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WEST-3 Wind Turbine Simulator Development

Volume 1: Summary

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Paragon Pacific Inc.

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FOREWORD

The work documented in this report was sponsored by the NASA Lewis Research Center, under Contract DEN3-247. The work was performed by Paragon Pacific Inc., 530 Maple Ave., Torrance, CA 90503. The NASA Project Manager was Mr. D. C. Janetzke.

Principal participants in the contract activity were J. A. Hoffman, D. Weisz and S. Sridhar of Paragon Pacific Inc., and Dr. M. D. Campbell of Talisman Systems, Drawer CP255, Manhattan Beach, CA 90266.

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SUMMARY

This report is a summary description of WEST-3, a new real-time wind turbine simulator developed by Paragon Pacific Inc.. The development which began as a refinement of WEST-2, an earlier hybrid (analog and digital) simulator, evolved into a totally new simulation concept. The new concept borrows from analog technology its best feature, the parallelism of operations inherent in an analog system, and hence high computational speeds. At the same time it retains the primary advantages of digital technology, programmability and accuracy. WEST-3 is an all digital, fully programmable, parallel processing system having significantly higher computational speed than most existing simulation systems.

The description of the WEST-3 hardware presented in the report is confined to the overall architecture and details of the major subsystems. WEST-3 consists of a network of Computational Units (CUs) working in parallel. Each CU is a custom designed high speed digital processor operating independently of other CUs. The CU, which is the main building block of the system, is described in some detail. A unique method of transferring data among the CUs is a major contributor to the high performance of the system. The software aspects of WEST-3 covered in the report include, the preparation of the simulation model (reformulation, scaling and normalization), and the use of the system software (Translator, Linker, Assembler and Loader).

Also given in the report is a definition of the wind turbine simulation model used in WEST-3, and some sample results from a study conducted to validate the system. Finally, efforts currently underway to enhance the user friendliness of the system are outlined; these include the 32-bit floating point capability, and major improvements in system software.

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INTRODUCTION

Wind turbines are a means of extracting energy from the wind for conversion to a useful form, either mechanical power or electricity. Over the past several years, there has been a continuing effort by the Government and industry to establish the necessary technology base for the use of wind turbines as viable sources of energy. As part of this effort, Paragon Pacific Inc. has developed the Wind Energy System Time-domain (WEST) series of simulators, the latest in the series being WEST-3. Presented in this report is a summary description of the development of WEST-3, a new and powerful real-time simulation system.

Background

Much of the earlier wind turbine technology was a direct adaptation of the aviation technology; in particular, that of rotorcraft. However, the need for a continuing improvement in the technology of wind turbines has been recognized. Presently the technology is benefiting from a number of activities ranging from basic research to analysis of data gathered during actual operations.

The phenomena involved in the generation of useful energy from the wind are very complex, covering a number of engineering disciplines including atmospheric fluid mechanics, aerodynamics, stuctural dynamics, and control systems. Accurate analytical simulations of such complex phenomena are indispensable for the design and development of a wind turbine. The usefulness of analytical simulation runs the gamut from preliminary design to training of operating personnel. It encompasses practically all phases in the development process including design refinements, failure mode analysis, and performance optimization. Analytical simulation, when used effectively, reduces the cost, the time, and more importantly, the risk involved in the development process. Further, it provides direction for on-going and future design changes. Recent experiences with the control of operational wind turbines have underscored the need for good simulation tools to support the design process.

For a wind turbine simulation to be useful it must meeet the requirements of high fidelity and speed. High fidelity is dictated by the complex nature of the mathematical models involved. High speed simulations are essential for providing timely inputs to the design and development process. Most past simulations have been non-real-time, relying upon main frame computers to solve the high fidelity models involved. Though these slower simulations have provided valuable design support, they are time consuming, costly, and hence, preclude extensive simulation studies.

A real-time simulation capability is necessary for even moderately extensive simulation studies, so that the time and cost involved are reasonable. Such a capability is mandatory if it is to be used in a mixed mode, i.e., where the actual field hardware is validated in a simulation environment before being integrated into the wind turbine system. For example, this validation can reduce the risk of operating with a new control system.

Wind Energy System Time-Domain Simulators (WEST)

Paragon's WEST series of real-time simulators began with the WEST-1 unit which was derived from a rotorcraft simulation system, with appropriate modifications to the mathematical models. The unit has a hybrid implementation, having both analog and digital hardware. The analog hardware is used to solve the mathematical models, with the digital hardware providing executive control over the analog processes (Reference 1).

The WEST-2 system is also hybrid, having expanded and refined mathematical models that were added to the baseline models of WEST-1. The additional features included statistical models of the wind, and a programmable general purpose hybrid subsystem for analyzing new designs, such as that of a new control system. The development of WEST-3 was begun with the objective of adding more features to the WEST-2. Needed were the models for the rotor gimbal (teetering) system, higher frequency blade elastic degrees of freedom, and more refined descriptions of the tower and the wind environment.

At the time the WEST-2 refinement was begun, Paragon was developing, under the aegis of another project, a new simulation concept which removes many of the objections raised in the past regarding systems such as WEST-2. The primary limitations of these systems are their "hardwired" analog implementation, and the associated limits in significant figure accuracy. The advantage of an analog implemetation is, of course, its high speed due to the presence of parallelism inherent in the architecture. The new concept borrows from the analog technology its best feature, the parallelism, and hence the high speeds. At the same time it retains the primary advantages of digital technology, programmability and accuracy. The new simulation system is an all digital parallel processor having a significantly higher computational speed than most existing simulation systems. In the face of this new and promising technology, the decision was made to redirect the WEST-2 refinement effort toward a totally new system, WEST-3.

This report summarizes the development of WEST-3, and is organized as follows: the next section of this report presents a description of the WEST-3 hardware. Subsequent sections present an overview of the software which has been developed for WEST-3, a brief description of the wind turbine simulation model that has been used in WEST-3, and the results of validation of the system. Some concluding remarks, and an outline of the future plans for WEST-3 are given in the last section followed by a list of References.

WEST-3 HARDWARE

Paragon's WEST-3 has been designed for the time domain simulation of wind turbines of widely varying system designs. Addditionally, WEST-3 can be used for control system synthesis and analysis, including mixed-mode simulations where actual control hardware is interfaced to the simulated rotor, tower, power train and wind models to evaluate system performance. The design objectives were high computational speed, low cost, and a high degree of programmability. The design features which enable WEST-3 to achieve these rather severe objectives are, the choice of the overall architecture, the specialized design of the computational modules, and the implementation of a unique method of data transfer. Complete details of the design can be found in Reference 2.

Overall Architecture

The overall architecture of WEST-3 is shown in Figure 1. The system consists of a number of Computational Units (CUs), each CU being a digital processor having its own memories, arithmetic facilities, and operating independently of other CUs. The other major subsystems are, the Initialization and Control Module (ICM), the Central Controller/Sequencer (CCS), the System Input/Output Data Interface (SIDI), and the Patch Panel. Following are brief descriptions of each of the subsystems.

The ICM is essentially a repackaged PDP-11 microcomputer system. Its role is that of an overall executive involving such operations as initialization, loading of instructions and data into the CUs, and controlling the SIDI. The ICM does not control the internal operations within the CUs. The CCS generates all the timing and control signals required by the system. The SIDI connects the system to an external device for communication of data, analog and/or digital.

Computational Unit

The CU is a custom designed high performance digital processor. Figure 2 shows schematically the major components of a CU. There are two separate memories, an arithmetic module, a local controller, and an IO Queue system. The processing memory, PRAM, is organized into 16-bit words and is used to store data. The instruction memory, IRAM, which is organized into 32-bit words is used to store the execution instructions and the PRAM addresses of the data. The arithmetic module consists of a high speed multiplier (MUL), and an arithmetic logic unit (ALU). A system of latches is used to connect the components, a latch being a device for holding a piece of data untill it is ready to be used. The local controller directs the execution of the instructions within the CU. The IO Queue system is connected to the PRAM of the CU via a parallel bus, a device capable of transferring one full word at a time. Also, the IO Queue system is interfaced to the Patch Panel through 16 serial ports, each port connected by a single wire.

The high computational speed of the CU is a consequence of the fact that the various operations within the CU take place in a "pipelined" manner, i.e., word (data and instruction) fetches and the arithmetic operations can take place concurrently. For example, as many as six operations, namely, instruction fetch and decode, two operand fetches, a multiply, an arithmetic operation, a result store, and an input/output operation can be performed within an instruction cycle of 250 nanoseconds.

Data Transfers

The serial ports from the IO Queue systems of all the CUs are accessible at the Patch Panel, where the user can easily link together any number of these ports. Since the interconnections among the CUs are made at the Patch Panel, the user can configure the overall system to yield optimum performance for a given application. The transfers of data through the IO Queue system take place concurrently with the execution of instructions within the CU, so that there is virtually no degradation of performance due to data transfers. It should be pointed out that such degradation, frequently referred to as "IO overhead", is of critical concern in parallel processing systems. At the instruction speed of 250 nanoseconds, the data transfer rate for a CU is 4 megabits per second per port. This unique method of data transfers (using the IO Queue systems and the Patch Panel) is a major contributor to the high performance and programmability of WEST-3.

Figures 3 and 4 show, respectively, photographs of the WEST-3 system and an individual CU. The WEST-3 shown in Figure 3 has four CUs. However, the tray in which the CUs are housed can accomodate a total of 24 CUs, with minor modifications to the system.

WEST-3 SOFTWARE

The overall performance and usefulness of any simulation system depends upon the effectiveness of the software; and WEST-3 is no exception. The primary objective of the software developed for WEST-3 is to make it easier for a user to conduct useful wind turbine simulations. To meet this objective, in addition to the usual complement of software found in any digital computer, WEST-3 has additional software modules specialized for the processing of wind turbine simulation models. Full details of the WEST-3 software can be found in Reference 3.

The simulation process on WEST-3 consists of, the preparation of the simulation model and the data, the use of the system software to generate the executable code, and running of the simulation and the inevitable debugging. Figure 5 shows an overall schematic of the WEST-3 software package. Following are brief descriptions of the components in the package.

Simulation Model and Data Preparation

Many subtle numerical problems arise in a wind turbine simulation; in particular, in the solution of the aeroelastic rotor equations. There are effects in the model that produce very large numbers. In the final results, differences of these large numbers yield small numbers which reflect some very important dymamical characteristics. The computation of the small differences of large numbers can lead to inaccurate results even in computers having large word sizes. On WEST-3, with its 16-bit fixed point arithmetic, this problem can completely destroy the accuracy of the simulation. The answer to this problem is to reformulate the equations in such a way that small, important effects are not masked during the computations. Such a reformulation calls for a thorough understanding of the physics of the problem.

The reformulated model goes through a process of normalization. This is a process of redefining all the variables in the model by using characteristic or reference values of dynamical quantities, such as, velocity, acceleration, force and moment. In most cases the process yields nondimensionalized solution variables and equations. The same normalized simulation model, with perhaps minor modifications, can be used for wind turbines of widely varying physical sizes.

The normalized model is then "scaled", a process which, essentially, ensures that each variable and constant in the model takes on values within the range of +1 and -1. Scaling is needed because all the computations in WEST-3 are done in 16-bit fixed point arithmetic, a feature which is a major contributor toward achieving a real-time simulation capability. The limited significant figure accuracy attendent in such arithmetic demands that special scaling techniques be used to process the equations (and the constant data) before they are solved on WEST-3. The scaling process is similar to the one used in analog computers. However, unlike analog computers, the all digital WEST-3 is rather unforgiving of scaling errors which cause over/underflows.

Reformulation, normalization, and scaling achieve the following:

1. Accurate simulations in real time are made possible.
2. The model is adaptable for wind turbines of varying physical sizes.

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Referring to Figure 5., the original mathematical model is converted into to a scaled model, the scale and normalization factors are defined, and the constant data file prepared. The constant data consists of physical data and specifications of the specific wind turbine to be simulated. This raw data is converted by a Preprocessor program into a form which can be downloaded into WEST-3 . In addition to relieving the user from generating the large numbers of constants used in the simulation, the Preprocessor also normalizes and scales the data.

System Software

From the inception of the design of WEST-3, it was recognized that having adequate system software was the key to making the system friendly to the user, and hence increase the usefulness of the system. The system software that has been developed for WEST-3 is fairly standard, in the sense that, the process of generating the executable code is similar to that in any other computer.

The scaled simulation model consists of a set equations which are coded in a subset of ANSI FORTRAN, the computer language used widely in engineering applications. The subset consists of the following: arithmetic expressions, logical IF statements, GO TO statements, CONTINUE statements, COMMON block definitions, and calls to FUNCTION subprograms and SUBROUTINEs. Though this subset of FORTRAN may seem restrictive, it has been found to be more than adequate for application to wind turbine simulations. Due to the modular design of the system software, future enhancements to the Translator, if any, can be readily incorporated. It should be emphasized that the user is not required to code the simulation model in the machine's native assembly language; programming in the assembly language is a nontrivial process.

The Translator converts the scaled model into WEST-3 assembly language mneumonics. The Assembler converts the output of the Translator into an Object Code suitable for processing by the Linker. The role of the Linker is traditional, in that it generates an executable Load Module by combining several Object Code modules; typically, a main program and several subroutines. The Translator, the Assembler, and the Linker constitute the bulk of the system software for WEST-3. For debugging purposes, several files, such as memory maps, are also generated while processing through the software.

The Loader performs the task of loading the memories of a Computational Unit: the instructions (Load Module) into the IRAM, and the scaled constants into the PRAM. The Loader has been designed to be as user friendly as practicable. For example, the choice of which Computational Unit is to be loaded, the list of input/output variables, and the configuration of the serial ports are all definable by the user at the time of loading.

Several utility programs are also available for debugging. Among other things they provide for the display of internal buses in a Computational Unit, single stepping through the program, and peek/poke capabilities. These utilites are invaluable for detailed debugging, when needed.

WIND TURBINE SIMULATION MODEL

The simulation model of a wind turbine is a mathematical description of a number of complex physical phenomena involved in the extraction of useful energy from the wind. The full model is formed by combining a number of smaller models of the various physical systems in the problem. For example, the rotor, the power train, and the control system are treated as separate systems. Presented here is an overview of wind turbine model as used in WEST-3.

Figure 6 shows the overall configuration of the simulation model. It is a synthesis of models for the rotor, the air mass, the support (tower), the power train, and the control system. Of all the models, the rotor model is by far the most complex accounting for the bulk of the computational load in the simulation. Figure 7 shows a more detailed description of the rotor model (comprehensive definitions of the simulation model are given in Reference 3). Some of the major features of the model implemented in WEST-3 are:

1. Upto three elastic degrees of freedom for each blade
2. Tower model with six physical (three modal) degrees of freedom
3. Gimballed/Teetering rotor capability
4. Blade tip loss, and flow retardation effects in the rotor
5. Nonlinear wind shear model
6. Bandpass wind gust filters
7. Tower shadow model
8. Power train model with two degrees of freedom

It should be emphasized that due to the modular nature of the implementation, and the full programmability of WEST-3, alternate models/tasks can be incorporated with relative ease. Following is an outline of the major tasks performed in each model, during numerical integration, for every azimuthal position of the rotor. The tasks listed correspond to those in the simulations of the MOD-0 (References 4, 5) and MOD-2 wind turbines, representing two successive generations of wind turbine design.

Aeroelastic Rotor Model

* Determine the influence of wind shear and tower shadow on the air flow as seen by the blades.

* Compute the aerodynamic loads on the blade by using strip theory. Each blade is divided into a number of radial segments and radial stations. The aerodynamic coefficients, as functions of the angle of attack, are obtained by table look-up.

* Determine the effects of elasticity on the blade deflection, velocity, acceleration, and loading at each radial station.

* Obtain the forces and moments at the rotor hub by a summation of the loads at all the radial stations of the blade.

* Account for the effects of the rotor hub degrees of freedom, i.e., gimbal (teetering), if present in the model.

Subsystems

Air Mass model:

- Define the linear and rotational velocities of air flow around the rotor.

* Compute the air flow retardation velocity as a function of the rotor thrust by using the standard Glauert momentum model (Reference 6).

* Simulate the effects of wind gusts by generating random number functions which appear as white noise in the system. The desired gust spectra are obtained by using quadratic filters.

Support system:

* Simulate the dynamics of the tower/nacelle by using the modal analysis, the modal information being typically generated by a finite element program such as NASTRAN.

* Compute the velocity and acceleration of the hub for use by the rotor model.

Power Train Model:

* Compute the rotational acceleration and velocity of the rotor, taking into account the dynamics of the power train components.

* Determine power generated and the reaction loads applied to the support.

Control System:

- Change the blade pitch angle to maintain the desired rotor speed and/or the power output.

VALIDATION OF WEST-3

To validate the WEST-3, extensive simulations of the MOD-0 wind turbine were conducted (Reference 7). The simulation results were compared with those obtained from previous MOD-0 simulations, and with test data measured during MOD-0 operations. The study was successful in achieving the major objective of proving that WEST-3 yields results which can be used to support a wind turbine development process.

Blade Bending Loads

Presented here are some sample results from the validation study. The results are associated with the so called MOD-0 Data Case IV, the operating conditions being,

Power output .... 100 kw
Rotor speed .... 40 rpm
Wind speed .... 28 mph at 12 degrees to the rotor axis
Wind shear .... 15 %
Tower shadow .... 28 % within 30 degrees sector
Yaw drive .... locked

Table 1 shows a comparative listing of the blade flatwise and edgewise bending moments (both peak and cyclic) at stations 40 (5% blade span) and 370 (49% blade span) obtained from four sources: nominal test data (Reference 4), MOSTAB computer program (Reference 8), WEST-2 simulator (Reference 9), and WEST-3.

Table 1. Blade Bending Loads of MOD-0 Wind Turbine for Data Case IV

		Flatwise Moment, $\pm 10^3$ ft-lbs		Edgewise Moment, $\pm 10^3$ ft-lbs	
Case	Source	stn 40	stn 370	stn 40	stn 370
PEAK	Nominal Test Data	66.5	15.2	54.3	10.7
	MOSTAB-HFW	81.1	19.7	57.4	12.1
	WEST-2	75.0	25.2	58.0	25.6
	WEST-3	70.1	26.8	44.1	16.9
CYCLIC	Nominal Test Data	35.0	10.2	40.0	8.1
	MOSTAB-HFW	40.8	11.9	40.0	8.4
	WEST-2	34.7	14.7	37.6	21.9
	WEST-3	41.5	11.7	34.0	14.4

Variation of Yaw Drive Stiffness

In the MOD-0 wind turbine there is yaw drive mechanism which can be used to align the rotor axis with the wind direction. The yaw drive can be configured to exibit different stiffnesses ranging from zero or a free condition, to a very high value corresponding to a locked condition. Test data, and previous studies of the variation of yaw drive stiffness (Reference 5) have indicated the presence of resonances in the blade moments, corresponding to 2 per rev, 4 per rev and 6 per rev responses.

Figure 8 shows the cyclic blade moments plotted as functions of the square root of the effective yaw stiffness of the tower. For convenience, the WEST-3 results were superposed on the figure which was taken from Reference 5. The effective stiffness is the equivalent stiffness of the yaw drive and the tower acting as two springs in series. The plot was obtained by using the analog input facilities of WEST-3 to do a very slow sweep of the tower torsional mode's natural frequency, which is directly correlatable to the effective stiffness of the yaw drive. Referring to Figure 8 it should be noted that the magnitude of a resonance peak is strongly dependent on the amount of damping acting in the the yaw direction. The value of the damping is not known exactly, so that a precise correlation of the peaks shown in Figure 8 was not expected.

The results of the validation study indicate that, in general, the the blade bending loads from WEST-3 correlate reasonably well with available MOD-0 data. The WEST-3 is also a significant improvement over the previous WEST systems as evidenced by its ability to predict the resonance phenomena observed in MOD-0 operations; for example, WEST-2 was unable to predict the resonances (Reference 9). The results of the study did indicate that some parts of the existing WEST-3 simulation model may have to be refined for future work; specifically, the aerodynamics, and the procedure used to couple the rotor model with the tower and the power train models.

CONCLUDING REMARKS

The development of WEST-3 is a significant milestone in the field of simulation, in general, and wind turbines, in particular. The design of WEST-3 is based on a new simulation concept which has been given the name Custom Architectured Parallel Processing System (CAPPS). The system is an all digital, fully programmable, parallel processor having a computational speed which is significantly higher than most existing simulation systems. The design features which make the system unique are,

* the high performance of the system is due innovative design which uses presently available components, and not the result of exotic and expensive hardware.

* the unique method of data transfers in the system eliminates, for all practical purposes, the degradation of overall performance due to such transfers; a problem which plagues most parallel processors.

* the system can be easily expanded by simply adding more Computational Units, the basic building blocks of the system. Also, the design can always be enhanced in special ways for special problems, because the architecture of the Computational Unit is accessible; i.e., it is not built into a chip.

* the user can easily configure the system for optimum performance, depending on specific problem that is being solved.

As a result of the experience gained during the development of WEST-3, efforts are underway to enhance the utility of the system in two major ways.

1. A 32-bit floating point system has been designed. Breadboard verification of a single Computational Unit is under progress, and a full system is expected to ready for use early in CY 1987. The floating point capability will eliminate a major drawback of the existing WEST-3, the need for extensive scaling of the simulation model which is a tedious and time consuming task.

2. The user friendliness of the system will be significantly improved. Toward this, development of a new suite of system software is underway. The user will be able to write programs in the ANSI FORTRAN-77 language; presently, only a subset of the language is permitted. Further, the user will have access to many more debugging tools than are available at present. The process of configuring the system, i.e., interconnecting the Computational Units, will be simplified as much as practicable.

Finally, it should be pointed out that application of the CAPPS technology is not restricted to simulation problems. Feasibility studies have indicated that the technology can be used very effectively to solve problems in areas such as Structural Analysis, Computational Fluid Dynamics, Electromagnetics, Controls, and Signal Processing.

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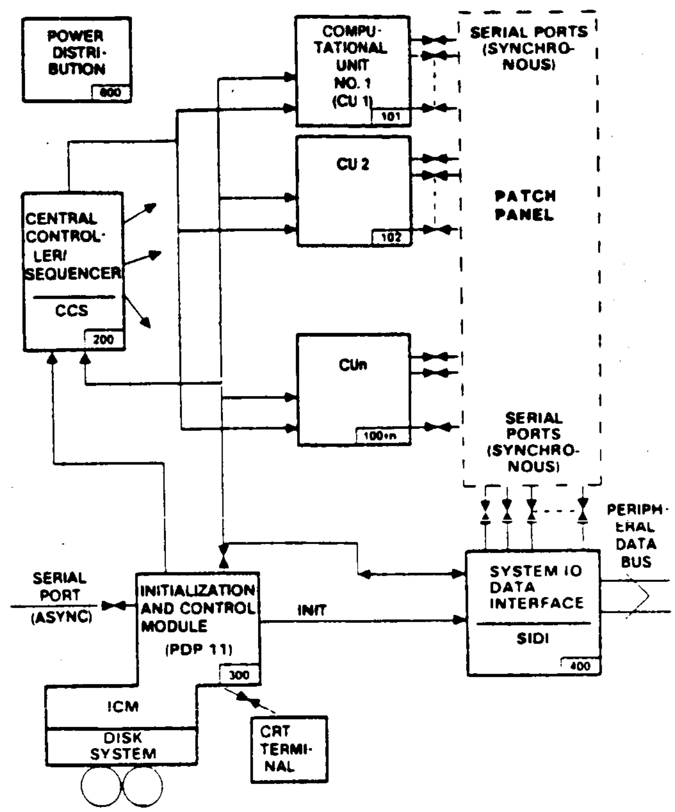

Figure 1. WEST-3 System Logic Diagram

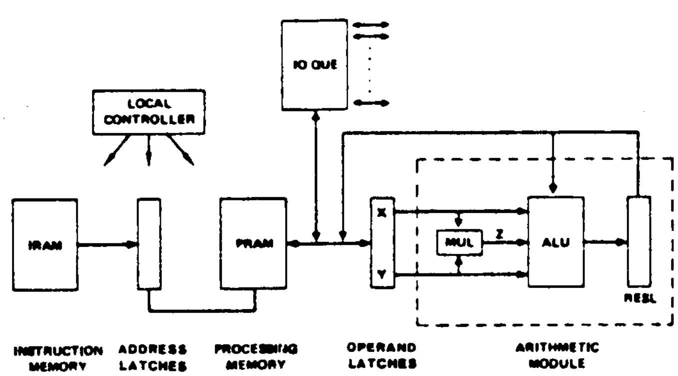

Figure 2. Computational Unit Logic Diagram

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Figure 3. Photograph of the WEST-3 System

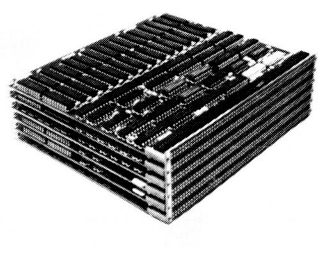

Figure 4. Photograph of a Single Computational Unit of WEST-3

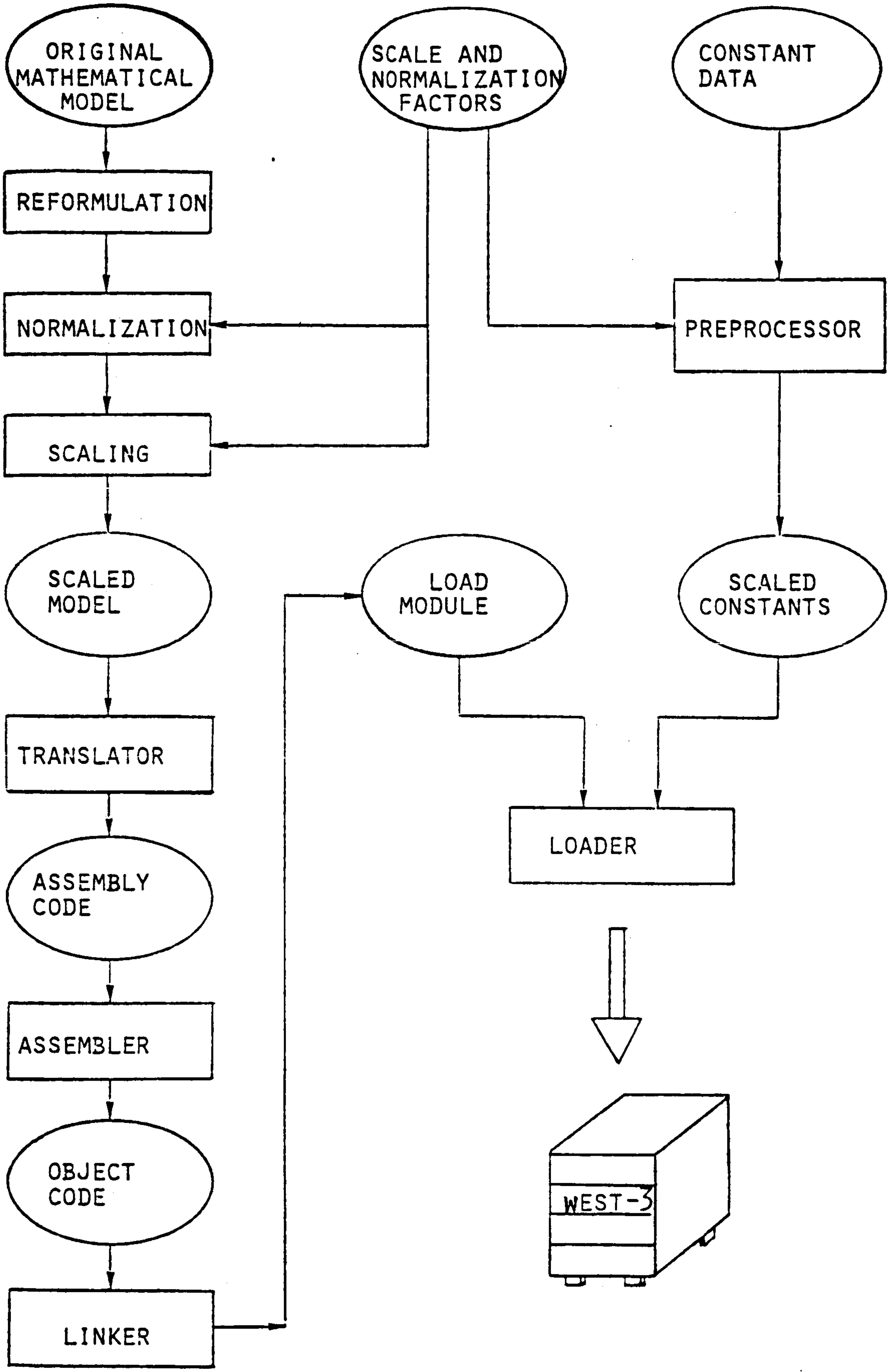

Figure 5. Software for the WEST-3 System

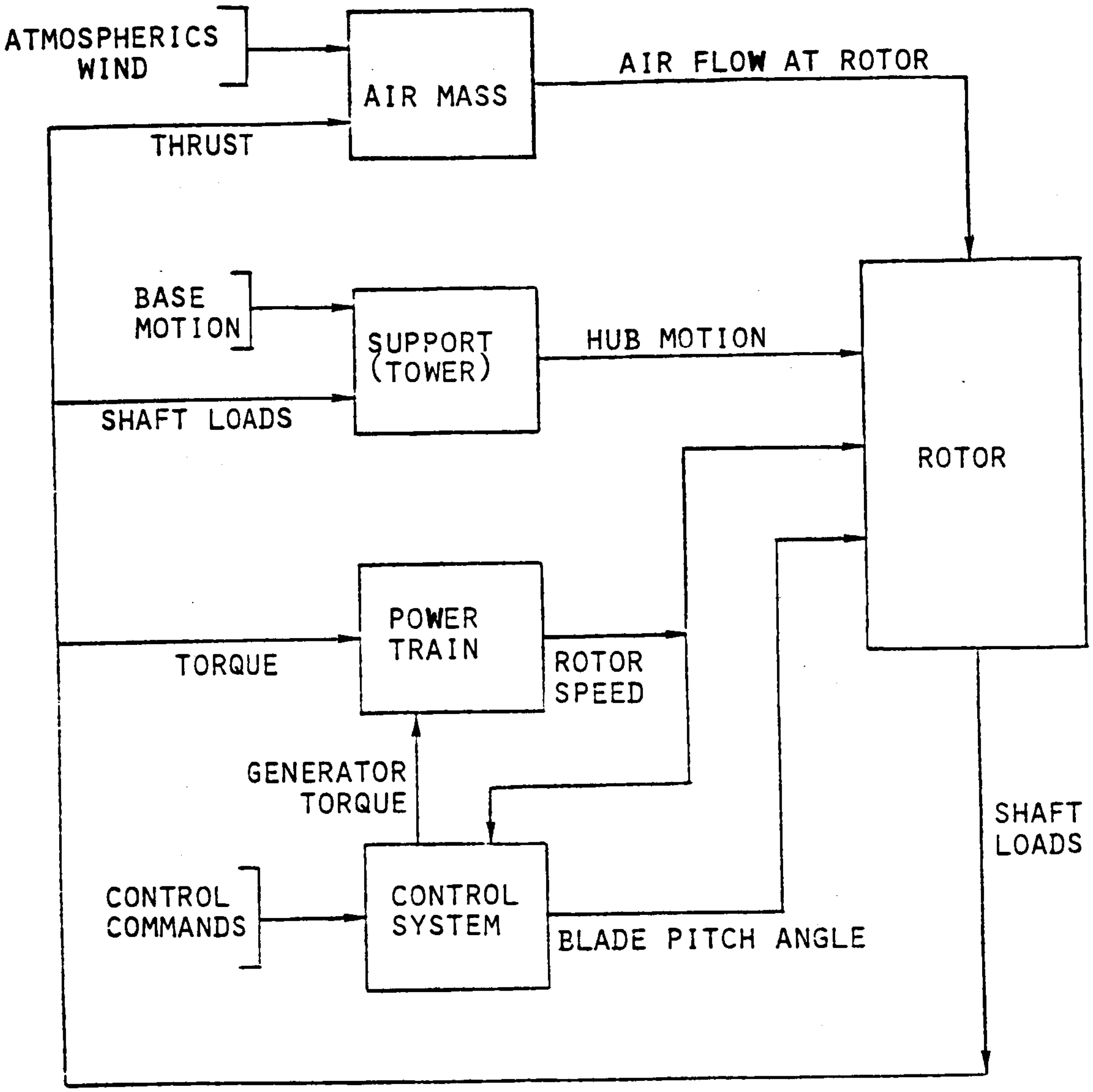

Figure 6. Schematic of Wind Turbine Simulation Model

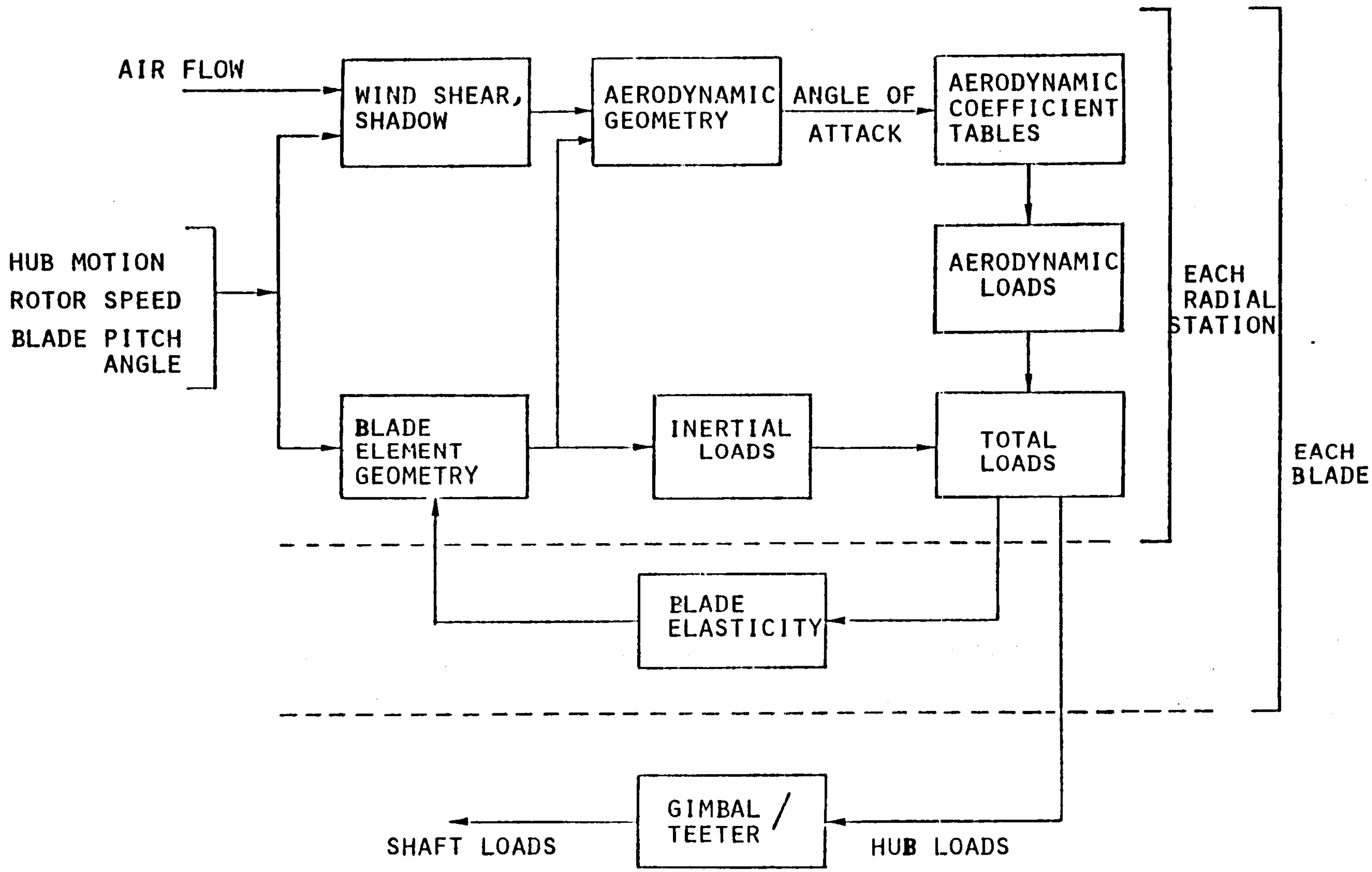

Figure 7. Simplified Schematic of Wind Turbine Rotor Model

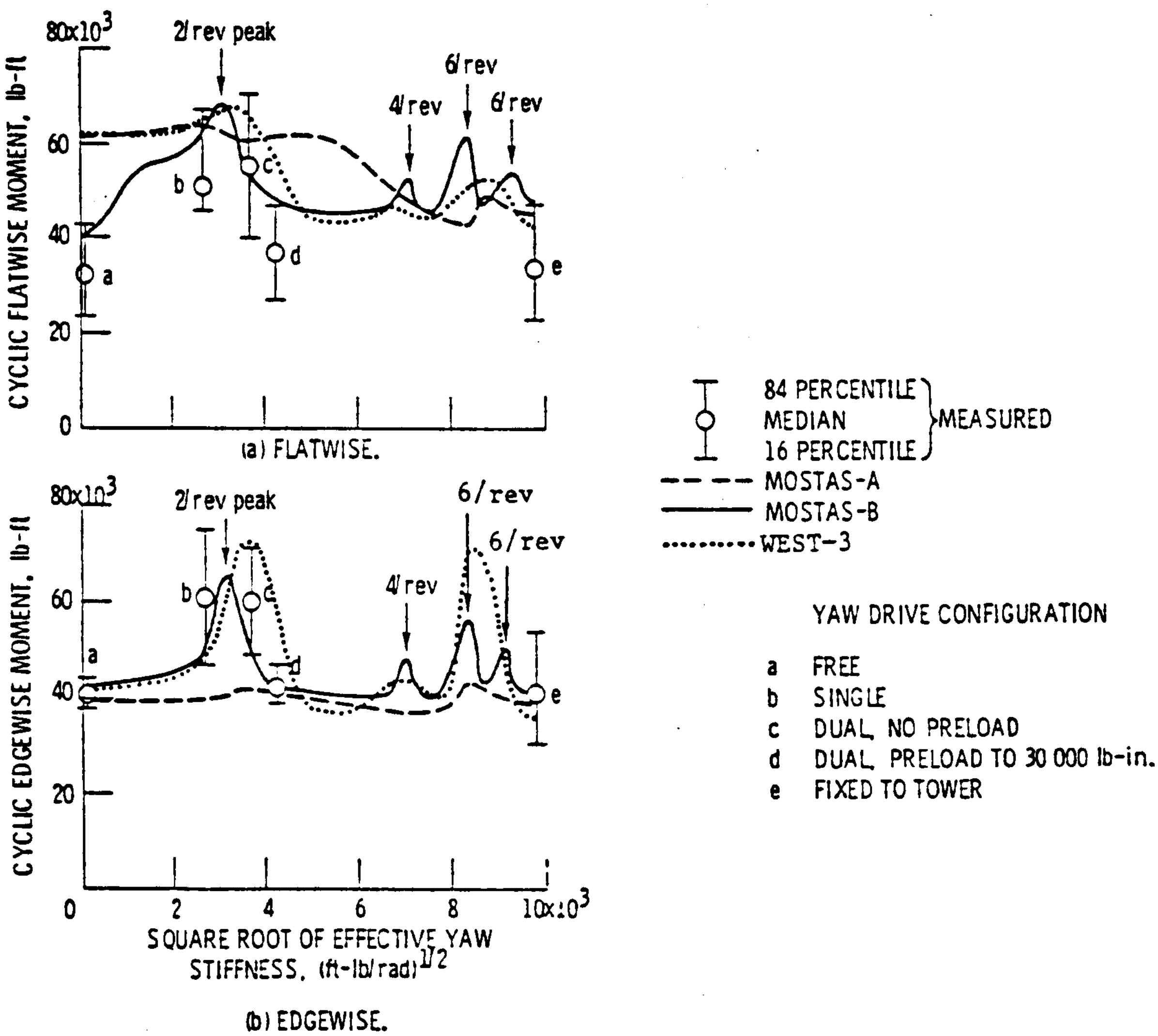

Figure 8. Blade Cyclic Bending Moments as Functions of the Square Root of Effective Stiffness of the Yaw Drive. (Station 40 Loads)

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16. Abstract

This report is a summary description of WEST-3, a new real-time wind turbine simulator developed by Paragon Pacific Inc. WEST-3 is an all digital, fully programmable, high performance parallel processing computer. Contained in the report are descriptions of the WEST-3 hardware and software. WEST-3 consists of a network of Computational Units (CUs) working in parallel. Each CU is a custom designed high speed digital processor operating independently of other CUs. The CU, which is the main building block of the system, is described in some detail. A major contributor to the high performance of the system is the use a unique method for transfering data among the CUs. The software aspects of WEST-3 covered in the report include, the preparation of the simulation model (reformulation, scaling and normalization), and the use of the system software (Translator, Linker, Assembler and Loader).

Also given in the report is a description of the wind turbine simulation model used in WEST-3, and some sample results from a study conducted to validate the system. Finally, efforts currently underway to enhance the user friendliness of the system are outlined; these include the 32-bit floating point capability, and major improvements in system software.

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