Indeed, instrumentation data (e.g., wind speed and direction vs time) taken at the site during test operations can be input directly to the WEST2 unit, and response comparisons then can be made. Adjustments to WEST2 math models can be made to achieve correlation with the results being recorded from the test.

TECHNICAL DESCRIPTION OF THE WEST2 ANALYZER

Figure 1 is an overall block diagram of a WEST2 system. For convenience, in describing the complete system, two separate sections have been defined; the nonrotor system (NRS) and the aeroelastic rotor system. Because of the relative complexity of the rotor compared to other components of wind energy systems, Figure 2 has been provided as a more detailed block diagram of the rotor component.

The technical descriptions which follow address the math models incorporated in the NRS and rotor, the electronic methods used for solving the math models, and the hardware architecture of the WEST2 units. Methods for programming the simulators for specific wind turbine units, and calibration, testing and maintaining the analyzers, are also described.

The Nonrotor System (NRS)

Part of the NRS occupies the top tray or drawer of the special purpose section of WEST2. Other NRS models are programmed on the general purpose simulation (GPURS) subsystem of WEST2. Components of the NRS are described below:

Air Motion Models - The motion of the air in the vicinity of the rotor is affected by the wind direction and speed, windshear (windspeed change with altitude), aerodynamic interference of wind flow from the tower (shadow effect), and retardation of the wind by the rotor. Models for all of these phenomena are included in the NRS.

The nominal windspeed and direction with respect to the rotor are defined from front panel controls. Panel controls can also be adjusted to produce step or ramp gust functions for the wind. Speed, direction, and swirl (rigid-body motion about a vertical axis) can be distributed in this manner.

The variation of windspeed with altitude (windshear) is also adjustable from the panel - the variation is currently assumed to be a linear function of altitude.

The tower shadow phenomenon is modelled as a step change in windspeed when the blade is in an azimuthal sector behind (or in front of) the tower. Both the strength and the sector size of the shadow model are adjustable from the front panel.

Wind retardation by the rotor is modelled using the Glauert momentum model. Retardation, of course, is a function of rotor thrust, air density, and net windspeed at the rotor disk. Air density is adjustable from the panel to conveniently model the influence of altitude.

The WEST2 NRS tray also includes a random gust synthesizer. A pseudo-random white noise generator produces the basic random signal. Three low pass filters with adjustable gain and bandwidth filter this noise to model random changes in wind speed, direction, and swirl.

Power Train - In WEST2, a single degree of freedom power train model is incorporated in the GPURS system. The generator model in the power train produces a torque on the system proportional to the rotor speed or to the phase angle of the power train with respect to an electrical network phase angle. The power demand is input on a GPURS panel potentiometer, simulating a field current control.

Front panel galvanometers display the key power train variables: power ratio (ratio of produced power to wind turbine rated power), shaft torque and rotor speed.

Flexible Supports - WEST2 contains a single degree-of-freedom shaft support, implemented on GPURS. The WEST2 support allows the rotor hub to move laterally and to yaw as the tower and yaw-drive mechanism move under loads applied by the rotor. The natural frequency, damping, mass and geometrical characteristics of the flexible support model are adjustable. The model can be expanded to include additional degrees of freedom.

Control System - The control system determines the blade pitch angle. In WEST2, a two-mode control system is implemented on GPURS. The mode is determined by a GPURS front panel switch. The startup/shutdown mode causes blade feathering to be commanded by a blade-angle control potentiometer on the NRS tray panel. At moderate rotor speeds, or above, the mode can be switched to speed command, in which the control system, by suitably pitching the blades, strives to maintain a speed commanded by a front panel control. If too much power is demanded at a given windspeed, however, the controller fails to maintain the commanded speed, the rotor slows, and usually stops.

The nonrotor elements of the Wind Generator System use straightforward simulation techniques, and represent no particular deviation from usual procedures incorporated in hybrid analysis. The overall system arrangement enables "stand-alone" simulation capability, or integrated capability where WEST2 becomes part of a larger simulation test facility. In the stand-alone mode, WEST2 can be used for basic research, controls development, response qualities assessment, blade loads analysis, etc.

Aeroelastic Rotor Analysis

The aeroelastic rotor model in the WEST2 simulator is characterized by the simplified block diagram of Figure 2. The digital section is essentially an executive monitor and sequencer which controls the computational sequences of the analog sections. The high frequency analog section contains the nonlinear math models associated with a blade element of infinitesimal radius. This same model is used for all blades in the rotor. The low frequency section contains the equations for the blade elastic degrees of freedom and various coordinate transformations of loads and motion signals between the fixed and rotating frames of reference.

A full set of nonlinear equations comprises the math model for a blade infinitesimal radial element. Aerodynamic loads are calculated using an airfoil model valid over a full 360-degree angle of attack range; airfoil parameters in the model are fully adjustable to simulate use of different airfoil designs. Distributed inertial loads caused by gyroscopic effects, coriolis accelerations, etc., are also represented by a comprehensive set of nonlinear blade-element equations.

The shaft accelerations and velocities with respect to the inertial frame and the shaft velocity with respect to the local wind are inputs to the rotor models. A series of Eulerian transformations is then used to solve for the airspeed, angle-of-attack and inertial acceleration of the blade-element model, at a specified radial position.

The blade-element model produces the loads, which are then resolved to shaft axes to define the infinitesimal shaft force and moment contributions made by the element. The elemental loads are also multiplied by the blade eigenfunction or modeshape and integrated along the span, to define the generalized forcing function which excites aeroelastic motion.

The analog implementation of the aerodynamic and inertial models described above uses a "sweeping" process, whereby the radial position of the blade element is varied as a sawtooth function, and the distributed loading functions are integrated with respect to time to produce shaft and modal loads. (Hence, a substitution of variable is occuring in the models, where very short time intervals take the place of radius in the radial integrations of distributed loads.)

The digital sequencer first inputs the state variables and azimuth position of, for example, blade number i to the high frequency section, and then "sweeps" out the radius, using radial position as a sawtooth input function. As the sweep proceeds, integrands for the modal generalized forcing function and shaft loads are generated in the geometry section. These are simultaneously integrated by the radial integrator units. At the end of the sweep, the integrator outputs, which represent the generalized forcing functions and shaft loads for blade i, are transferred to sample/hold units. (The outputs of these units are summed for all blades to get the total shaft loads. They are also applied as forcing functions to the blade motion equations.) After the short duration required to set the sample/hold units, the digital section resets the radial integrators to zero, advances the multiplexors to treat blade number i + 1, and repeats the process.

As the sweeping process occurs, programmable radial function generators produce variable blade properties such as chord, modeshape, twist, and mass distribution; these properties are input to the blade-element aerodynamic and inertial math models.

Currently, the WEST2 simulator, uses a single degree-of-freedom modal representation for the rotor blade aeroelastic properties. The second-order equations in the blade mode generalized coordinates are implemented using standard analog techniques. These models respond to the generalized forcing function variables produced during the sweep integration. The resulting blade motion is then multiplexed back into the blade element models to include the influence of aeroelastic blade motions on the distributed aerodynamic and inertial loads.

Electronic System Architecture

Paragon Pacific, Inc. has developed an extensive library of printed circuit cards called computational module cards. Each card has a number of groups of electronic devices, each group performing a specific mathematical function. For example, the multiplier card has ten multipliers, each performing an independent analog multiplication. Analog, digital and hybrid functions are contained in the library. Analog functions include summers, integrators, sample/hold units, etc. Digital devices include gates, one-shots, flip/flops, Random access Memory (RAM) units, etc. Hybrid cards contain analog-to-digital (A/D) converters, digital-to-analog (DAC) converters, etc.

Two different techniques are used to combine these precision electonic computational modules into a full system such as WEST; special-purpose and general-purpose architecture are described below.

Special Purpose Systems

In special-purpose programming, the module cards are plugged into a standard card cage. Each card cage, or drawer, can receive 120 math module cards. The cards plug into an assembly called a "pin plane" which is horizontally situated near the bottom of the drawer. The pin plane receives the card edge connectors on its top side, and connects each card circuit to a gold-plated vertical pin emerging from the bottom of the plane.

Each pin plane contains 8,640 pins, whose positions are very precisely located within a matrix. The special purpose drawer is programmed to be a specific function, such as a WEST, by wiring these pins together, thereby connecting the math modules on the cards into the desired circuits. A process called "wire-wrapping" is used to do this. The small wires are stripped and wrapped very tightly on the pins to form the desired circuit. Up to 8,640 wires are placed in one pin plane.

The wire-wrapping is done by machine and is fully automated. Specialized computer programs are used to convert the sustem design information, produced originally in the form of diagrams, into a deck of punched data processing cards. The automatic wire-wrapping machine reads these cards and wires the entire tray without making an error. In essence, computers are now reproducing themselves.

The special purpose trays are inserted into a cabinet, where connectors on the rear panels engage a "gallery" installed at the rear of the cabinet. The gallery contains wiring that connects the drawers together and supplies them with power.

In WEST2, the top drawer is the NRS, the center tray is the rotor, and the bottom half-size drawer contains the power supply. The power supply drawer also contains the maintenance system called the Verification and Calibration Equipment (VACE), which is described later.

General Purpose System (GPURS)

The GPURS system uses the same computational module cards as those used in the special purpose systems, except that they are inserted into the left front panel card cage. The card edge connectors are connected to the removable patch panel, where they can be conveniently wired into any system.

GPURS is a very flexible system, since both its wiring and its architecture are variable. Wiring is changed at the patch panel, and architecture is varied by plugging in different computational module cards.

GPURS accepts 17 module cards, and contains its own power supply and front-panel functions (pots, switches, interface trunks). GPURS also has an internal card cage and rear panel trunking system for special interfacing functions.

GPURS can be configured as a pure digital system, pure analog system, or any combination of both because of its flexible architecture and because of the availability of the large array of module cards.

As mentioned previously, WEST2 incorporates a GPURS at this time. The WEST2 GPURS component currently includes models for the wind turbine flexible supports, power train and control systems, and a gimbal or teetering rotor support.

MOSTAB-HFAWM, described in general terms in Reference 1, has been validated with test data taken from the NASA/DOE Mod 0 experimental wind turbine located at Plum Brook Station, near Sandusky, Ohio. Results of MOSTAB correlation-efforts are documented in Reference 2.

Programability

Special Purpose Hybrid Computers can be programmed in two ways by selection of optional subsystems:

- Mechanical adjustment of trim potentiometers;
- Potentiometers and Random-Access Memory (RAM) units which are set automatically, by external user command.

The mechanical potentiometers provide the least expensive and most compact programming means, and, hence, this approach was selected for the WEST2 unit. When the user requires rapid programming capability, however, the digitally-controlled pot and RAM units can be installed, enabling fully automated programming from data stored on a floppy disk device.

A Digital Support System (DSS), using Paragon's Modular Stability Derivative Program (MOSTAB) as a key component, calculates all required programming data using standard MOSTAB input data. The DSS is run on a digital batch processor, and performs most WEST2 calculations which do not change with time during wind turbine simulation (e.g., mass integrals, initialization co-efficients, etc.). If the fully-automated programming capability is incorporated in lieu of the trim pots, the DSS creates the data on the floppy disk, with no user intervention required.

Self-Testing: The Automatic SPHYC Test and Calibration (ASTAC) System

The ASTAC system has been procured with the WEST unit. ASTAC is a fully automated test system. A micro-based controller and interface unit open and close electronic switches within the WEST circuits by command from data contained on a "floppy disk" storage device. Test signals are substituted into the open circuits, and resulting subsystem performance is measured. The measured performance is compared to theoretically-correct performance indices also contained on the floppy disk. Incorrect operation is flagged by ASTAC and printed, giving the WEST2 maintenance technician complete informaton required to repair the fault and confirm normal operation.

WEST2 Maintainance: Verification And Calibration Equipment (VACE)

Unlike most printed circuit cards incorporated in computers, the computational module cards do not contain the actual algorithms associated with system operations. These are contained in the pin planes and on the GPURS patch panel. Consequently, all inputs and all outputs from each computational element on each card leave the card through the card edge connector.

This unique characteristic permits the module cards to be externally maintainable, because each function can be externally tested for proper performance and calibration.

The VACE unit performs the function of connecting the modules on the computational cards into specialty circuits, for purposes of rapid performance verification, fault detection, and calibration.

The card to be tested is plugged into a card-edge connector on the VACE front panel. Two plug-in units, also inserted into the front panel, program the VACE to deal with the specific module card under test. A series of procedures is then executed using VACE panel switches, and prescribed measurements are made using standard test instruments (for example, a digital voltmeter and oscilloscope). The procedures for testing and calibrating each card are detailed in a comprehensive VACE manual. They are arranged so that personnel who have no electronics training can execute the tests, verify acceptable performance, identify specific components on the card that have failed, and fully calibrate each module on the card, if required.

The VACE unit is also used, in calibration mode, to program the cards for a specific system; i.e., for a specific wind energy system design in WEST2.

Validation of the WEST2 Analyzer

The primary approach taken to validate WEST2, during this initial development effort, involved the extensive use of the ASTAC system, described in the previous section. This validation effort essentially involved an electronic system verification, which proved that each WEST electronic subsystem does indeed execute the intended equations. ASTAC reads the program equations in FORTRAN form, executes these on a general purpose digital computer to produce the theoretically correct calculation, and then compares the WEST2 subsystem performance to the theoretically correct results. In this manner, each WEST2 subsystem is summarily checked.

As a final verification, a dynamic check of WEST2 performance was made by comparing blade-load time histories produced by WEST2 to those produced by the MOSTAB-HFAWM digital analysis. The very good comparison is presented as Figure 3.

Additional Documentation

More details of the WEST2 system is presented in Reference 3. References 4 and 5 contain the full description of all equations and programming techniques incorporated in the system.

CONCLUSIONS

The fundamental conclusions of the WEST simulator work to date is that the Special Purpose Hybrid technology can solve the complex nonlinear equations associated with wind energy systems in real time. Additionally, such implementations solve these equations with sufficient accuracy to compare well with proven alternative analysis methods.

The WEST analyzer concept enables thorough examinations of wind energy systems, including statistical analysis in nonlinear operating regions and transient functions of special interest. Such studies are totally impractical using the slower and more costly digital simulation methods.

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5. Hoffman, John A.: Math Modelling and System Design Report Conversion of the Wind Energy System Time-Domain Simulator Unit 1 (WEST1) System Design to the WEST2 Design. PPI-1030-4, July 1979.

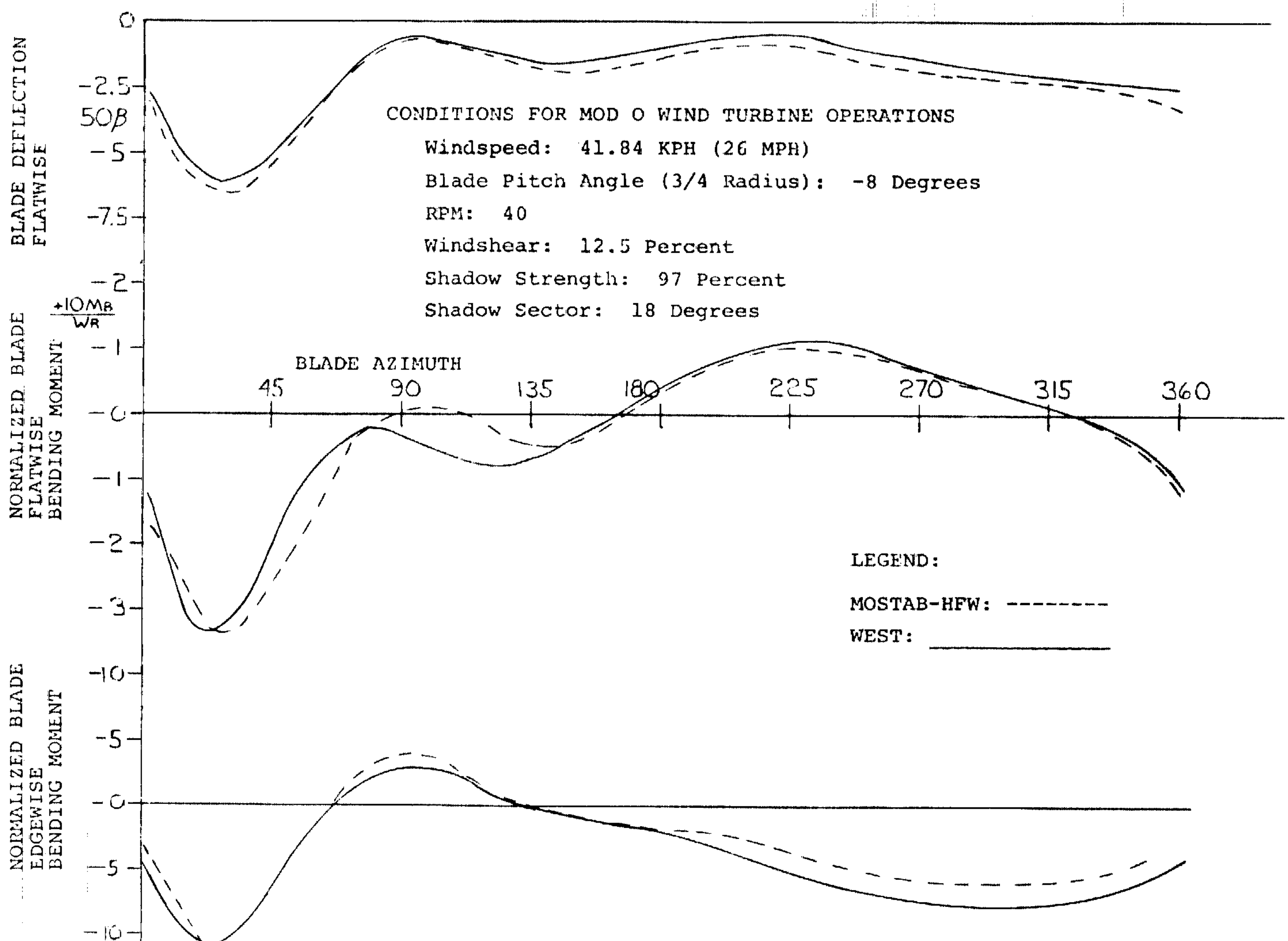

FIGURE 3. - COMPARISON OF BLADE MOTION AND LOAD TIME HISTORIES PRODUCED BY WEST AND MOSTAB-HFW; MOD O WIND TURBINE RESULTS

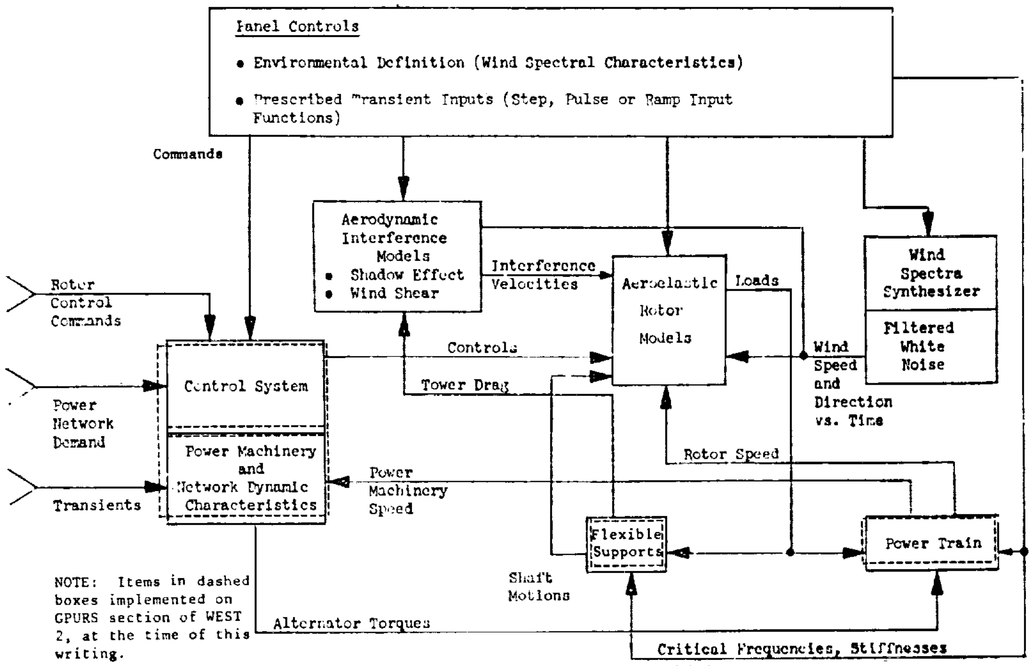

FIGURE 1. - WEST ANALYZER OVERALL SYSTEM DIAGRAM

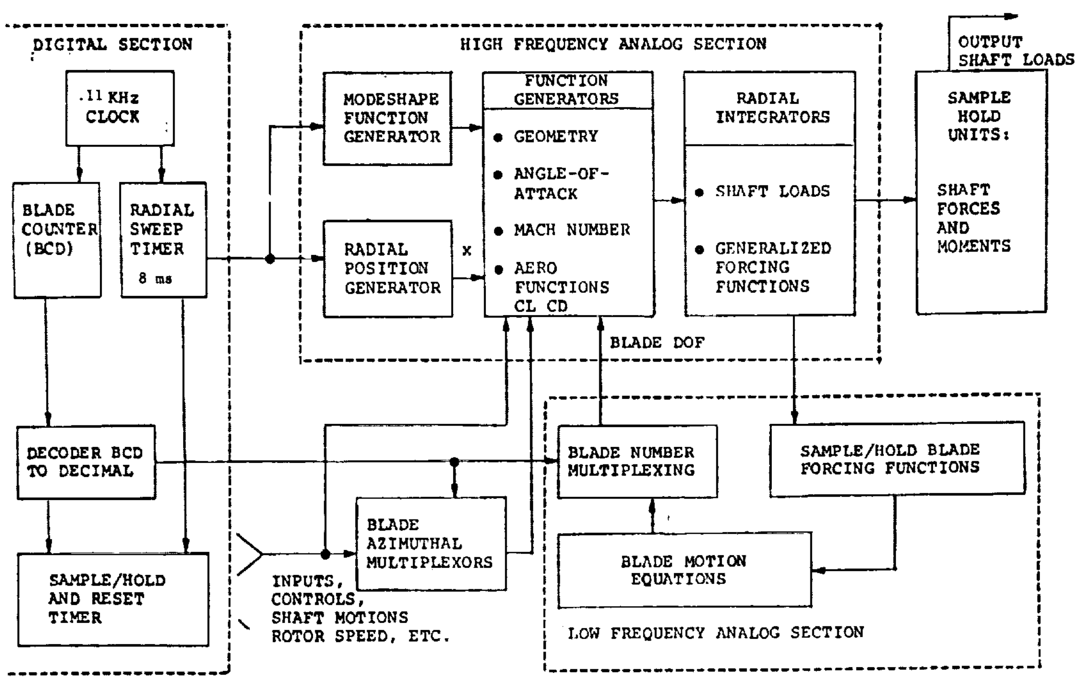

FIGURE 2. - WEST AEROELASTIC ROTOR MATH MODELS

QUESTIONS AND ANSWERS

J.A. Hoffman

From: W.E. Holley

Q: Suggest adding additional gust inputs to account for turbulence variations across rotor disc.

A: *The gust model is currently three-dimensional, providing for statistical variations in speed, direction and "vertical swirl" (the air rotating as a rigid body about a vertical axis). The swirl, of course, produces horizontal variations across the disk that would be associated with turbulent conditions.*

From: C. Rybak

Q: What is the cost of the WEST system?

A: *Between $80K and $120K depending on options.*

From: Anonymous

Q: How do you model the wake geometry to determine inflow and angle of attack?

A: *A Glauert (momentum) model is used for wake retardation caused by rotor thrust. Deviations from Glauert are superimposed to account for windshear and shadow phenomena.*

From: G. Beaulieu

Q: Do you have visual displays or what kind of output features do you use?

A: *Panel galvanometers are incorporated for basic data such as delivered power, shaft loads and tip-path deflections. Rear panel ports produce signals for digital data acquisition or for presentation on standard strip-chart recorders. These output signals are analog lines.*