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WIND ENERGY SYSTEM TIME-DOMAIN (WEST) ANALYZERS USING HYBRID SIMULATION TECHNIQUES

John A. Hoffman
Paragon Pacific Incorporated

October 1979

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Lewis Research Center
Under Contract DEN 3-26

for
U.S. DEPARTMENT OF ENERGY
Energy Technology
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DEVELOPMENT REPORT: WIND ENERGY SYSTEM
TIME-DOMAIN (WEST) ANALYZERS
USING HYBRID SIMULATION TECHNIQUES

John A. Hoffman
Paragon Pacific, Inc.

SUMMARY

A qualitative description of each element of the WEST analyzers is presented. Uses for the analyzers in examining wind energy system operation in the random wind environment are identified.

The results of limited correlation efforts are presented, which show good performance of the WEST units when compared to alternative analytical methods. A description of the WEST verification procedure is also included.

INTRODUCTION

This report describes two Wind-Energy System Time-Domain (WEST) analyzer systems developed recently by Paragon Pacific, Inc. under contract with the NASA Lewis Research Center, Cleveland, Ohio. The analyzers have been named WEST 1 and WEST 2. WEST 2 is a more refined version of WEST 1, containing more detailed models for some wind energy system components. The technological approach in implementing the complex rotor models is identical in either unit, however. Figure 1 is a photograph of the WEST 2 analyzer.

General Description of the WEST Analyzer

The WEST simulator is a complete coupled wind turbine dynamics analysis unit. The analyzer contains nonlinear dynamic math models for all components of a wind generator system, including the 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 WEST simulator is able to perform critical analyses that are totally impractical using other available methods.

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

WEST, 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 element 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 the WEST unit makes real-time analysis practical.

The WEST analyzer features a stroboscopic display system, depicted by Figure 2, which enables convenient viewing of distributed loads and blade deflections during normal analyzer operation. When the rotor enters a narrow azimuthal sector defined by the WEST operator using front panel controls, the distributed functions are "painted" on the oscilloscope for all blades in the rotor. The specific function presented is selectable using a front panel switch.

In addition to the special-purpose portion of WEST, a general purpose simulation unit (GPURS) is incorporated for modelling those components of the wind generator system which may change from time to time, as the designs of wing energy devices evolve. Examples of such systems which may vary are the control and power management systems. Figure 3 is a photograph of a GPURS unit.

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 system hysteresis are significant to the analysis results;
- Stochastic processes are involved (e.g., predicting the fatigue lives of critical components in an environment of statistically-varying operating conditions such as windspeed);
- Real-time operation is required (e.g., operator training - when wind generators are to be routinely operated in association with a utility network, and for failure modes and effects analysis with human intervention);
- 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, perhaps, many other analysis areas, the WEST concept is technically superior and much lower in cost than the alternative methods associated largely with general-purpose digital computers.

Organization of the Remaining Sections of This Report

The next section addresses the need for a WEST analyzer and shows how its unique capabilities are used to further the wind energy technology.

Following the applications section, a technical description of the WEST analyzer, showing the various components of the system, their interfaces, and the special hybrid methods that are used to exercise the complex math models associated with wind energy systems, is presented. Maintenance and verification procedures for the WEST hardware are also described.

A section discussing efforts made to date to validate the WEST technology is included. This section contains the results of limited correlation efforts.

The last section presents conclusions reached during this first developmental process of the WEST analyzer technology, and forwards recommendations for additional effort toward refining and applying the WEST systems.

THE NEED FOR AND CAPABILITIES OF A WEST 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; specifically, operating conditions will include high gusty winds for which wind velocity and direction take on random properties. 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 WEST analyzer simulates the complete nonlinear dynamic characteristics of the wind energy system at speeds that make realistic environmental analysis practical. The WEST system includes random gust function generators, so that the system loads, stability, and controllability are analyzed in a statistical sense. The WEST unit is able to simulate the operation of a given wind system in real time for side-by-side operation with the real system during test and evaluation phases.

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, the WEST system 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 presented below:

- a) Design Parametric Synthesis, wherein key design parameters in the wind generator system are input from front-panel or adjustable internal controls, and the system performance results are instantly revealed by the WEST simulator. Parameters such as blade chord, rotor tip speed, blade modal frequencies, power train critical stiffnesses, 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.
- b) Statistical Analyses are performed using internal random environment generators in the WEST 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.
- c) Real Time Control System Synthesis can be performed using the WEST analyzer/synthesizer system. Figure 4 presents such an arrangement, for which control laws synthesized using the WEST 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 are used in a real system. Also, the WEST analyzer will enable rapid implementation of candidate systems, since the simulation control hardware can also be used directly to control the machine. Special procurements of wind turbine system control hardware can be deferred in this manner, until the adequacy of the control concepts has been established by test.
- d) 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 WEST unit, and response comparisons then can be made. Adjustments to WEST math models can be made to achieve correlation with the results being recorded from the test.

A few example applications of an advanced WEST analyzer have been presented above. Many more applications could be cited. The next section presents some technical detail on how the WEST unit is constructed.

TECHNICAL DESCRIPTION OF THE WEST ANALYZER

Figure 5 is an overall block diagram of a WEST system. For convenience, in describing the overall 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 6 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 WEST units. Methods for programming the simulators for specific wind turbine units, and for 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 WEST (Figure 1). Other NRS models are programmed on the general purpose simulation (GPURS) subsystem of WEST 2. 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 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 WEST 2 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 (Figure 7).

Power Train - West 1 receives a definition of rotor speed and acceleration from front panel controls (Figure 7), so the power train motion is essentially prescribed in this model. In WEST 2, 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. Figure 8 is a photograph of these displays mounted on the NRS tray front panel.

Flexible Supports - West 1 assumes that the rotor shaft is supported on rigid structure, while WEST 2 contains a single degree-of-freedom shaft support, implemented on GPURS. The WEST 2 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 West 1, the blade pitch is commanded from a front panel control (Figure 7). In WEST 2, 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 mode 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

the WEST unit becomes part of a larger simulation of test facility. In the stand-alone mode, the WEST analyzer can be used for basic research, controls development, response qualities assessment, blade loads analysis, etc.

Aeroelastic Rotor Analysis

The aeroelastic rotor model in the WEST simulator is characterized by the simplified block diagram of Figure 6. 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 back 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 enables the use of 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 variables is occurring in the models, where very short time intervals take the place of radius in the radial integrations of distributed loads.

Figure 9 shows key phases of the blade sweeping calculations. 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 functions 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.

The current WEST simulators use 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.

Figure 10 is a photograph of a few of the cards in the library which currently contains more than sixty such modules.

Two different techniques are used to combine these precision electronic 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, such as depicted by Figure 11. 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 circuit. 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 system design information, produced originally in the forms 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.

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.

Figure 1 is a photograph of the WEST 2 special-purpose unit. 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 in a later subsection of this report.

General Purpose System (GPURS)

The GPURS system, depicted by Figure 3, 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 convenient 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 function (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, only WEST 2 incorporates a GPURS at this time. The WEST 2 GPURS component currently includes models for the wind turbine flexible supports, power train and control systems, and a gimbal or teetering rotor support.

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 current WEST units. 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), which uses 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 WEST calculations which do not change with time during wind turbine simulation (e.g., mass integrals, initialization coefficients, 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 can be procured with the WEST unit, as an option. 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 WEST maintenance technician complete information required to repair the fault and confirm normal operation.

Both WEST units were fully confirmed using ASTAC, verifying that each electronic subsystem correctly executes the proper programmed equations.

WEST Maintenance: 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 (bottom tray of Figure 1) 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 the WEST analyzer.

VALIDATION OF THE WEST ANALYZERS

The primary approach taken to validate the WEST units, 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 uses the program equations in FORTRAN form, executes these on a general-purpose digital computer to produce the theoretically correct calculation, and then compares the WEST subsystem performance to the theoretically-correct results. In this manner, each WEST subsystem is summarily checked.

As a final verification, a dynamic check of WEST analyzer performance was made, by comparing blade-load time histories produced by WEST, to those produced by the MOSTAB-HFW digital analysis. The very good comparison is presented as Figure 12.

MOSTAB-HFW, 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.

CONCLUSIONS AND RECOMMENDATIONS FOR ADDITIONAL WEST-ANALYZER DEVELOPMENTAL WORK

The fundamental conclusion 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. Such studies are totally impractical using the slower and more costly digital simulation methods.

Recommendations for Additional Work

Two key areas for additional developmental effort can be identified: refinements to the existing units, and extensive correlation of WEST results with available test data.

Refinements

Certain refinements are known now to be desirable for the WEST units and others are likely to arise as the simulators are integrated into the real world.

Refinements known to be desirable at this time fall into three categories: additional math model refinement, advanced input/output data handling techniques, and upgrading of WEST 1 to WEST 2 technical status.

Advanced/Refined Math Models

The following refinements are known to be desirable at this time.

- A gimballed rotor analysis should be incorporated within the overall WEST concept, to address teetering wind turbine designs. A teetering analysis is currently incorporated on the WEST 2 GPURS unit. This analysis should be installed in the special purpose portion of WEST 2.
- The addition of an aerodynamic tip loss factor

- Refinement of the shadow model to repeat on each revolution (reduce "aliasing" now present)
- Inclusion of a nonlinear wind-shear gradient with programmable properties
- Advancement of current WEST 2 wind-gust generators from low-pass to band-pass (quadratic) filters
- The addition of a blade edgewise degree of freedom

Other model refinements will probably arise as special studies are conducted using the WEST analyzers.

Input/Output Data Handling

Because of the enormous data producing capabilities of WEST, special consideration needs to be given to the input/output (IO) processing of WEST data. This is true in general, but especially true when stochastic processes, such as wind-gust responses and fatigue life, are being studied.

Use of ASTAC

The WEST units are going to be maintained and verified on a day to day basis using the Automatic SPHYC Test and Calibration (ASTAC) system.

ASTAC includes a microcomputer system which is ideal for WEST IO data handling. ASTAC can receive a table of operational spectra (i.e., windspeed, probability density functions, wind gust power spectra and power network loading spectra) entered from the keyboard. Then, ASTAC can automatically set up the WEST controls for the desired cases, run each case or series of cases for a prescribed time period, interrogate and log data (e.g., peak and trough stresses in the blades at various radial points) on the floppy disks, and finally, retrieve the data, post-process it if necessary, and print or plot the data as required. ASTAC has a full FORTRAN capability so all of the available software used for data processing (e.g., FFT's, Miner's rule, etc.) can be used.

Additionally, ASTAC can produce plots using existing software and standard plotters, including the drawing and labelling of scales, and printing of figure titles, enabling convenient production of large amounts of plotted data in final report form, and at low cost.

With the possible exception of a plotter, the hardware and almost all necessary software required to do the data-handling sequences addressed above, are already available in the WEST/ASTAC systems. A small amount of additional effort will integrate and finalize these systems, preparatory to the anticipated WEST production runs.

Upgrading WEST 1 to WEST 2 Status

Two fundamental items are required to upgrade WEST 1 to the WEST 2 status.

- The addition of wind gust spectral models
- The addition of a gimbal dynamics package

Correlation

Correlation efforts are always necessary to validate new analysis methods and WEST is no exception. Although limited correlation was done (against other analytically-produced data) as part of the WEST development contracts, far more work should be done in this area. The suggested correlation effort would permit the following benefits:

- validation of the WEST models over a broad range of operating conditions and design parameters;
- correction or refinement of WEST models where the correlation efforts show discrepancies;
- aid in training service-center staff personnel in the effective use of the WEST units and the associated ASTAC and GPURS systems;
- identification of limitations in the WEST technology for possible future refinement.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio 44135
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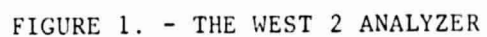




FIGURE 2. - WEST STROBE DISPLAY

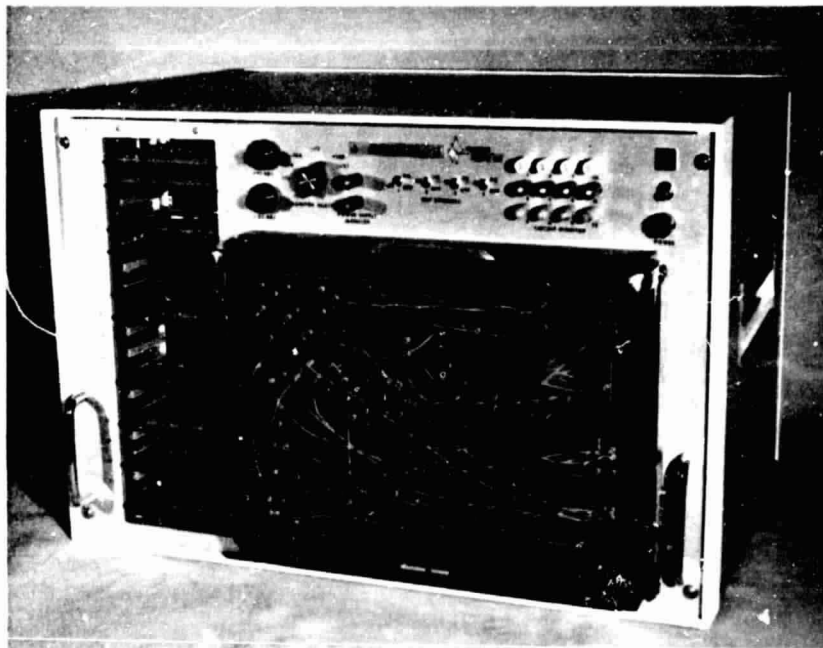
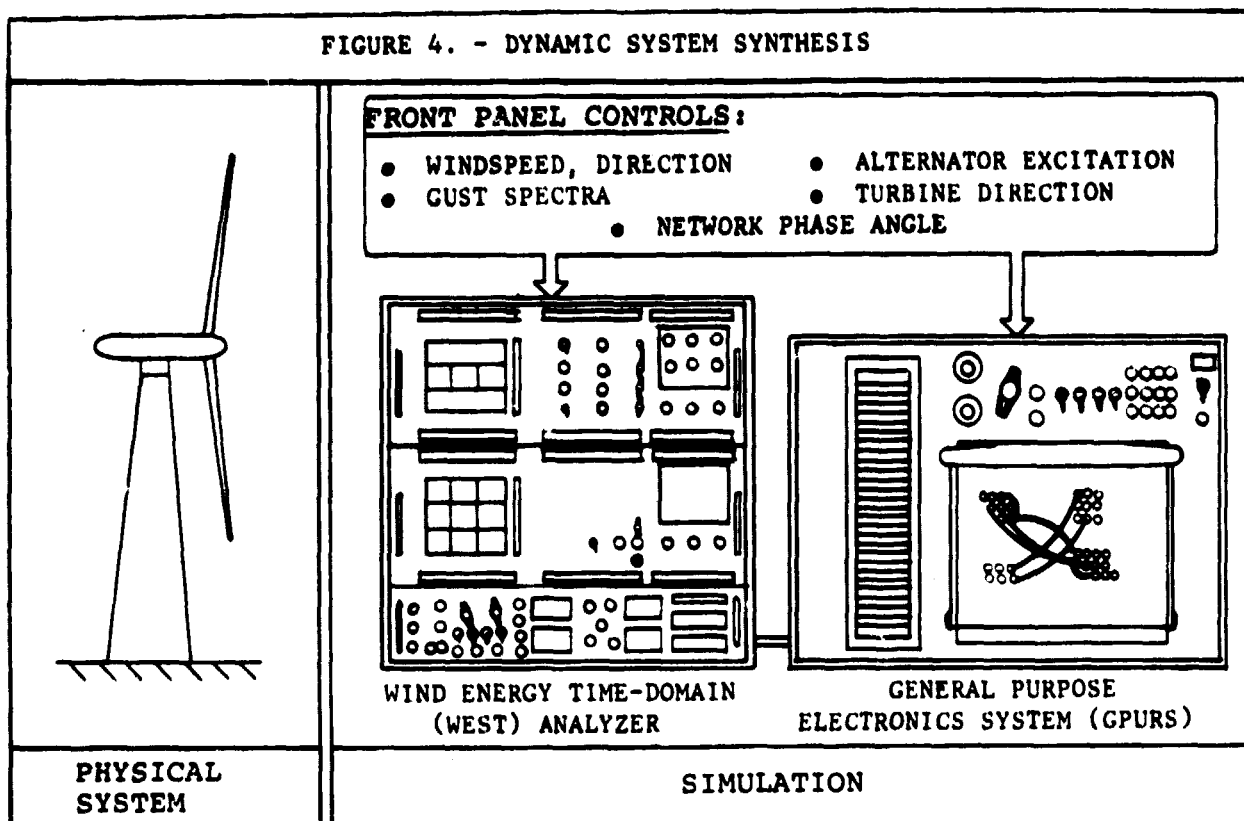


FIGURE 3. - GENERAL PURPOSE ELECTRONICS SYSTEM
(GPURS) COMPONENT OF WEST 2 SYSTEM

FIGURE 4. - DYNAMIC SYSTEM SYNTHESIS



The process of dynamic system synthesis involves configuring a system which performs a certain function, usually associated with some physical plant. For example, consider the depicted computer system, programmed to simulate the wind turbine "physical plant." An accurate simulation of the wind turbine is programmed into the special purpose section of the WEST simulator. Key parameters which vary are programmed-in on the WEST front panel. These include wind speed and gust spectral characteristics, wind direction and turbine direction. In addition to the special purpose section of the simulator, a series of uncommitted math modules (summers, integrators, multipliers, flip-flops, etc.) are incorporated in a separate general purpose electronics system (GPURS).

The user programs the general purpose components into the desired configuration in the usual fashion, by proper "patching" on the external panel and setting of potentiometers. This system might represent the wind turbine rotor and alternator control loops, power network dynamic characteristics or other elements under design.

The synthesized general purpose section is first run with the WEST simulation to evaluate stability and performance. Then, if satisfactory, the synthesized system could be switched over to perform the actual control functions, closing the loop around the real physical system. Testing the control approach first on the WEST helps avoid costly failures in the actual system due to implementation of improper control techniques.

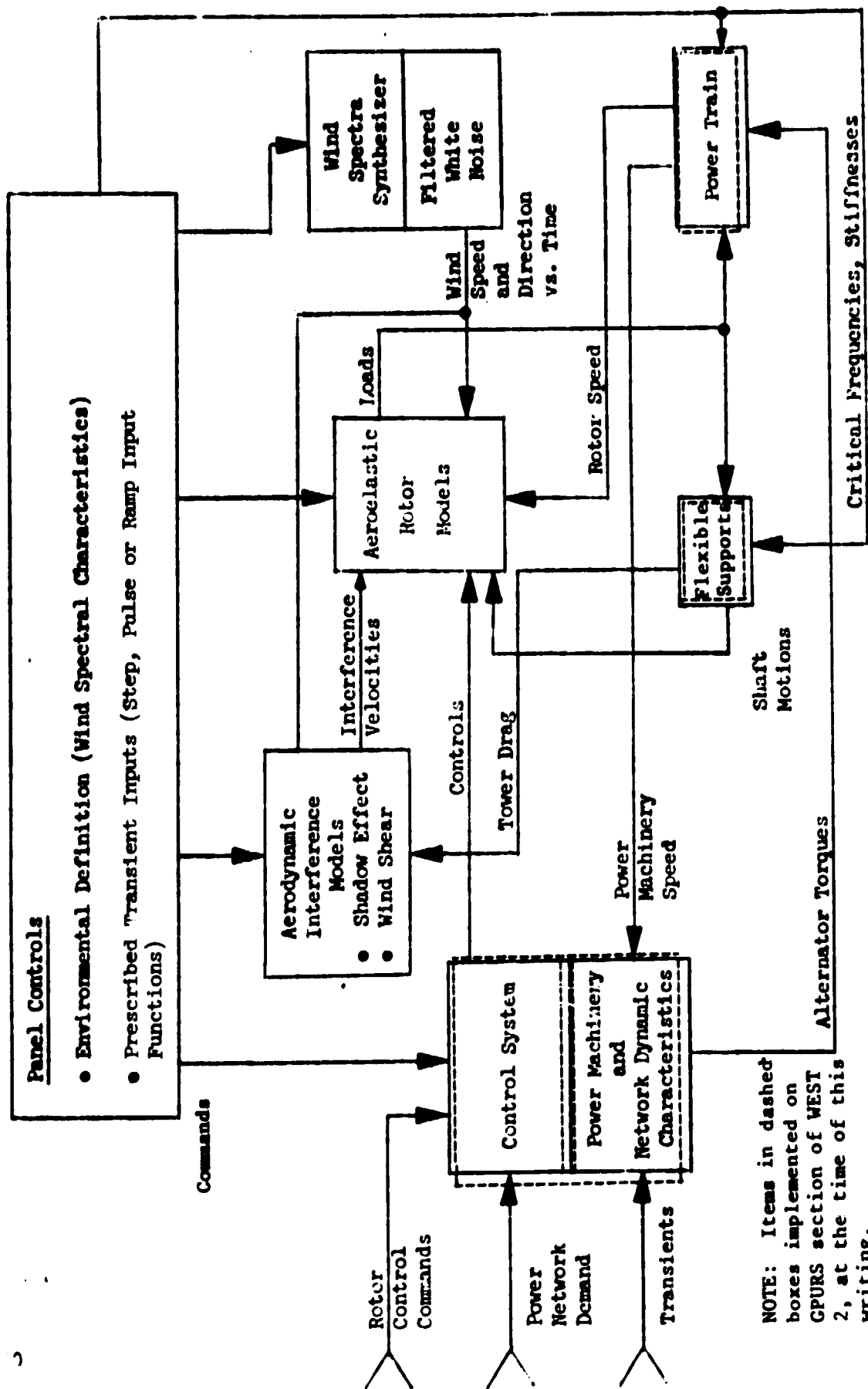


FIGURE 5. - WEST ANALYZER OVERALL SYSTEM DIAGRAM

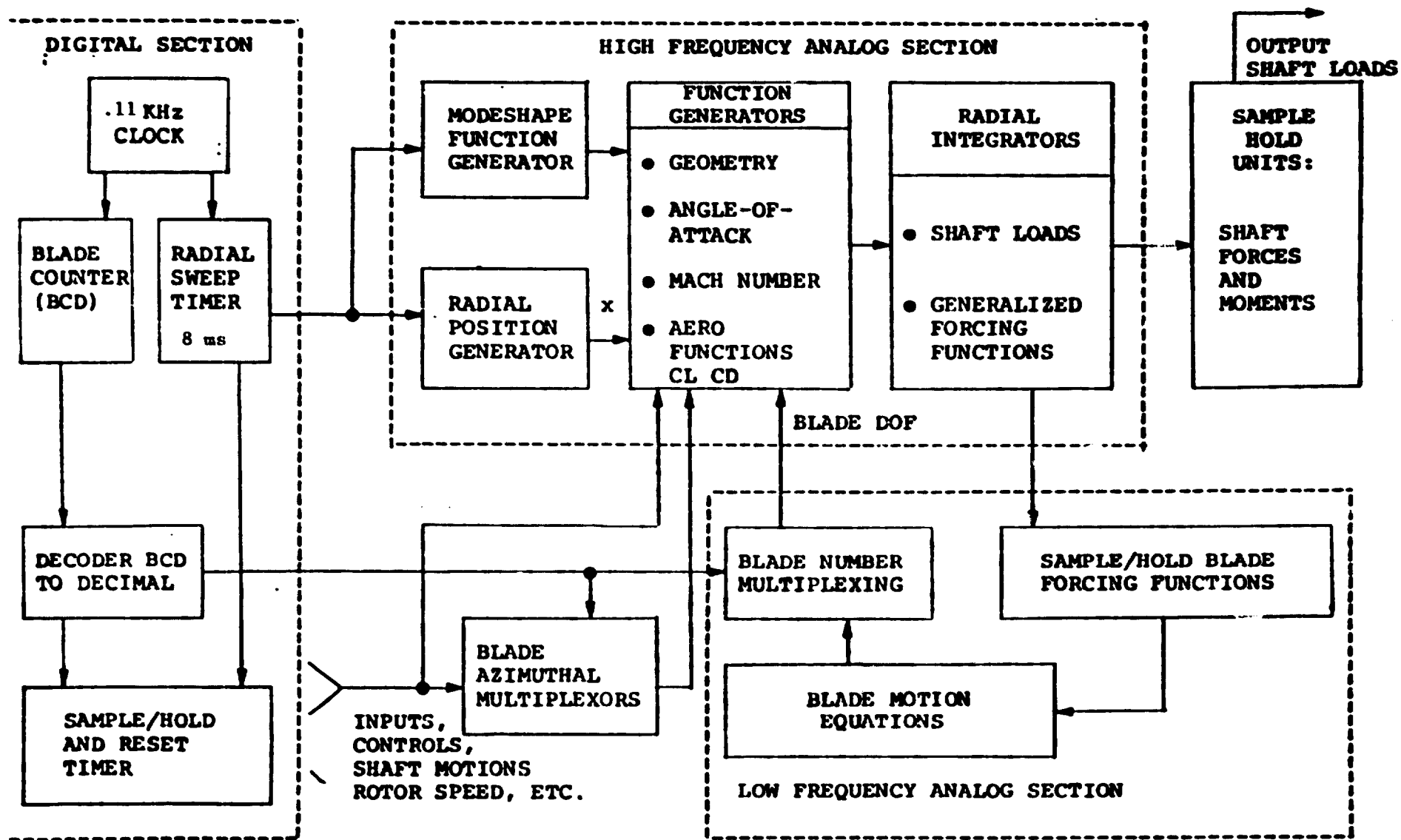


FIGURE 6. - WEST AEROELASTIC ROTOR MATH MODELS

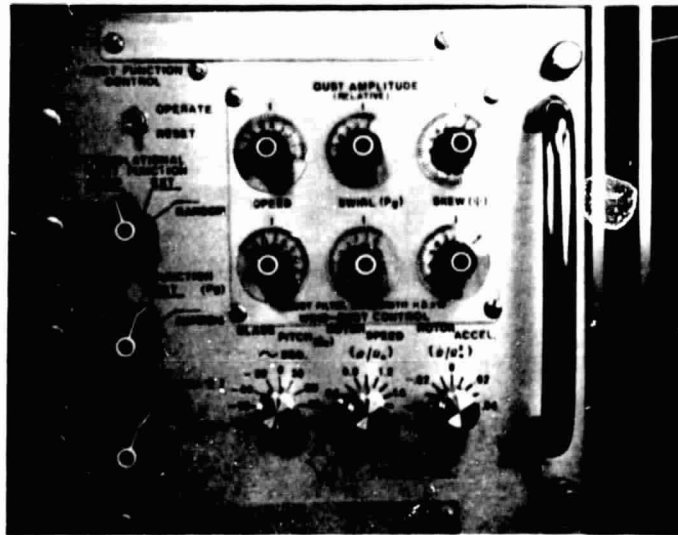
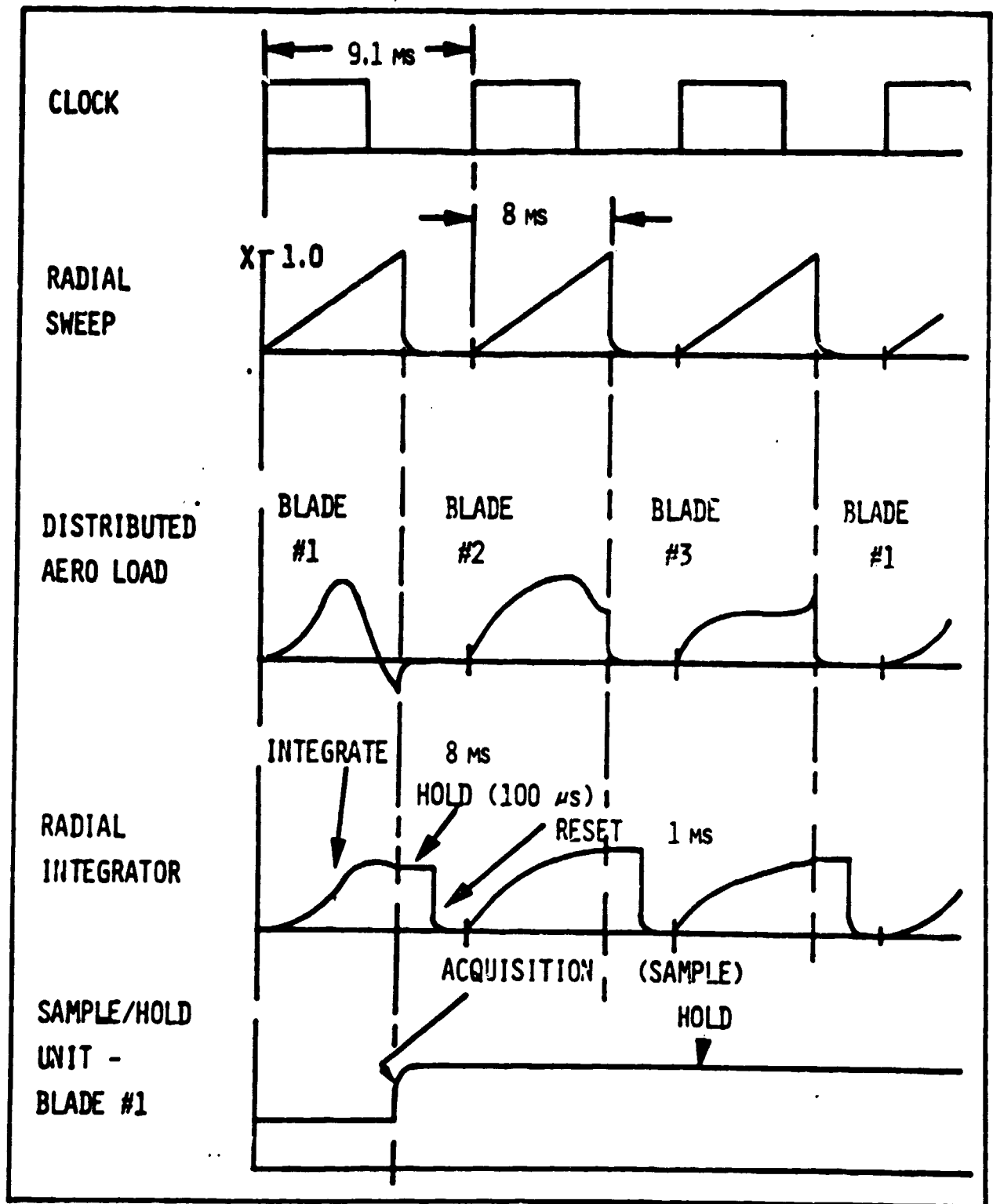


FIGURE 7. - WEST 2 PANEL CONTROLS FOR DETERMINISTIC (LEFT) AND RANDOM GUST MODELS. ALSO DEPICTED ARE ROTOR CONTROLS.



FIGURE 8. - POWER TRAIN MONITORS

FIGURE 9. - WEST SYSTEM EXECUTIVE LOGIC



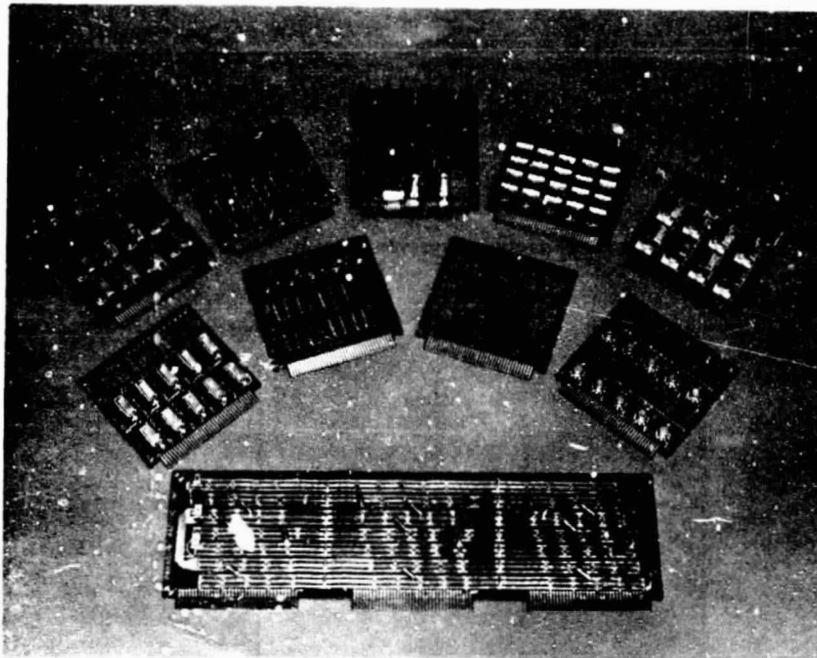


FIGURE 10. - COMPUTATIONAL MATH MODULE PRINTED
CIRCUIT CARDS AND POWER BUS CARD

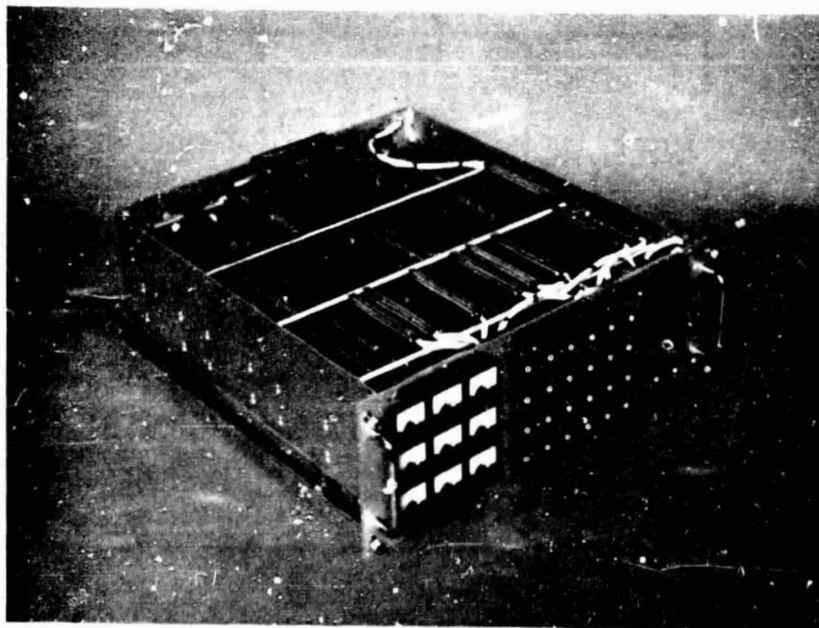


FIGURE 11. - SPECIAL PURPOSE HYBRID
COMPUTER DRAWER

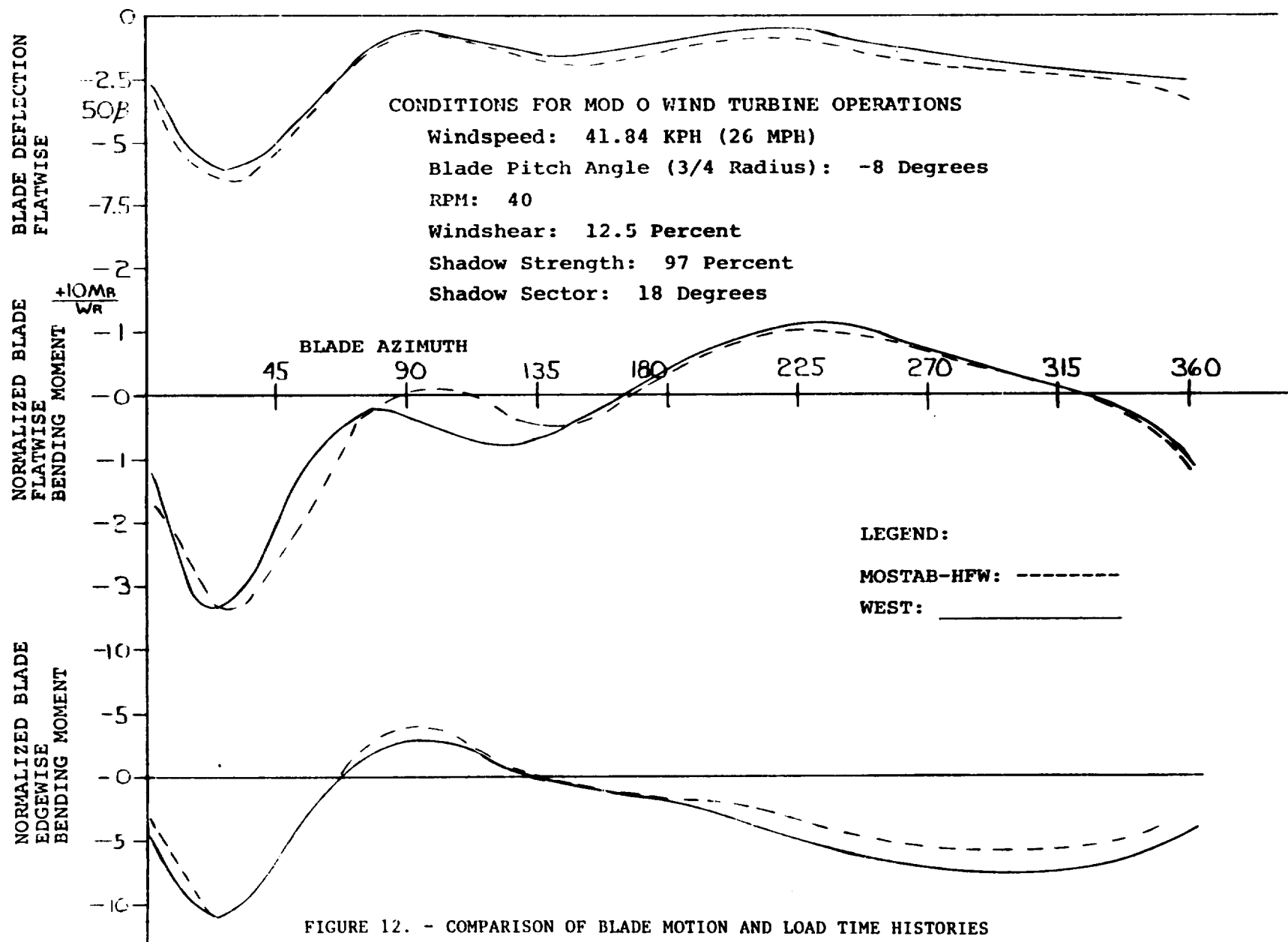


FIGURE 12. - COMPARISON OF BLADE MOTION AND LOAD TIME HISTORIES
PRODUCED BY WEST AND MOSTAB-HFW; MOD O WIND TURBINE RESULTS

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16. Abstract Two stand-alone analyzers have been constructed, using the latest hybrid electronics technology, which simulate, in real time, the complex dynamic characteristics of horizontal-axis wind energy systems. Math models for an aeroelastic rotor, including nonlinear aerodynamic and inertial loads, are implemented with high-speed digital and analog circuitry to enable real-time performance. Models for elastic supports, a power train, control system, and a rotor gimbal system have also been included. Both analyzers feature stroboscopic display systems which graphically depict distributed blade loads and deflections on a cathode ray tube. The display gives the viewer a clear representation of rotor dynamics during startup, shutdown, and during normal operation in the presence of gusts or other disturbances. One of the units contains an internal wind-gust synthesizer. Limited correlation efforts have shown good comparisons between results produced by the analyzers, and the results produced by a large digital simulation; the calculations of the digital simulation have been successfully correlated with test data.			
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