GRUMMAN WS33 WIND SYSTEMS

Phase II - Technical Report

Prototype Construction and Testing

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FEDERAL WIND ENERGY PROGRAM

Contract No. DE-AC04-76DP03533

ABSTRACT

In January, 1978 Grumman Energy Systems, Inc. was awarded contract No. PF71787-F, Development of an 8 kW Wind Turbine Generator. Administered by the Rocky Flats Wind Systems Program which is managed by the Rockwell International Corporation for the U.S. Department of Energy, the contract covered a two phase program to develop an 8 kW small wind energy conversion system (SWECS). Phase I involved design of the unit and was reported in a separate report. This report documents work in Phase II, Prototype Fabrication and Testing. The completed prototype unit was delivered to the Rocky Flats Wind Systems Test Center in December, 1979.

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1.0 INTRODUCTION

In March 1979, Grumman Energy Systems, Inc. commenced the second phase of Contract No. PF71787-F, "Development of an 8 kW Wind Turbine Generator". The Statement of Work called for fabrication and pre-delivery testing of one prototype unit and tower.

The Grumman Windstream 33 (WS 33) is a three bladed, down wind machine (see Figures 1 and 2) designed to interface directly with an electrical utility network. The initial design specification required an 8 kW production capability at 20 mph. The machine as finally designed and fabricated however, is rated at 15 kW at 24 mph and peak power of 18 kW at 35 mph. Single or three phase electric power can be generated and interfaced with a 110, 240 (208) or 480 volt (60 cycle) electrical grid. Voltage compatibility is achieved through generator modification or synchronizing transformers. Utility compatible electrical power is generated in winds between a cut-in speed of 9 mph (4.0 m/s) and a cut-out speed of 35 mph (15.6 m/s) by using the torque characteristics of the unit's induction generator combined with the rotor aerodynamics to maintain essentially constant speed. The induction generator chosen for the 8 kW prototype (Westinghouse 284T) utilizes a narrow slip range (3%) to achieve full power. This means the unit with its 25.1:1 gearbox will cut-in at about 72 RPM with full power being generated at a little above 74 RPM. A blade pitch control system positions the rotor at a coarse pitch (27°) for start-up; fine pitch for normal running; and a feather position for shut-down. The pitch control system incorporates a primary actuator for normal operation with a back-up, secondary actuator for emergency operation. Blade angle is changed by push-rod movement through the main shaft and into the hub where a spider-assembly, three torque links and crank arrangements transfer this motion into rotational motion on the blade stubs. Operation of the machine is controlled by a self-monitoring, programmable logic microprocessor.

Figure 2 shows the general arrangement of the machine as presented and approved at the Phase I Final Design Review. During fabrication of the prototype, a small number of detail design modifications were incorporated to facilitate production. These changes involved material substitutions due to availability (i.e. 4130 steel for Corten Steel) and had no effect on functional operations or representations. They were:

Component		Substitution	Reason
Rotor Hubs	-	Substitute 4130 steel for Corten Steel	Availability
Tower	-	Substitute Corten Steel (Rolled) for Corten Tube	Availability
Strongback	-	Thicker Corten Steel in Deck	Availability

The unit, as delivered to Rocky Flats, is depicted in Figure 3.

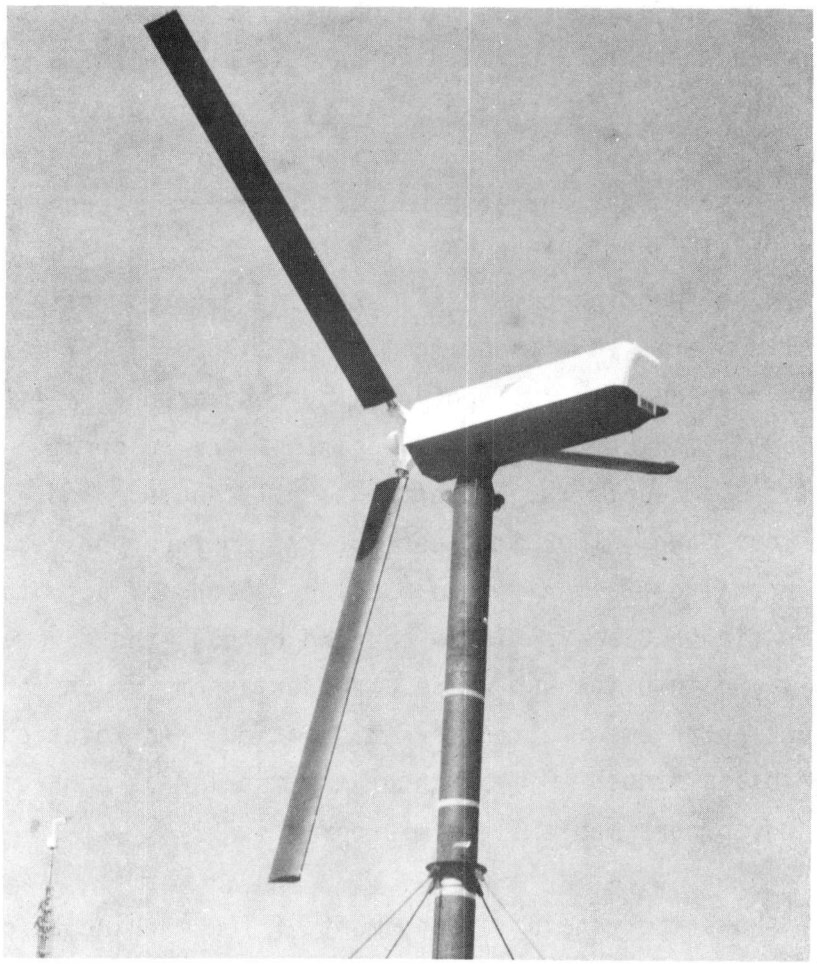
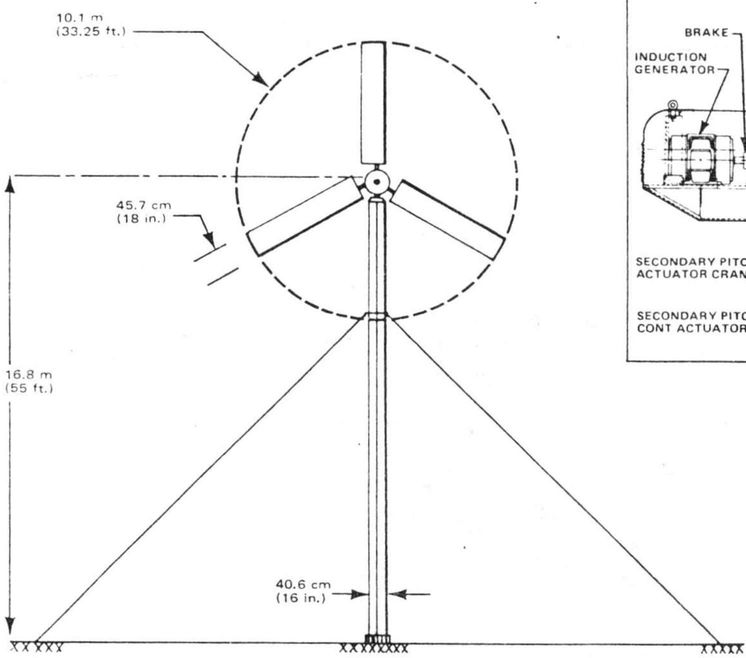
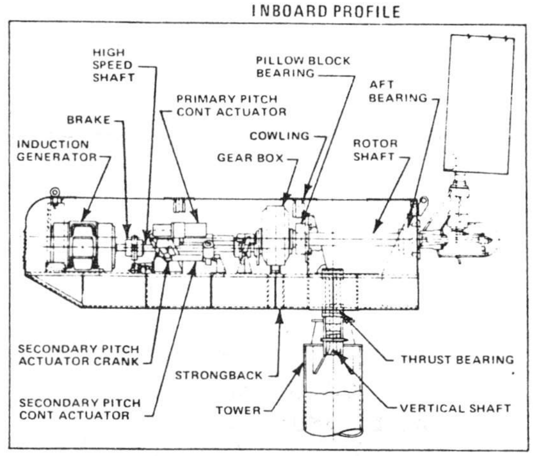


Figure 1 The Grumman Windstream 33



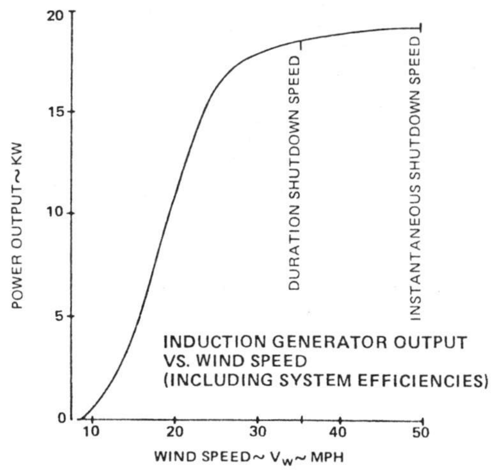


WINDSTREAM 33 CHARACTERISTICS

Induction Generator Rating	20 KW
Induction Generator Speed Range	1800-1860 R.P.M.
Gearbox Ratio	25.1 : 1
Rotor Speed	74.1 R.P.M.
Rotor Diameter	33.25 ft.
Rotor Solidity	0.0615
Blade Chord	1.5 ft.
Power Coefficient, Max ($C_{P\,MAX}$)	0.38*
Tip Speed Ratio at $C_{P\,MAX}$	5.25*
Wind Speed at $C_{P\,MAX}$	17.0 M.P.H.
System Efficiency at $C_{P\,MAX}$	83%
Output Power at V_W = 24 M.P.H.	15 KW*
Rotor Coning Angle	3 1/2°
Rotor/Nacelle Assembly Wt.	2,589 lb.
Drive Axis Height	55 ft.
Tower Section	16.0", 0/DIA, 3/8" Wall.
Guy Base	80 ft.

*PREDICTED

Specifications subject to change without notice



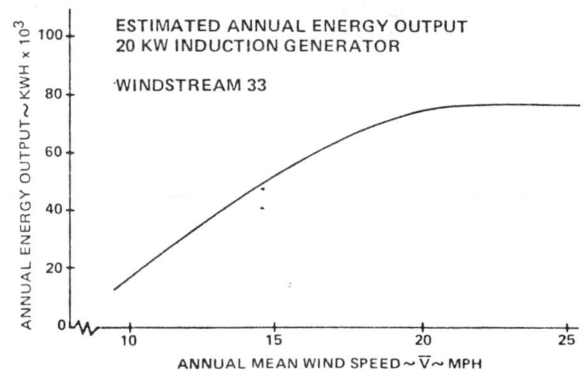


Figure 2 Grumman 8 kW Characteristics

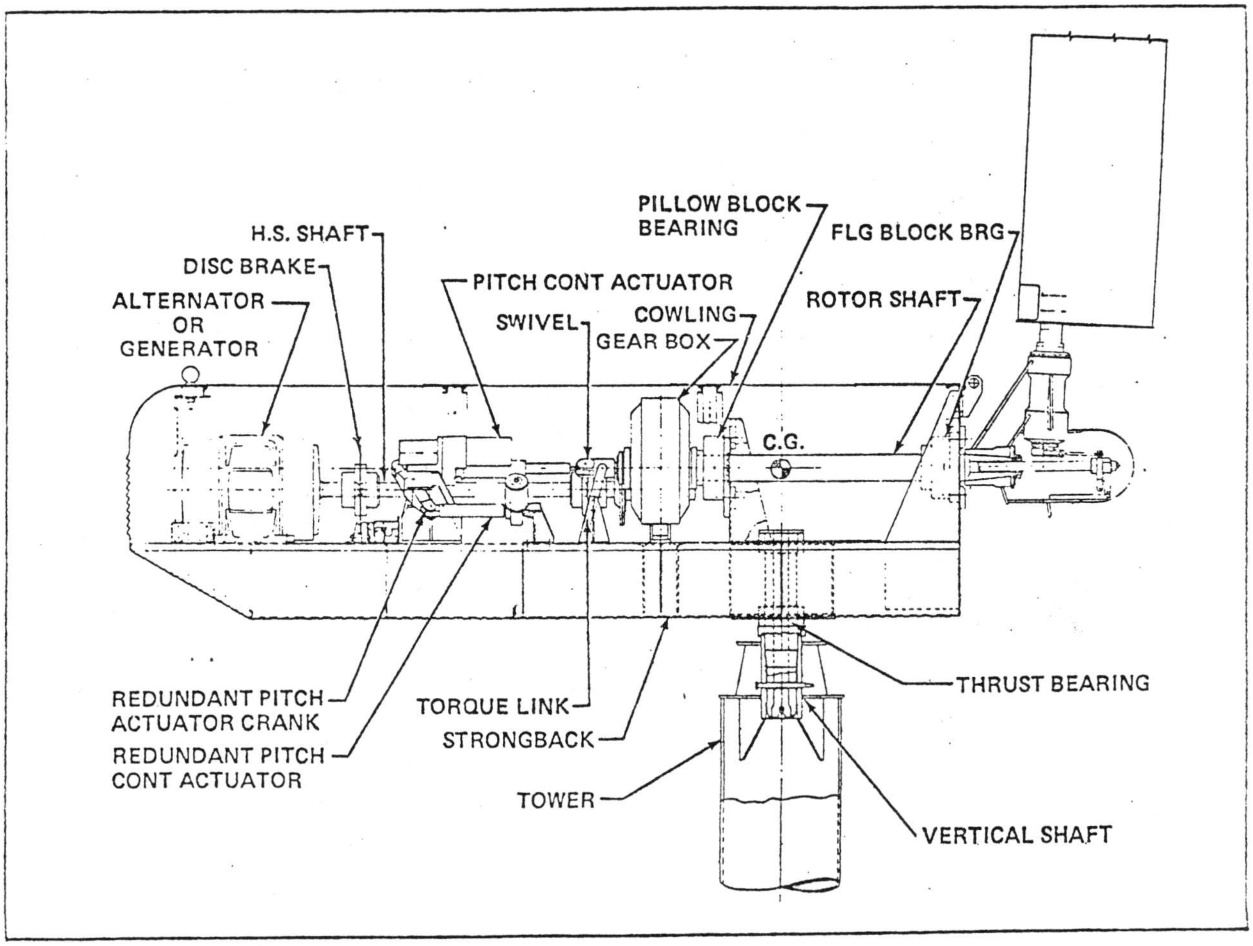


Figure 3 Critical and Final Design Review Prototype System

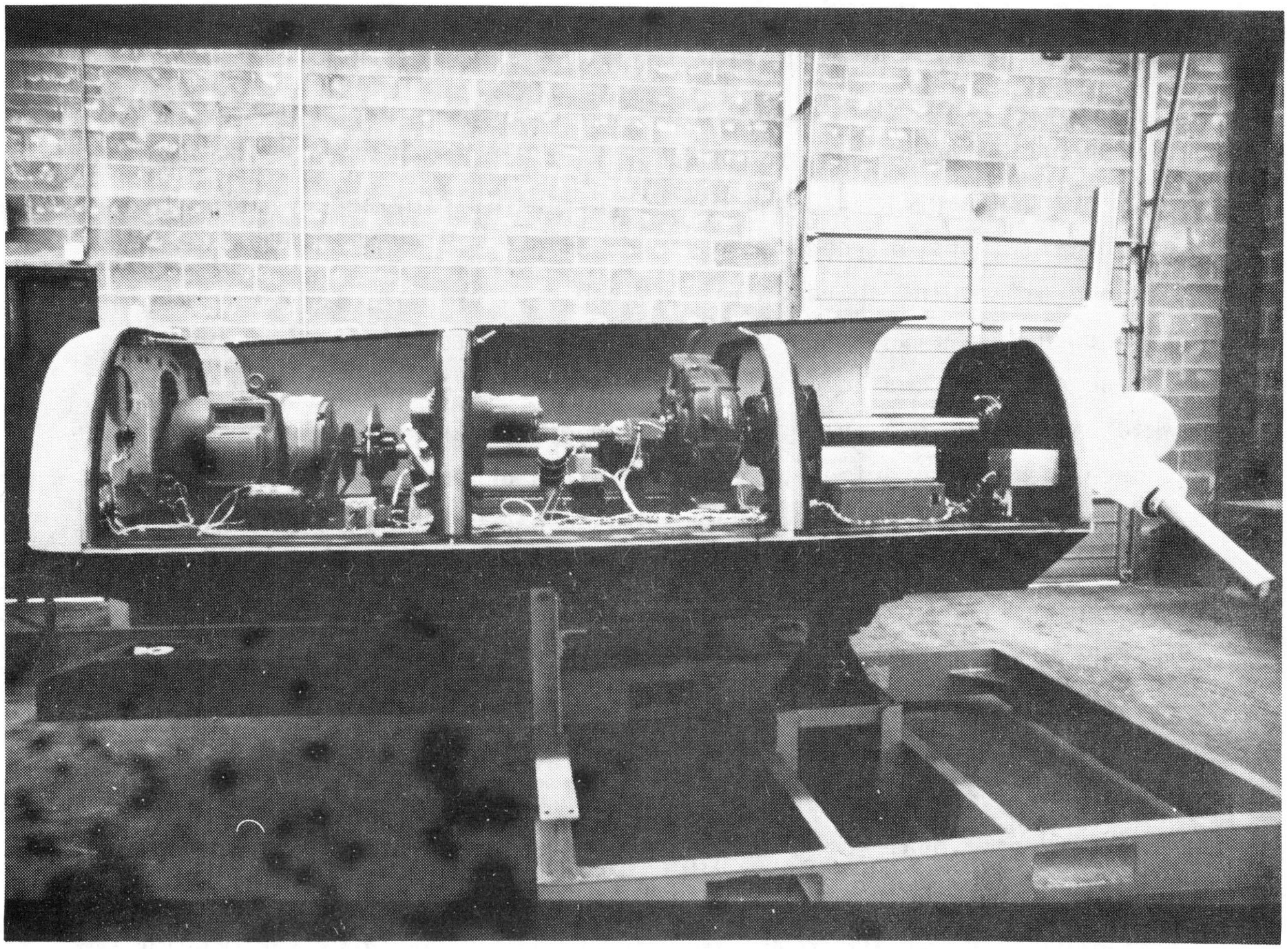


Figure 4 Prototype Configuration As Delivered to Rocky Flats

2.0 PROTOTYPE CONFIGURATION

2.1 SYSTEM DESCRIPTION AND OPERATION

The WS-33 is designed to operate in parallel with an electric utility grid network. It provides constant frequency, constant voltage, and 3Ø ac power at varying levels between a 9 mph (4.02 m/sec) cut-in speed to a 35 mph (15.6 m/sec) cut-out speed. Rated at 15 kW at 24 mph, the WS 33 is predicted to produce 32,000 kWh/year in an annual mean wind speed of 12 mph (5.4 m/s). Peak power is 18 kW at 35 mph.

Power is generated by a 240/480 volt, 3Ø, 60 Hz induction generator with a 20 kW capacity. Synchronous current is provided by maintaining essentially constant generator speeds of between 1800 and 1835 rpm at all operating wind speeds. This is achieved by using the pull-out torque characteristics of the induction generator in combination with the aerodynamic characteristics of the rotor. An induction generator, which is in essence an induction motor driven mechanically by an outside source, is characterized by its ability to produce constant frequency and voltage when run above synchronous speed up to its break-away torque limit. Up to this point the generator resists the mechanical power input with progressively increasing torque levels. The aerodynamic characteristics of the rotor are such that it performs with maximum efficiency or power coefficient when operating at a specific tip speed ratio (i.e. the relationship of the speed of the rotor blade tips to the speed of the ambient wind). If the rotor is constrained to a nearly constant rotational speed as wind speeds increase, its power coefficient is reduced but the net power output is increased because of the additional energy provided by the wind. The operating principle of the machine may therefore be described as follows: when cut-in wind speeds are experienced the motor is free to spin up to its nominal rotational speed of 72 rpm, driving the generator at 1800 rpm by means of a gearbox. At this speed the generator is on the borderline between running as a motor or a generator; a motor if deriving power from the utility, or a generator if drawing mechanical power from the wind.

As the wind increases, the rotor turns slightly faster causing the generator to produce more power and at the same time the generator applies an increasing amount of resistive torque to the rotor effectively controlling its speed. This changes the tip speed ratio at which the rotor is operating which, in turn, changes its efficiency - increasing efficiency up to 17 mph and reducing it thereafter. At 35 mph, the generator is at full power. The machine is automatically shut down if sustained winds are experienced above this value.

The machine has a three bladed, down wind rotor, 33-1/4 feet in diameter. The individual blades are extruded aluminum alloy with a modified NACA 644 421 airfoil section. The blades are adjusted in pitch by a dual (redundant) pitch actuator system controlled by a solid state programmable logic controller, the Microprocessor Control Unit (MCU). The MCU directs all functions of the unit. The overall weight of the nacelle and rotor assembly including the blades is 2,589 pounds. The blades weigh 185 pounds each.

The rotor pitch control system consists of redundant, electrical, linear actuators operated by the MCU and appropriate push rods and bellcranks. The primary actuator, 115V, 60 Hz, is capable of moving the blades from the high speed run to the feather position in 5 seconds. Actuator travel is determined by limit switches. This actuator also is used to position the blades to 27° for machine start-up. The 27° blade position is determined by a pulse generator within the actuator which drives logic circuits within the MCU to control actuator movement.

3.0 PROTOTYPE FABRICATION

The 8 kW prototype was assembled at the GESI plant in Bohemia, Long Island and functionally tested prior to delivery to Grumman's Bethpage facility for installation and operational testing.

3.1 SYSTEM COMPONENTS

3.1.1 Make or Buy Decisions

When approval was received at the final design review to proceed with prototype construction, Grumman established a team to oversee and coordinate fabrication schedules. The team consisted of personnel from:

- Purchasing
- Manufacturing Methods
- Scheduling
- Engineering

The team reviewed the fabrication methodology for each component and where items were direct purchased parts, purchase orders were issued immediately. Where parts required sophicated machining, Grumman's capabilities and schedules were measured against outside vendors' cost and delivery estimates. Make or buy decisions were made based on these findings (Table 1).

The majority of the structural and mechanical components were subcontracted to local machine shops and sheet metal parts fabricators. Vendor performance was satisfactory, although some schedule delays were experienced in the manufacture of the strongback, hub and nacelle covers. These delays were, in general, associated with the use of soft tooling typical for prototype parts fabrication. In some instances, minor modifications were incorporated into the design to permit the use of alternative manufacturing methods. Delays were also minimized by selective use of the Grumman Aerospace machine shop facilities.

3.1.2 Component Tracking And Liaison

Each component, whether manufactured outside or made in-house, was tracked to the purchase order schedule. This tracking was reviewed on a weekly basis until parts were within a week of delivery. Parts were then tracked to a daily schedule.

Component	Make or Buy	Reason
Hub	Buy then Make	Cost then Schedule
Strongback	Buy	Cost
Shaft - Low Speed	Buy	Cost
Hub Component Parts	Make	Cost
Shaft - High Speed	Buy	Cost
Bearing Supports	Make	Cost & Schedule
MCU (Microprocessor Control Unit)	Make	Cost & Schedule
Gear Box	Buy	Schedule

Table 1 Fabrication/Purchase Findings

Components were also classified as to complexity. Items that were deemed complex were assigned a liaison engineer to insure that each process was completed correctly.

3.1.3 Component Inspection and Repair

When delivered, each component was compared to its associated drawing or specification prior to being placed in stock. Any discrepancy was noted and routed to the appropriate engineer for disposition.

3.2 PROTOTYPE ASSEMBLY

Assembly of the prototype was straightforward and presented no major problems. Some difficulty was originally experienced with alignment of the generator and gearbox due to a slight distortion in the welded structure of the strongback. This was corrected by selective use of shims under the generator mounting. The unit was built up in the following sequence, illustrated in Figure 5.

A. Assemble pivot shaft to strongback and install on workstand.

B. Install low speed shaft and bearings.

C. Install Gearbox.

D. Install high speed shaft, coupling, brake disc and generator.

E. Install caliper brake and operating cable. Install pitch control push rod.

F. Install primary and secondary actuator and mechanism. Assemble blade stubs and hub and mount on drive shaft. Install hub pitch control mechanism.

G. Install permanent magnet generator and electrical components.

H. Install wiring harness. Install nacelle cover frames.

I. Functional Testing (see Paragraph 3.4).

J. Install nose piece and access doors.

K. Install hoist beam and remove unit from stand for crating.

To accommodate machine fabrication at reduced or minimum planned rates, six positions were developed at which assembly could be performed. Figure 6 illustrates the anticipated flow in such instances.

3.2.1 Assembly Operation Arrangement/Crew Size

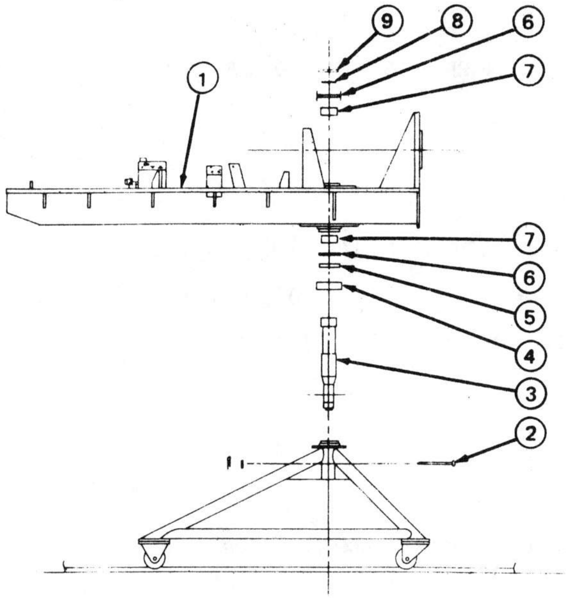
The assembly/checkout operations were accomplished at 11 positions which were established based on specialized tooling and test equipment requirements for individual operations. Operations performed at positions A, C and F (Figure 5) were primarily accomplished by a single operator, with limited assistance required for some handling/installation tasks. The remaining operations were accomplished with two men.

Subassembly of the gear box, high-speed shaft, and rotor hub were accomplished as bench operations by a single operator.

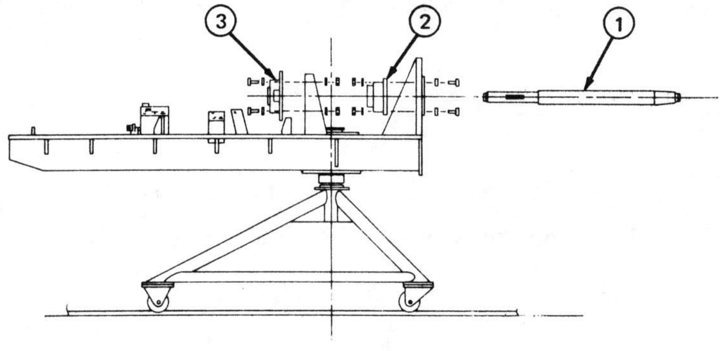
3.2.2 Tooling And Test Equipment

The tool required for assembly/checkout operations was a holding stand and work dolly used to support the strongback for all operations performed.

The work dolly was designed to support the strongback on its pivot shaft and the cantilevered portion of the strongback during the assembly, installation, and checkout operations. It was configured for optimum operator access and was equipped with casters to permit movement between work/test positions.

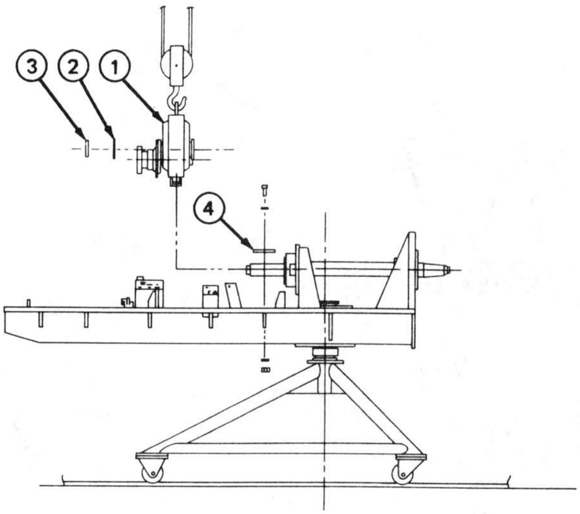


A.
1. STRONG BACK WELDED ASSEMBLY
2. PIVOT SHAFT LOCKING PIN
3. PIVOT SHAFT
4. THRUST BEARING RETAINER
5. THRUST BEARING
6. PIVOT SHAFT BEARING RETAINER
7. PIVOT SHAFT SLEEVE BEARING
8. SHIM(S)
9. PIVOT SHAFT RETAINER

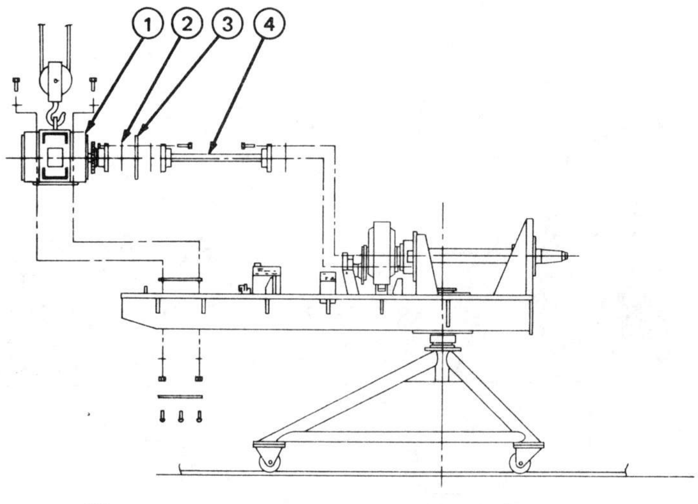


B.
1. LOW-SPEED SHAFT
2. AFT BEARING
3. FORWARD BEARING

Figure 5.a Assembly Flow for 8kW Prototype

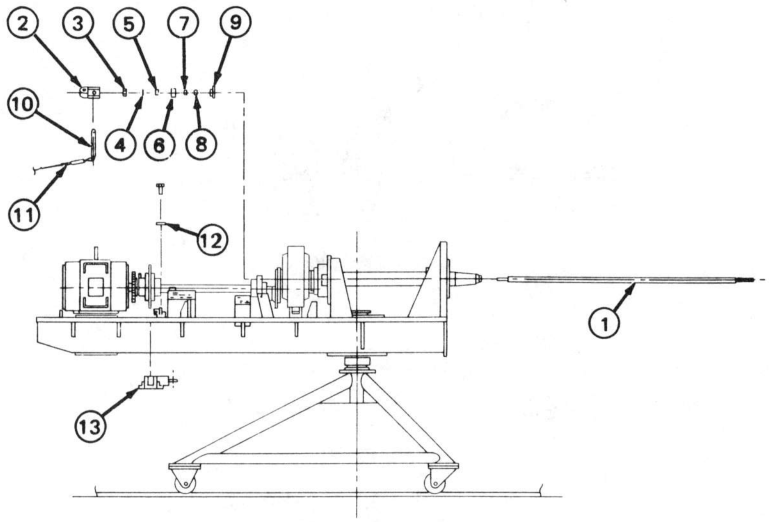


C. 1. GEAR BOX ASSEMBLY
GEAR BOX
BACK STOP
FAN
COUPLING RIGID HALF
TAPER LOCK BUSHING
KEY
TORQUE LINK
LINK ANCHOR FITTING
2. LOCKING RING
3. NUT
4. KEY



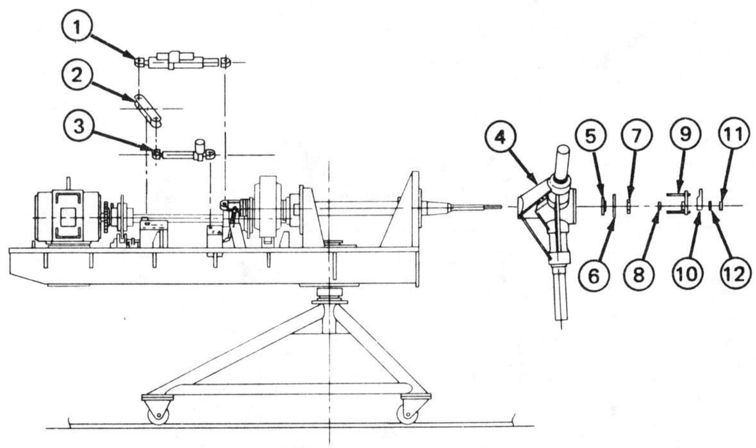
D. 1. INDUCTION GENERATOR ASSEMBLY
INDUCTION GENERATOR
PULLEY
COUPLING RIGID HALF
TAPER LOCK BUSHING
KEY
2. GASKET – 3 PLACES
3. BRAKE DISC
4. HIGH-SPEED SHAFT ASSEMBLY
SHAFT
COUPLING FLEX HALF – 2 PLACES
KEY – 2 PLACES

Figure 5.b Assembly Flow for 8kW Prototype



E.

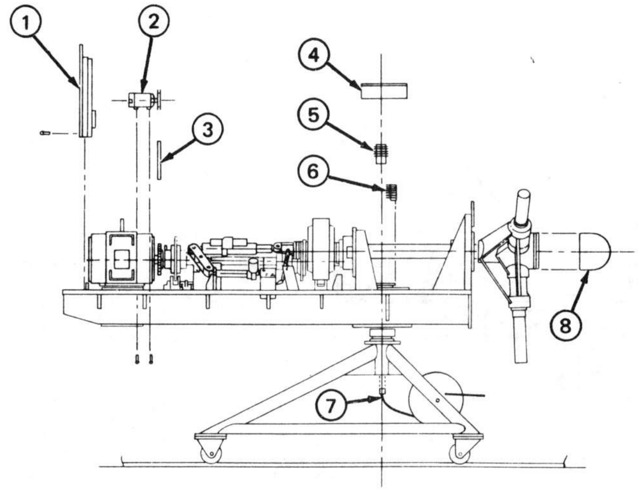
1. ROTOR PITCH ACTR ROD.
2. SWIVEL FITTING
3. NUT
4. WASHER
5. SPACER
6. THRUST BEARING
7. SPACER
8. NEEDLE BEARING
9. SWIVEL FITTING NUT
10. BRAKE ACTUATOR ARM ASSY.
11. CABLE ASSY
12. PULLEY
13. BRAKE CALIPER ASSY.



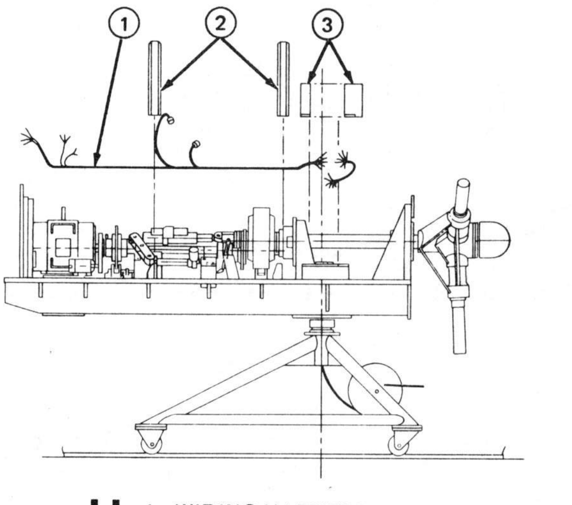
F.

1. PRIMARY ROTOR PITCH ACTUATOR
2. CRANK
3. SECONDARY ROTOR PITCH ACTUATOR
4. ROTOR HUB ASSEMBLY
5. BELLEVILLE WASHER
6. NUT LOCKING WASHER
7. ROTOR HUB NUT
8. WASHER
9. YOKE ASSY
10. TORQUE ARM
11. NUT
12. WASHER

Figure 5.c Assembly Flow for 8kW Prototype

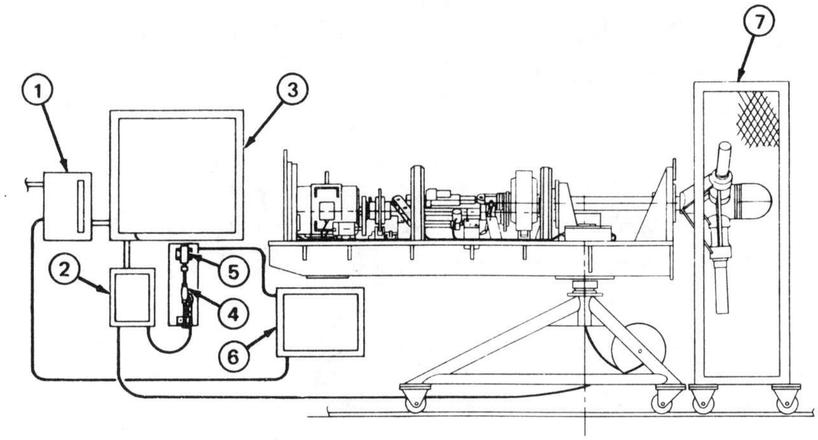


G.
1. FWD BULKHEAD ASSY
   BULKHEAD
   ELECTRICAL COMPONENTS
2. PERMANENT MAGNET GEN.
3. "DYNA-SYNC" BELT
4. NACELLE J-BOX
5. SLIP RING ASSY
6. BRUSH ASSY
7. TOWER CABLE ASSY.
8. HUB COVER



H.
1. WIRING HARNESS
2. COWLING FORMERS
3. SLIP RING COVERS

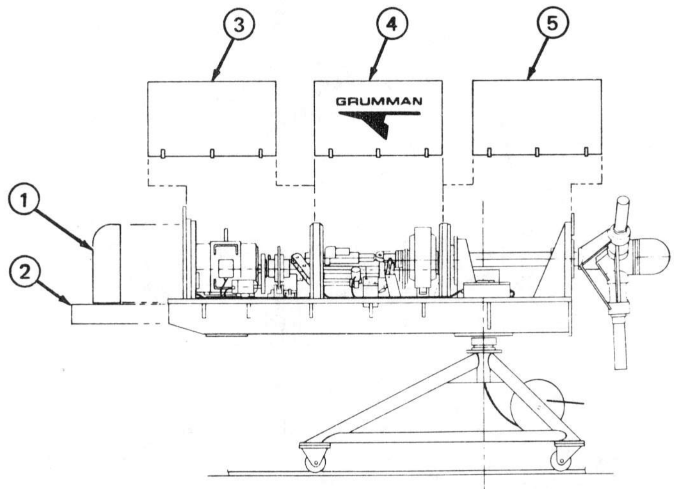
Figure 5.d Assembly Flow for 8kW Prototype



I.

1. UTILITY CONTROL BOX
2. STAND-IN TOWER J-BOX
*3. WINDSTREAM CONTROL BOX
*4. ANEMOMETER
5. WIND SYNTHESIZER MOTOR
6. AUTOMATED TEST PROGRAMMER
7. PROTECTIVE SCREEN

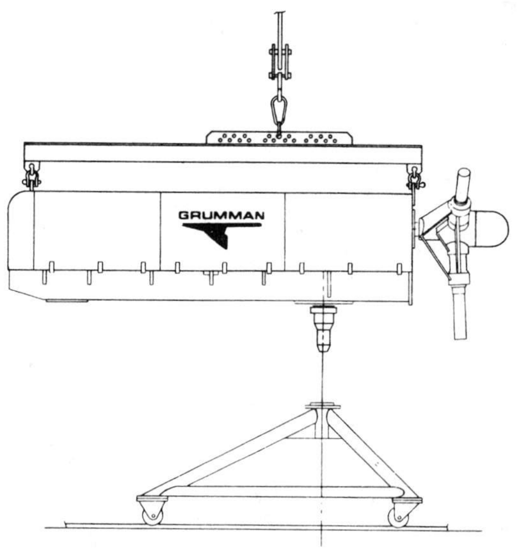
*TO BE SHIPPED WITH WTG SYST.



J.

1. NOSE PIECE
2. COOLING AIR LOUVER
3. FORWARD COWL
4. MIDDLE COWL
5. AFT COWL

Figure 5.e Assembly Flow for 8kW Prototype



K. COMPLETED MACHINE

Figure 5.f Assembly Flow for 8kW Prototype

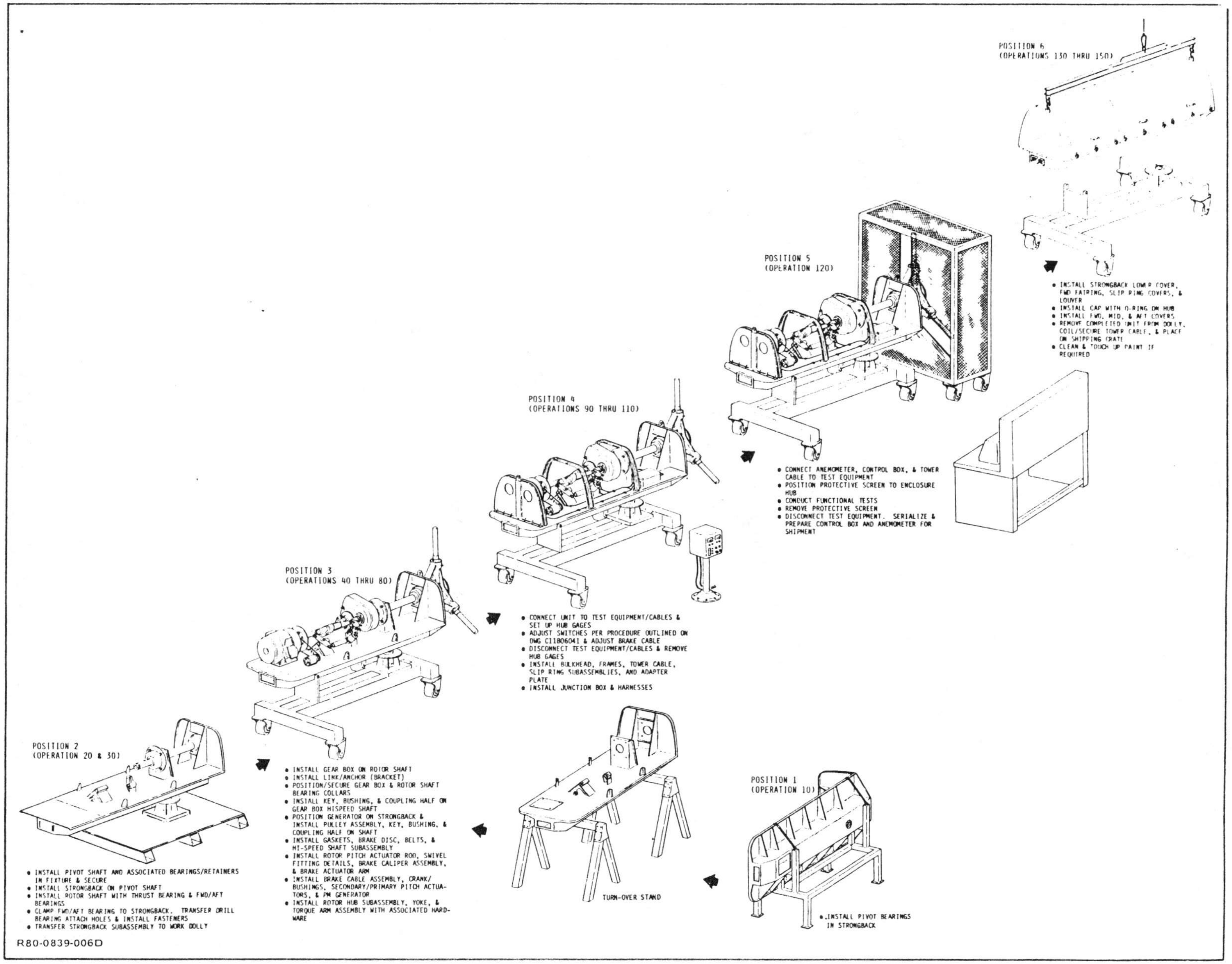


Figure 6 Assembley Flow at Minimum Planned Rate

Other design tools required were work stands for holding parts during assembly buildup, installation tools/gages, and slings for handling the strongback, rotor hub, and the completed wind turbine generator assembly.

Test equipment requirements are limited to the items needed in support of checkout operations. They comprise:

- Test stand with cable to provide electrical power for actuator drives during switch adjustment.
- Test bench with cables for connecting to control box, anemometer, and strongback tower cable for functional testing of the completed unit.

3.2.3 Facility Requirements

Approximately 2,600 sq ft of floor space was allocated in the facility for assembly/checkout of the wind system assemblies. This area was required to accommodate the 11 assembly/checkout positions as planned. It also provided for an adjacent floor/bench subassembly area for buildup of the gear box, high speed shaft, and rotor hub to permit optimum utilization of the two-man crew. Equipment requirements for this program consisted of a bridge-type overhead rail/hoist system (2,000 lb capacity)

3.3 ASSEMBLY INSPECTION PROCEDURE

During the assembly and check-out phase each sub-assembly and component was physically inspected to insure proper form and fit and compliance with the design drawings. In addition, each stage of assembly (Figure 5) allowed time for a general "housekeeping" (i.e. safety wire, adhesive, lubricants, fasteners, etc.) inspection. When the unit was complete, a ground run was made using the generator as a motor. All moving parts were again inspected to ensure that the dynamic clearances complied with the static readings taken previously. Special care was taken in adjusting the micro-switches associated with the feather and high speed run positions of the pitch control system.

Appendix A gives the original inspection procedures.

3.4 FUNCTIONAL TESTING

All mechanical and electro-mechanical components were bench tested prior to installation in the unit. The gearbox input and output shaft aignment was checked by installing the gearbox in a "slave" nacelle consisting of a strongback, drive train and induction generator. The generator was run as a motor and the wobble motion of the gearbox measured. The first gearbox tested was excessively noisy and had a pronounced wobble. A second gearbox was then tested and proved to be acceptable, having a low noise level and a wobble that was within the specified limit of $\pm$ 3/64 in. Power output of the generator at speeds above synchronous was checked against the manufacturer's specification on a dynamometer at the Grumman Aerospace Electrical Test facility.

Adjustment and functional testing of the complete system was performed during the final stages of the assembly process (see Paragraph 3.2). This operation consisted of the following:

- Adjust high speed run position limit switches so that all blade stubs are within $\pm$ 1/2° of the nominal high speed run position.
- Adjust limit switches to provide 92° feather position.
- Check that both primary and secondary actuators satisfactorily operate the pitch control mechanism with the machine at rest and running at full speed.
- Simulate loss of grid by spinning up the machine by hand and checking operation of the permanent magnet generator.
- Check action of parking brake.

- Using a "slave" control box, check shutdown operation due to malfunction.

- Safety wire all limit switches and repeat operational test of pitch control actuators.

3.5 TOWER FABRICATION

The original design for the prototype tower called for its construction from seamless CORTEN steel tube, swaged from 18 in. to 16 in. diameter. However, during the course of construction, it was found that the purchase cost of a small amount of this material was excessive. The tower was therefore redesigned to use rolled and seam-welded steel plate.

The prototype tower was designed to interface with its foundation by means of a tower base flange with holes to match a pattern of bolts embedded in the concrete of the foundation. Subsequent to the manufacture of the tower, Rocky Flats made the decision to mount the tower on a universal foundation; an adapter was therefore made to permit the tower to be mated with the new bolt pattern.

4.0 PRE-DELIVERY TESTING

4.1 ACCELERATION SURVEY

Prior to delivery of the 8 kW prototype to Rocky Flats, the machine was installed and checked out for two weeks on the tower at Grumman's Bethpage wind systems test facility. During this period, an acceleration survey of the nacelle was performed, at Rocky Flats' request, to determine the machine's response to blade passage excitation. It was found that acceleration and deflections were relatively small and would not have any significant effect on the loading of the system.

Four accelerometers were mounted inside the nacelle allowing a determination of the accelerations, frequencies and displacements in the three orthogonal axes.

One accelerometer was mounted close to the vertical shaft to measure lateral acceleration. The other three accelerometers were mounted on a single black, 55.5 inches forward of the vertical shaft to measure lateral, fore-aft and vertical accelerations.

During routine system operation, readings were taken of the peak accelerations and associated frequencies. They were averaged and are presented in Table II.

TABLE II

Frequencies, Accelerations & Peak Deflections

Accelerometer Direction and Location	Frequency f_n (Hz)	Acceleration ($\pm$ g)	Deflection ($\pm$ in)
Fore-Aft: FWD	3.63	0.088	0.065
Vertical: FWD	3.83	0.200	0.133
Lateral: FWD	3.66	0.101	0.074
Lateral: AFT	3.65	0.037	0.028

It can be seen that the readings were similar in all three directions. The frequency in each direction (3.63 to 3.83 Hz) matches the frequency of the blade passage past the tower at operating speed. Excitation of the nacelle is obviously caused by the cyclic off-loading of the blade from tower shadow. Accelerations and deflections are relatively small and will not have a significant effect on the loading.

4.2 SECONDARY ACTUATOR

During the two weeks allotted for pre-delivery dynamic tests mostly calm winds were experienced at the Bethpage facility and only limited data could be gathered. The testing period was therefore extended, with Rocky Flats concurrence, to include tests during the predicted passing of Hurricane David and to gather more extensive performance data. Testing was started as the storm intensified at 7:35 a.m. on Thursday, September 6, 1979. Testing continued for about 40 minutes, during which time wind speeds occassionally exceeded 50 mph. At 8:12 a.m., the blades oscillated violently and the unit shut down. Subsequent investigation revealed the following damage to pitch control components identified in Figure 6.

	Component No.
° Fracture (lug tear-out) of the secondary actuator tube.	3
° Elongation of the actuator crank support around the top pivot pin hole.	2
° Indentation of the crank from contact with the primary actuator.	2
° Bending of the primary actuator threaded fitting.	1
° Each of the blade stub shaft links were bent and contact marks with stub shaft crank seen.	10

All of the listed damage is consistent with an initial failure of the secondary actuator, permitting travel of the control system beyond its design limit. The secondary loads were dynamic in nature, produced by bottoming the primary actuator onto the crank. Further support of this conclusion was derived from the strip chart. Prior to the failure, the strip chart showed a blade oscillation of 10^{0} range (at 4.5 Hz) -- a movement consistent with the elongation of the secondary actuator lug bolt holes (see Figures 7 and 8).

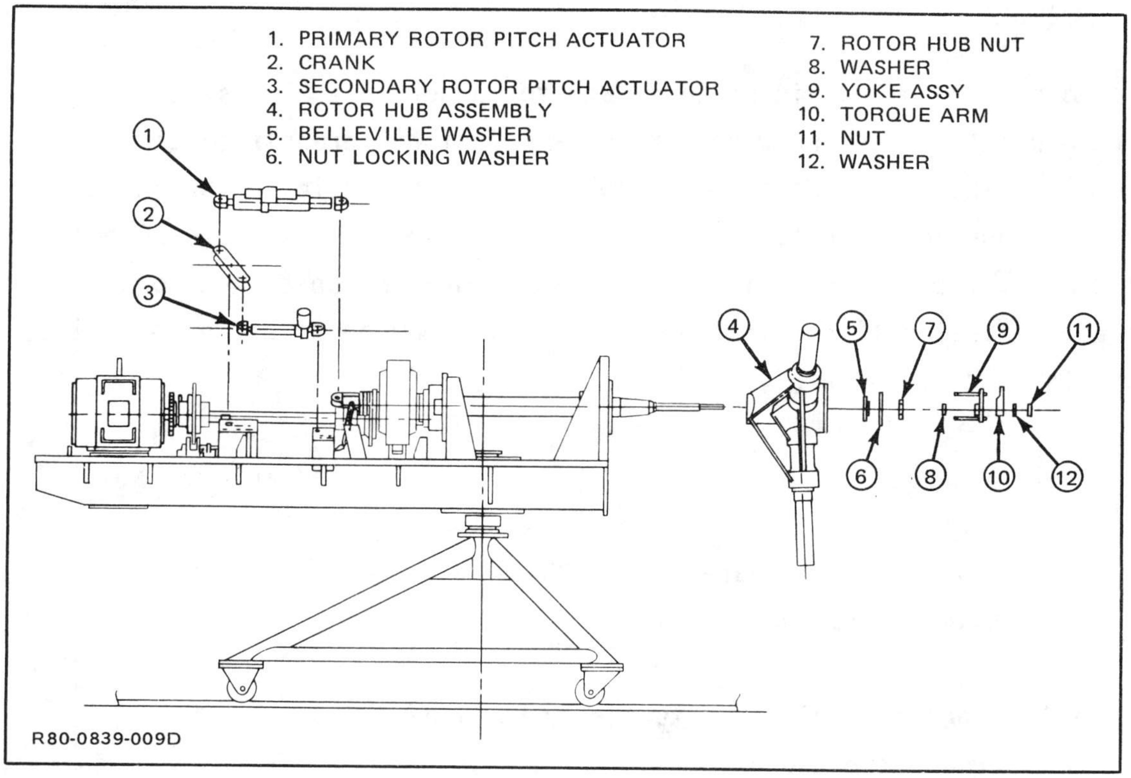


Figure 7 Pitch Control System Components

Based upon this initial evaluation it was decided to conduct appropriate failure analyses and initiate corrective measures. It was further decided that when these steps had been completed, the unit should be shipped immediately to the Rocky Flats facility to avoid further schedule slippage.

4.2.1 Pitch Control System Loads vs Actuator Capability

During the design of the pitch control system, a maximum design load of 1,100 pounds was derived. The secondary actuator was stated by the manufacturer to have a 100% duty cycle rating of 1,100 pounds operating; 25% duty cycle rating at 1,500 pounds operating and an ultimate strength of 3,800 pounds.

4.2.2 Failure Analysis

Control system loads were re-analyzed to determine if excessive loads could be induced by:

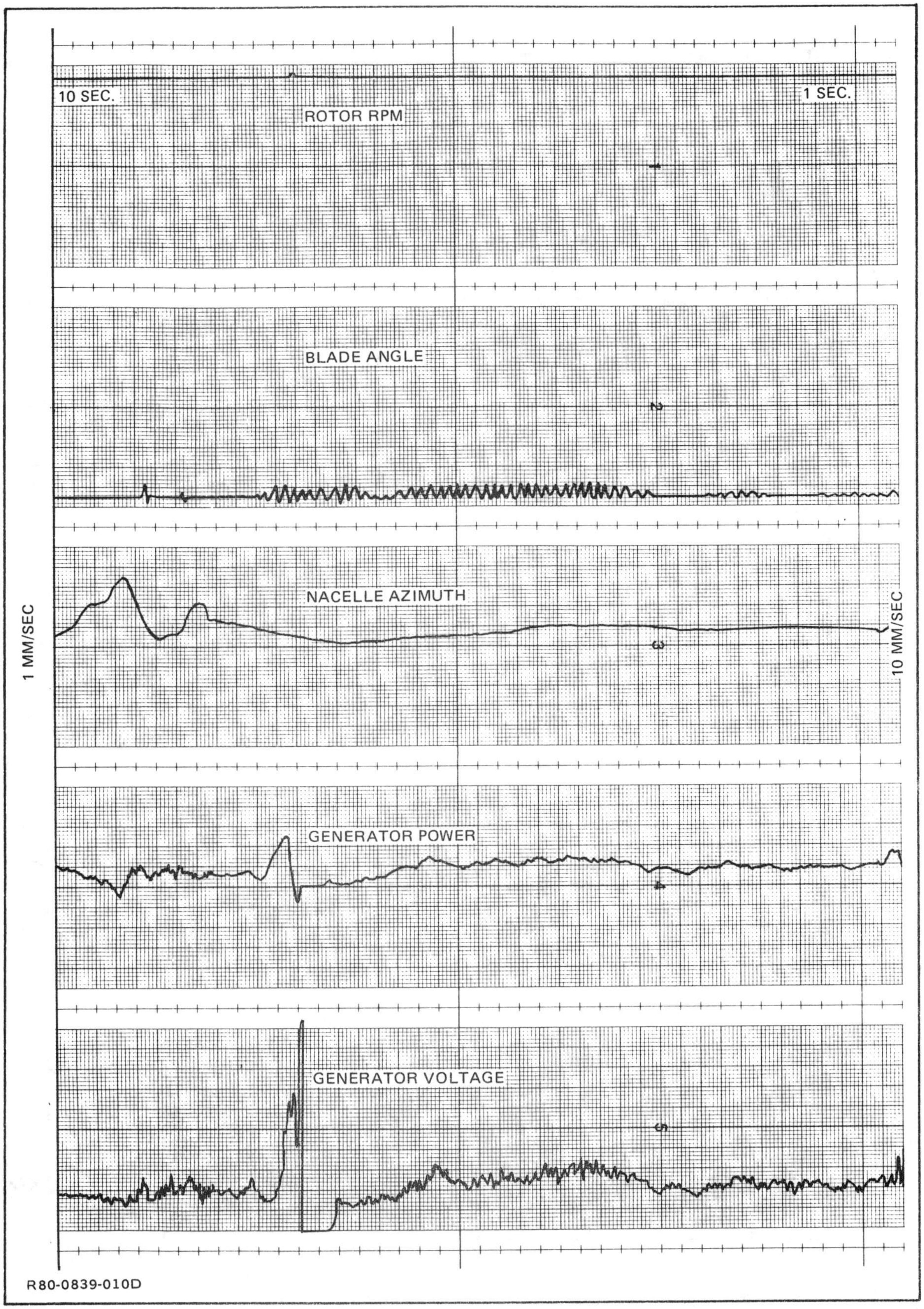


Figure 8 Blade Oscillation Prior To
Secondary Actuator Failure

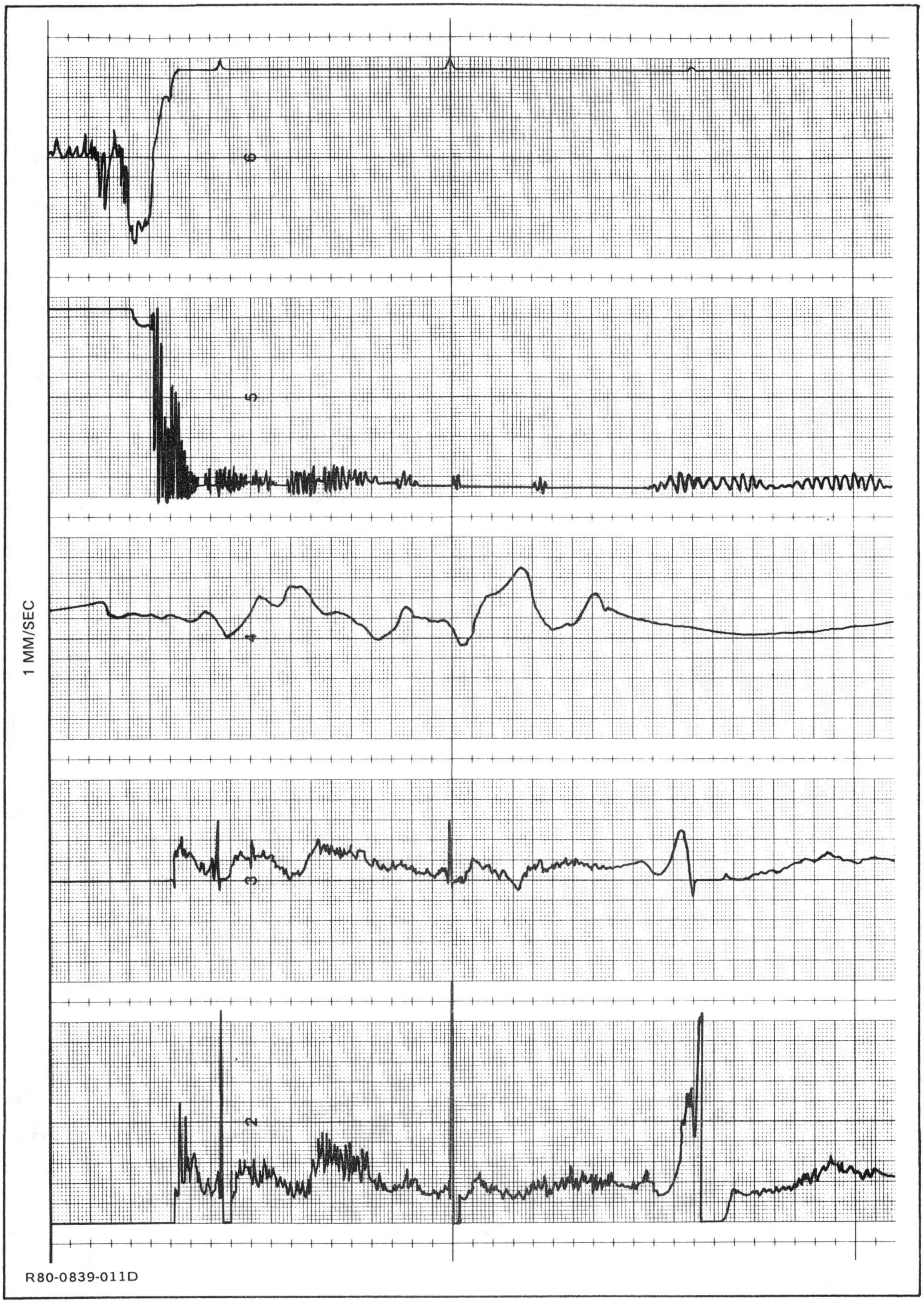


Figure 9 Strip Chart Recordings of Test

1. Dynamic loads applied to the pitch control system if the blades (supported by the pitch control system) should oscillate in pitch.

2. Static or dynamic loads applied to the pitch control system by highly stalled blades.

Each of these modes was analytically reviewed, and tested.

4.2.3 Dynamic Analysis

During the design phase the pitch control stiffnesses were analyzed and used as a blade support torsional flexibility. A flexibility of 8.52 x 10^{-6} rad/in. lb. was found giving a natural frequency of 15.7 Hz. This was well separated from the blade bending frequency over the operating range of the rotor.

Subsequent to the failure, this analysis was repeated using actual, "as built", dimensions. It was also found that the blade moment of inertia (polar) about the hinge axis was higher than that originally calculated. The analysis considered symmetrical and asymmetrical loading of the blades. The asymmetric loading was pronounced in introducing bending deflections into the long span pitch control rod, thus introducing a significant deflection. Also included in the analysis was theoretical system backlash. The system frequency was predicted to be between 5.5 and 8.6 Hz. As seen in Figure 9, these frequencies were in the range where flutter could possibly develop in very high winds. It was also appreciated that some of the pitch control system flexibilities may not have been fully described (such as the actuators) because of lack of information and the complexity of the structures. For this reason, ground vibration tests were conducted on the unit to determine actual control system natural frequencies. These tests revealed a higher frequency system than predicted and that flutter could not occur at wind speeds less than 170 mph.

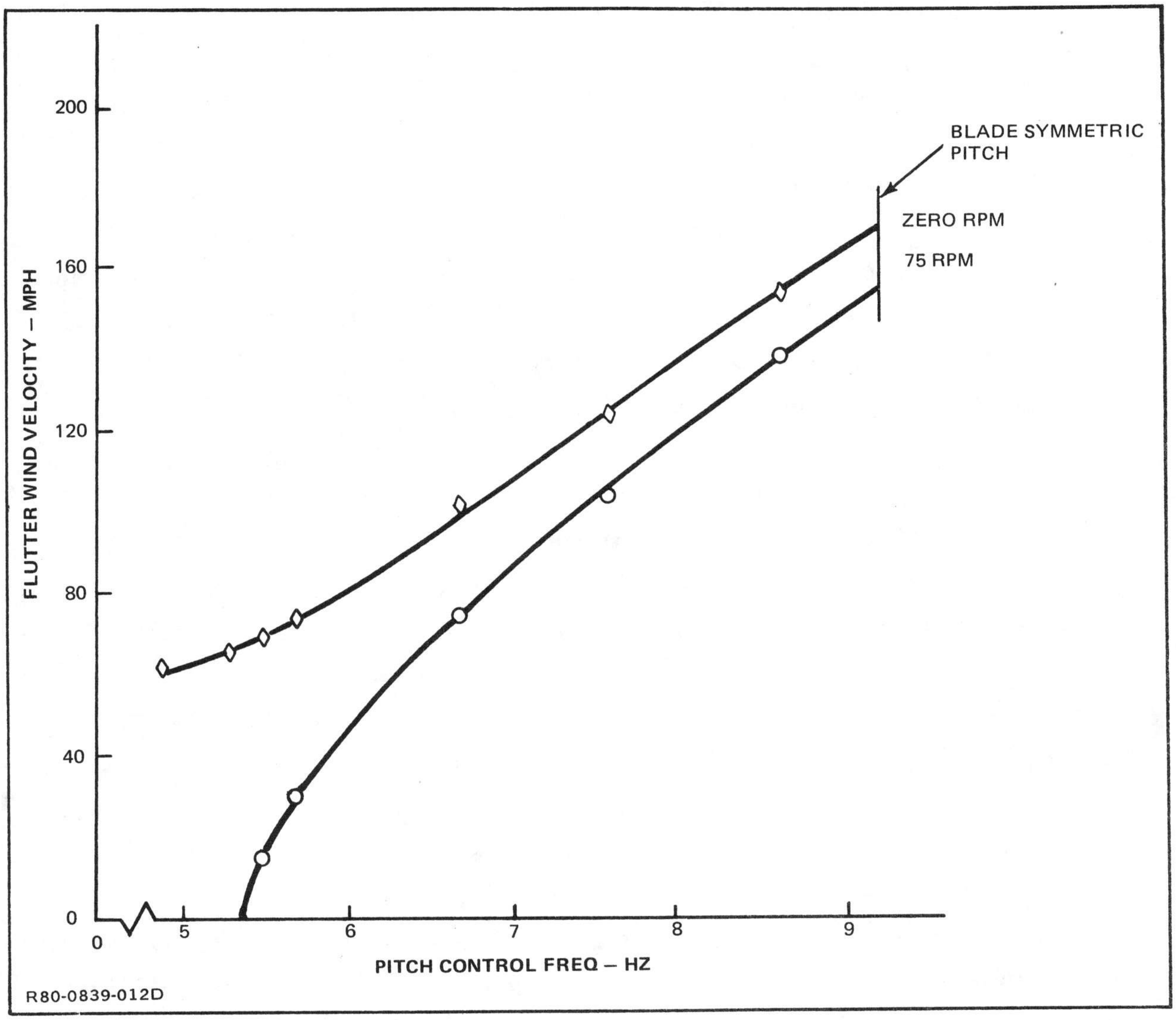


Figure 10 Flutter Speed vs
Pitch Control Frequency

4.2.4 Dynamic Testing

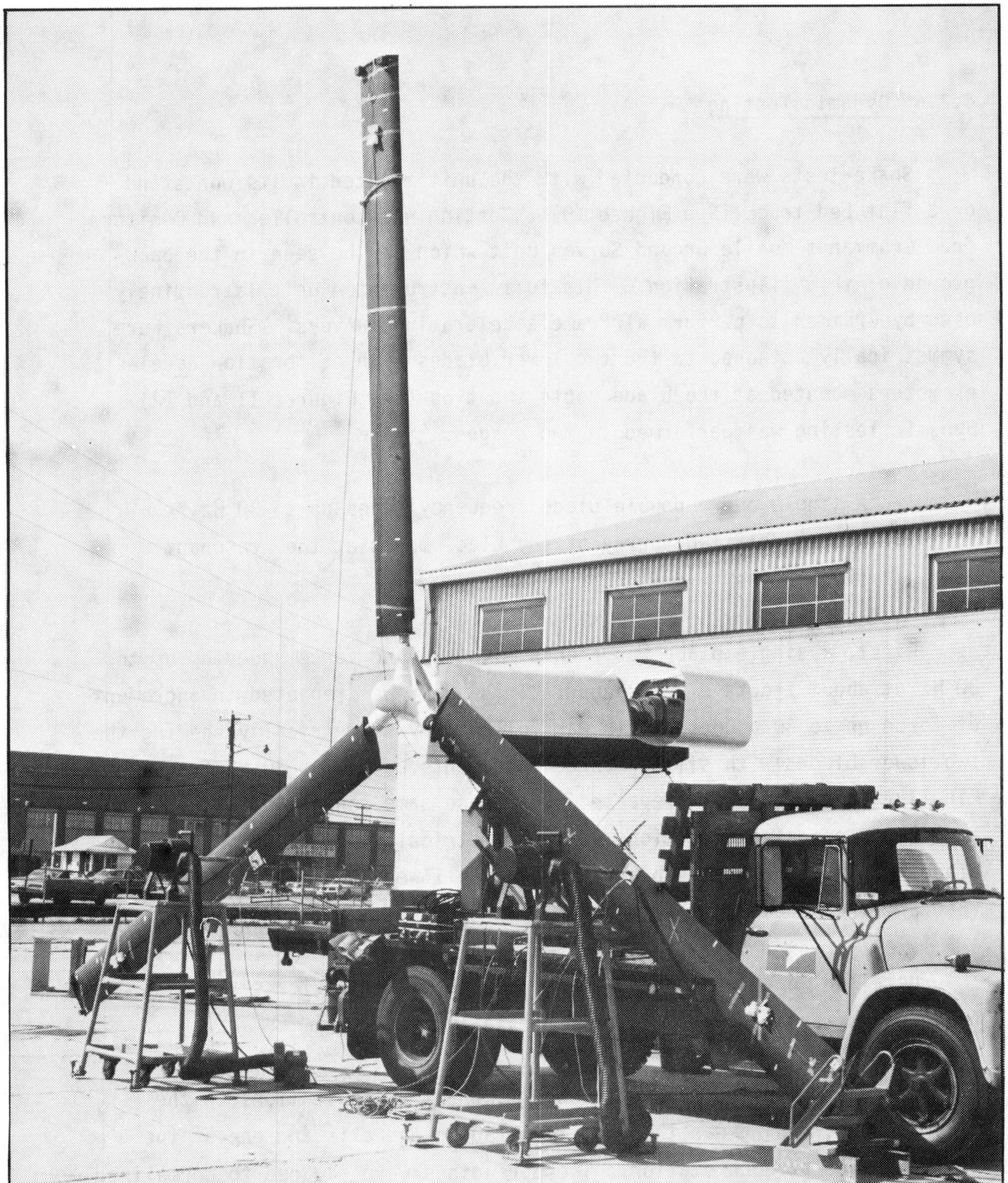
Shake tests were conducted with the unit mounted in its workstand on a flat bed truck (See Figure 10). Testing was controlled and monitored from Grumman's Mobile Ground Survey Unit which can be seen in the background of this illustration. This fully instrumented unit is routinely used by Grumman to perform airframe acceleration surveys. Shakers were symmetrically attached to the two lower blades with calibration accelerometers mounted at the blade roots and tips (see Figures 11 and 12). Dynamic testing was performed in two stages:

1. A single and a double blade frequency sweep up to 30 Hz.
2. A more detailed survey of the blade modes at the resonant frequencies.

First, a single blade was shaken with 5 pound force sweeping up to 30 Hz at about 1 octave per second. This sweep was repeated in increments of force up to 40 pounds. This was followed by symmetrically shaking the two lower blades with similar force increments up to the 30 Hz frequency. Finally, the sweeps were repeated over these same ranges but with forces applied in opposite directions (anti-symmetrically). Automatic plots of blade acceleration versus blade frequency allowed identification of resonant frequencies.

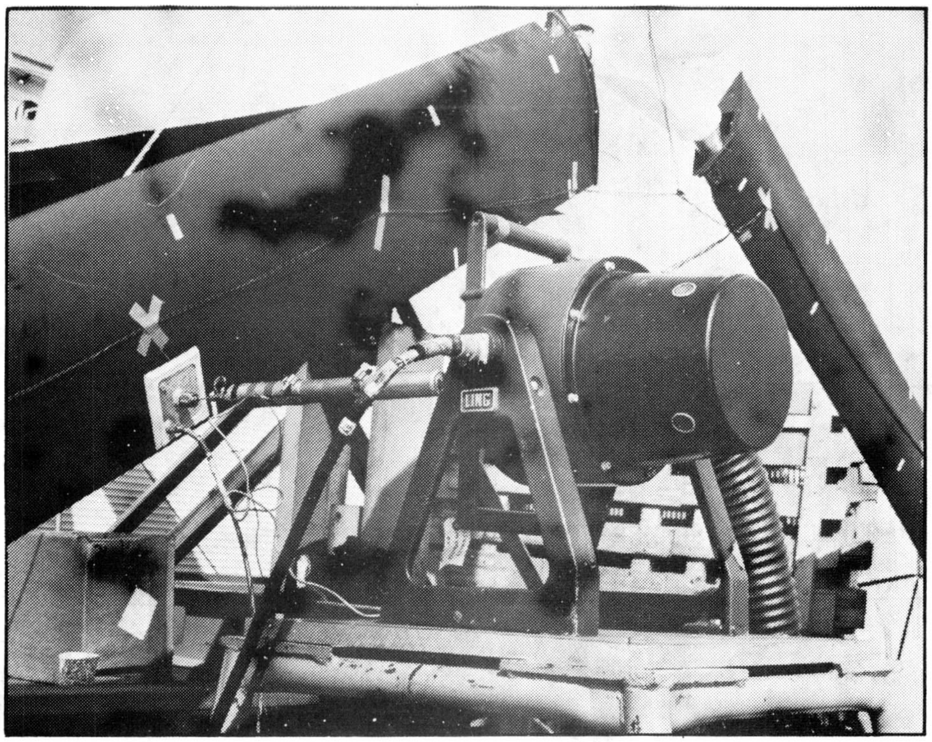
Detailed mode shape measurements of the blades at these resonant frequencies were made, as listed in Table III.

Readings of blade movements were taken at seven stations on the blades. One reading was taken at the blade hinge axis and one at the trailing edge at each station. These readings were reduced to normalized blade deflection, twist and the mode line for each mode. Results are shown in Figures 13 through 16.



R80-0839-013D

Figure 11 Dynamic Test Set-Up



R80-0839-015D

Figure 12 Shaker and Accelerometer Installation (1)

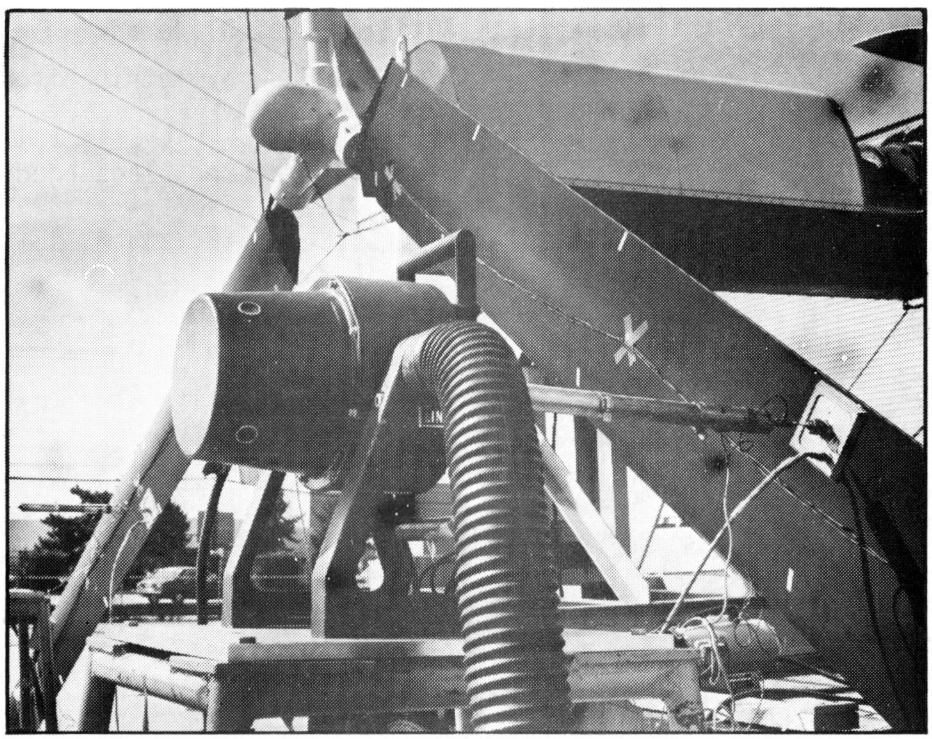


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Figure 13 Shaker and Accelerometer Installation (2)

TABLE III

Blade Mode Shape Measurements

MODE	RESONANT FREQUENCY (Hz)	SHAKER FORCE (lb.)	SHAKER DIRECTION	DESCRIPTION
1	3.06	11	Symmetric	1st Blade Bending
2	9.20	20	Symmetric	Blade symmetric pitch
3	12.30	20	Anti-Symmetric	Blade anti-symmetric pitch
4	21.80	20	Symmetric	2nd Blade bending

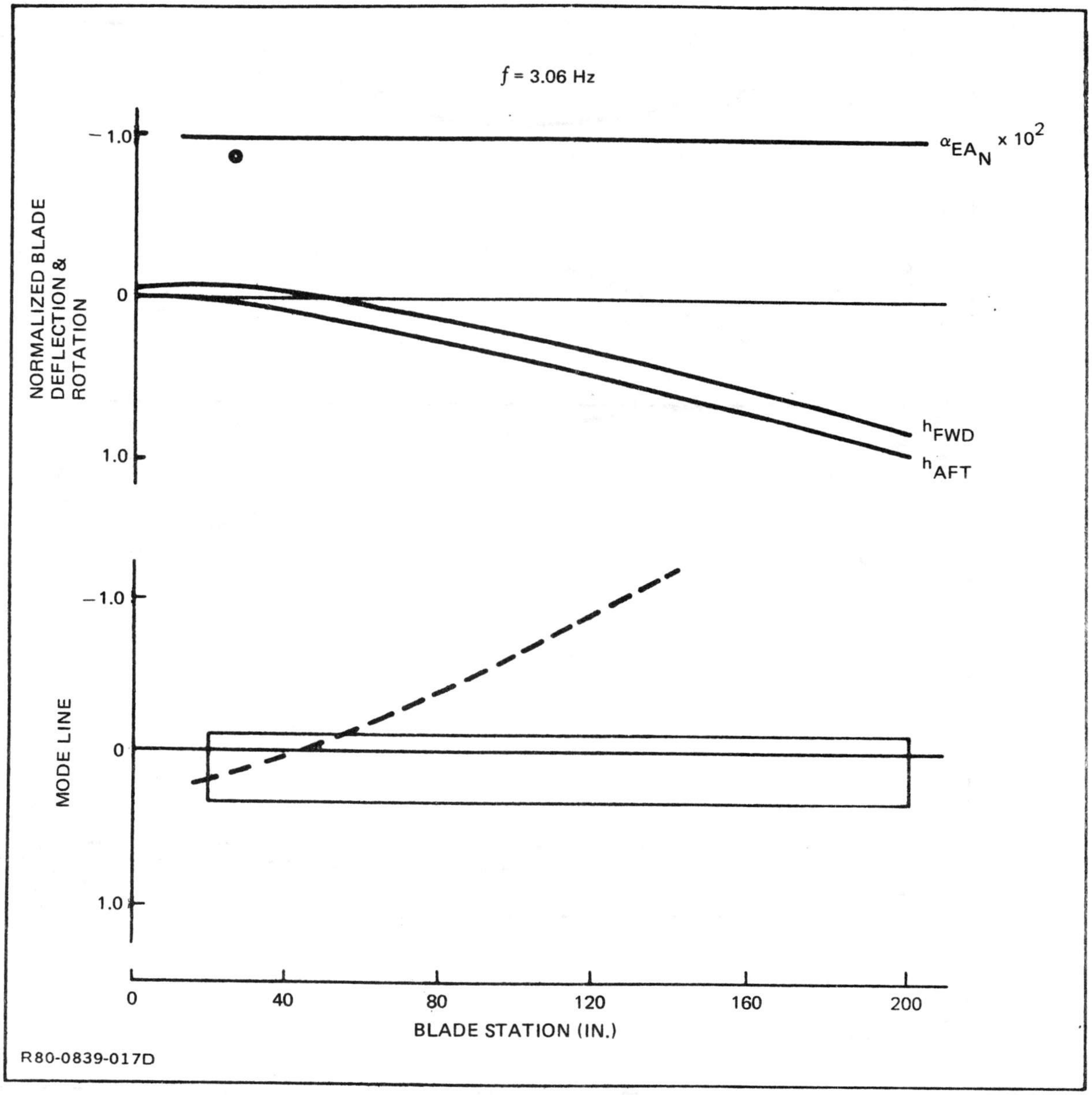


Figure 14 Mode 1 Pitch Control Vibration Survey

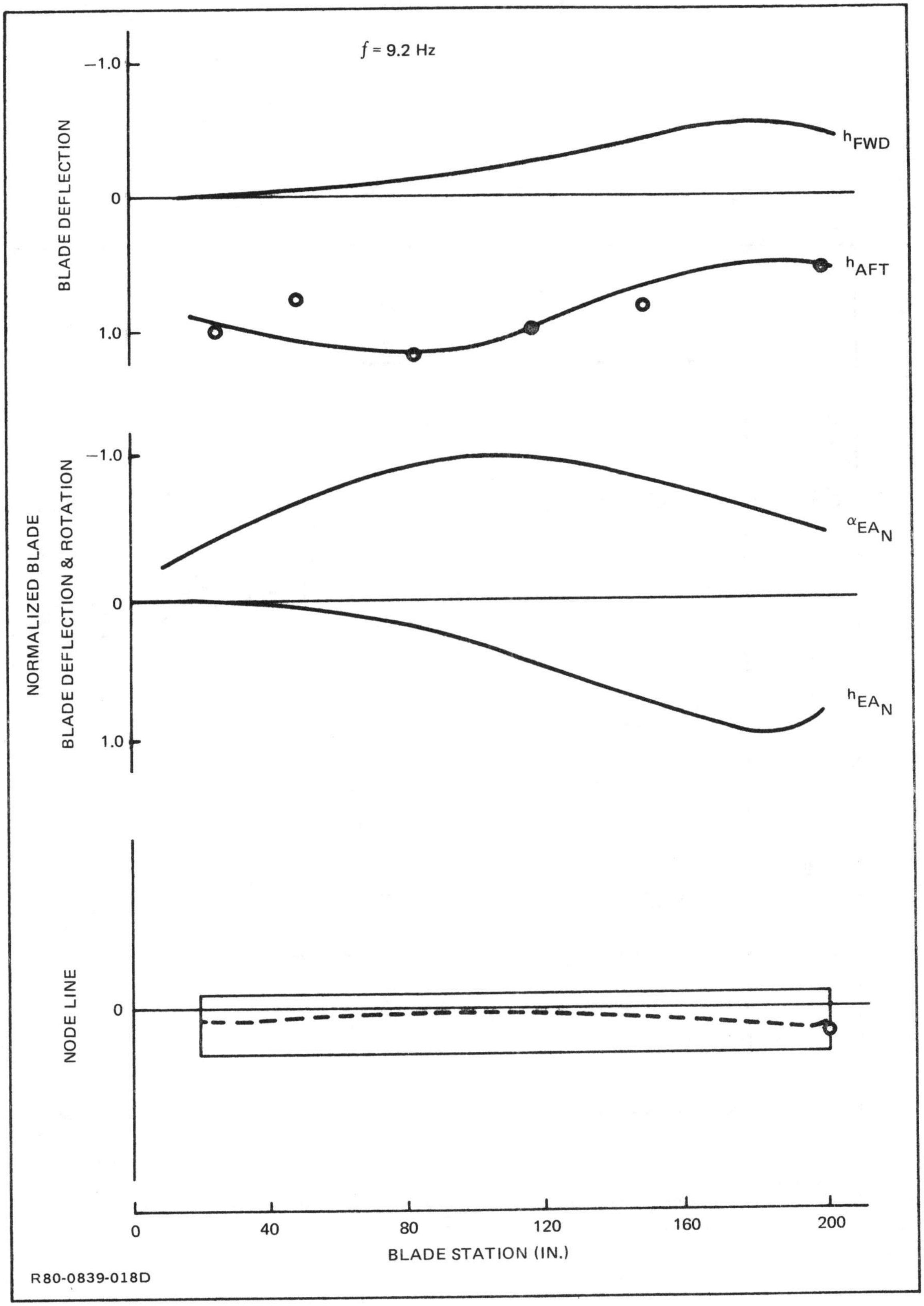


Figure 15 Mode 2 - Pitch Control
Vibration Survey

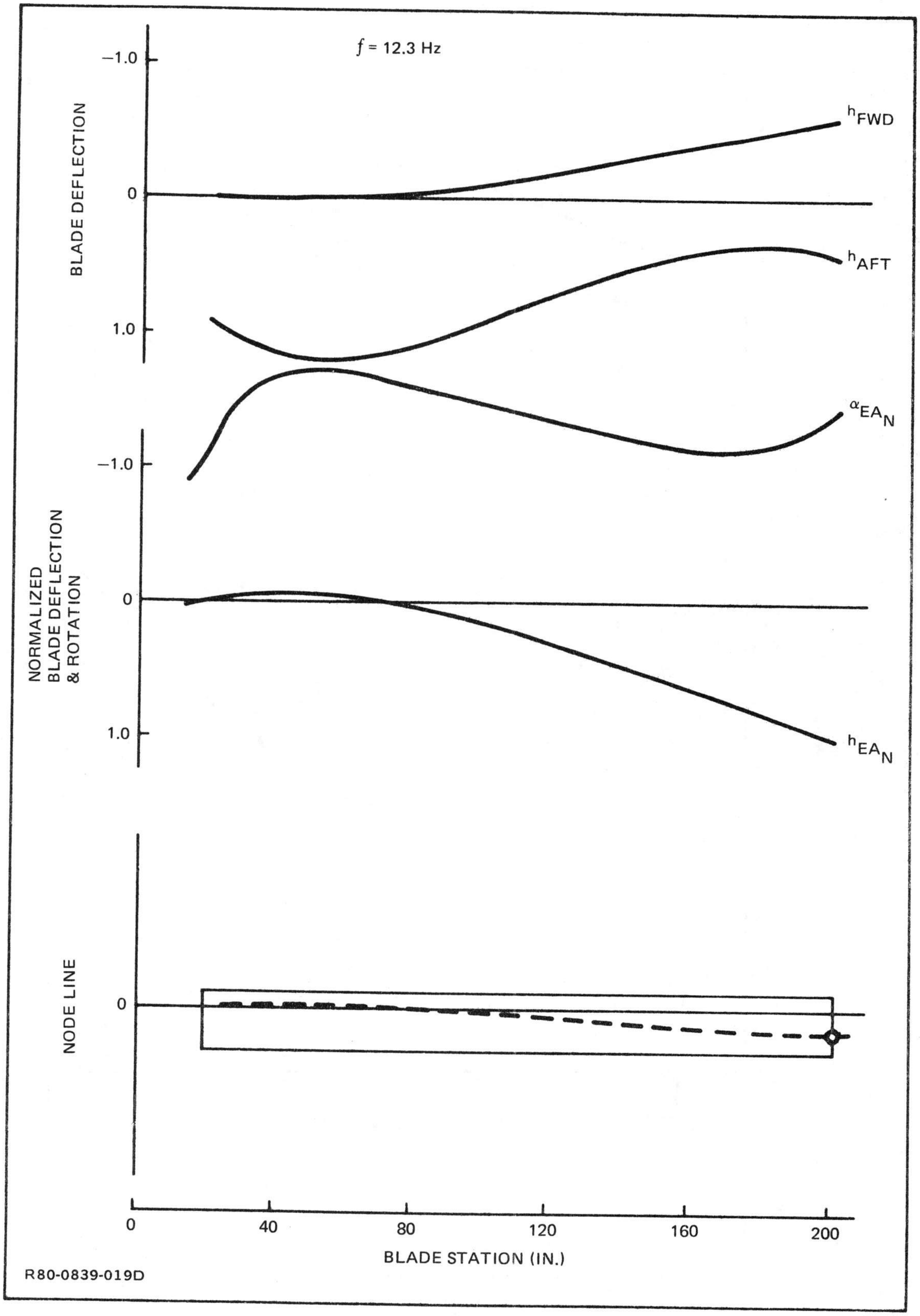


Figure 16 Mode 3 - Pitch Control Vibration Survey

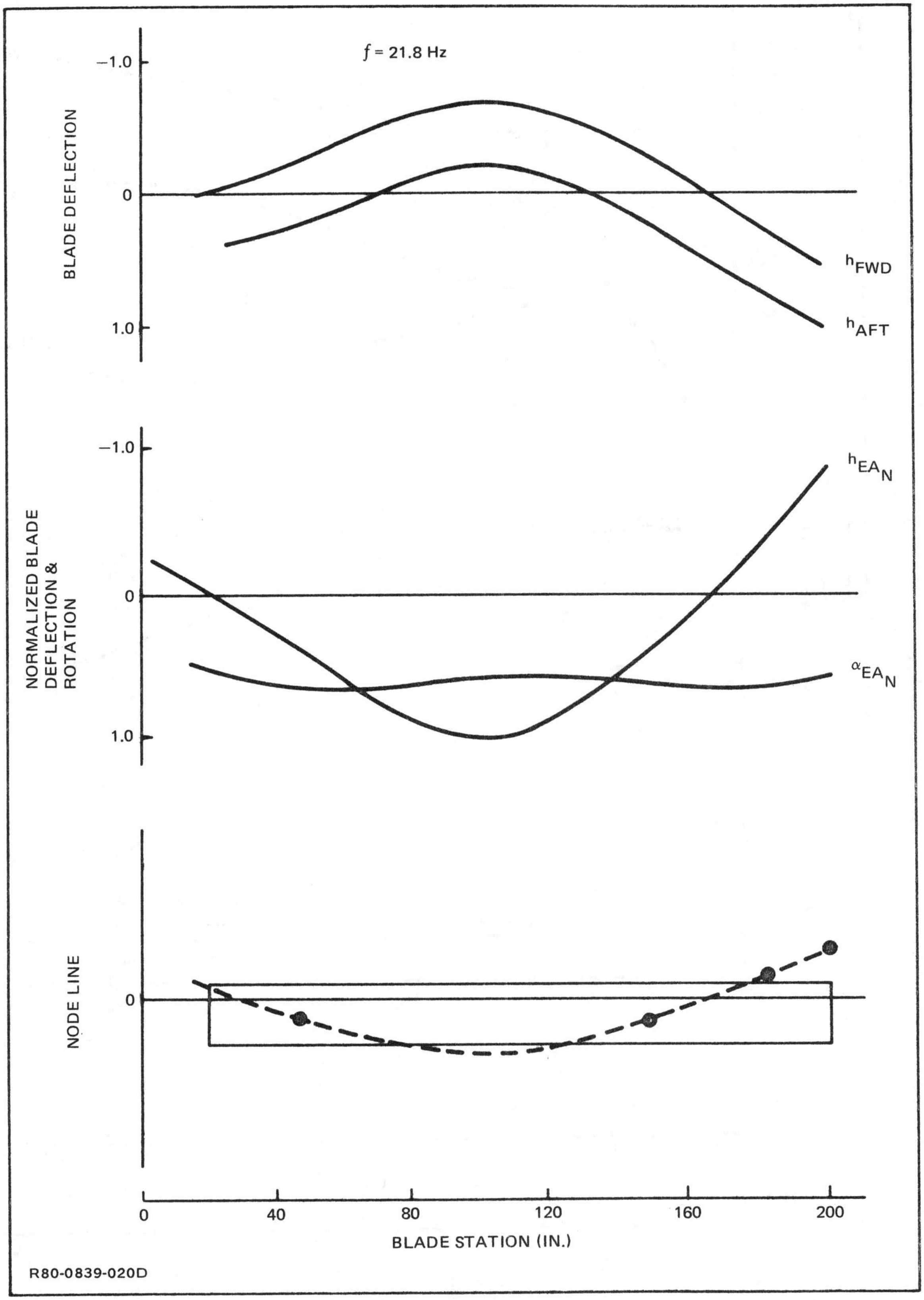


Figure 17 Mode 4 - Pitch Control
Vibration Survey

The Grumman Dynamics section analyzed the data and determined that an operating system without backlash would not be critical in winds less than 170 mph. However, The introduction of free play (such as hole elongation) in the pitch control system (backlash) would reduce the wind speeds at which flutter could develop.

4.2.5 Static Analysis & Testing

A lug analysis of the failed secondary actuator tube, using dimensions measured on the failed component showed an ultimate strength of 2,600 to 3,000 pounds. The lug bearing/tear out strengths matched for the particular geometry.

Following the secondary actuator failure, the damaged tube was trimmed off and new holes, representative of the original installation, drilled. The new holes were sufficiently clear of the damaged material not to retain any damage from the unit test. The actuator was given a load-deflection test up to 2,400 pounds and plots made (see Figure 17). Although the readings were somewhat scattered, the deformations at each hole indicate that yield was initiated at about 700 pounds in the actuator. This hole elongation (i.e., increased backlash) would result in lower system frequencies causing the system to become flutter critical at progressively lower wind speeds.

The failed actuator tube shown in Figure 18 (wall thickness = 0.055 in.) was replaced with a tube of 0.120 inch wall. Tests on this actuator showed no deformation of the holes, with final failure occurring at 5,400 pounds when the lug at the opposite end of the actuator failed. Subsequently, the modified design was incorporated into all secondary actuators.

4.2.6 Corrective Action

The following actions are currently being taken to learn more about the loads applied to the system and to stiffen the system, if necessary:

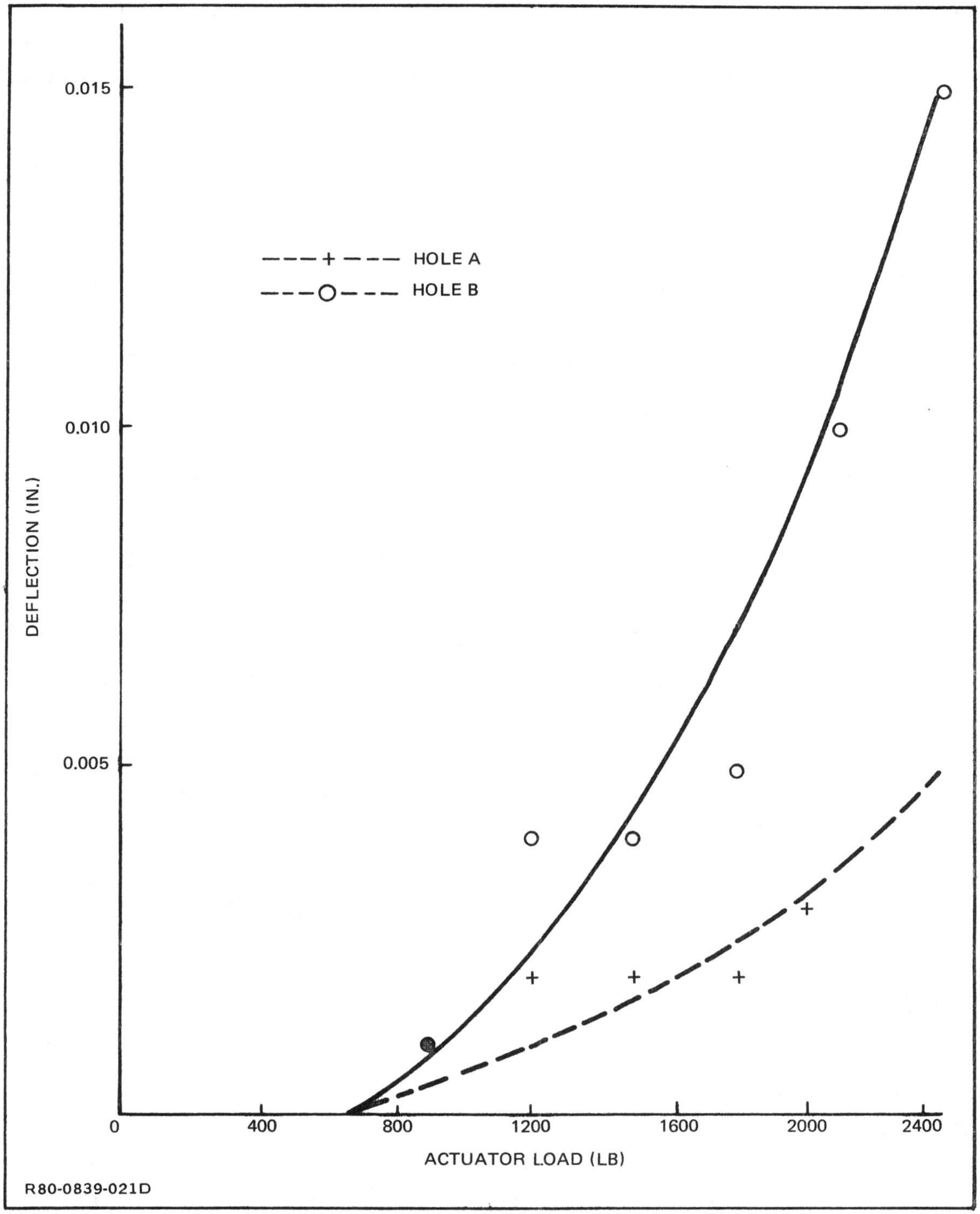
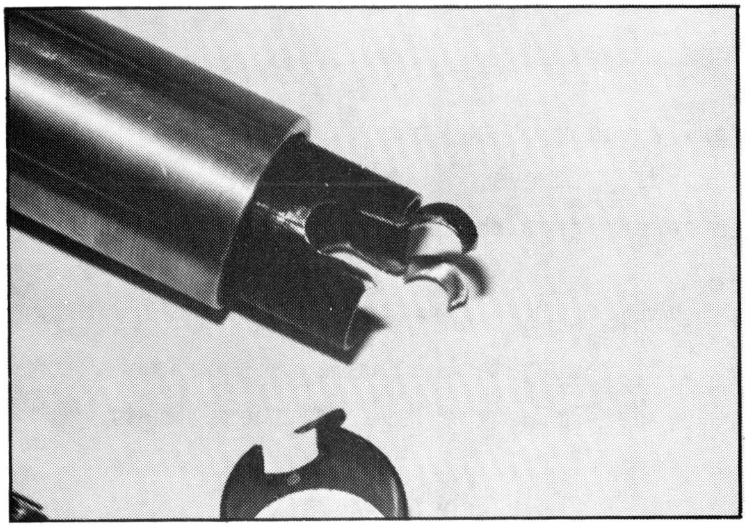
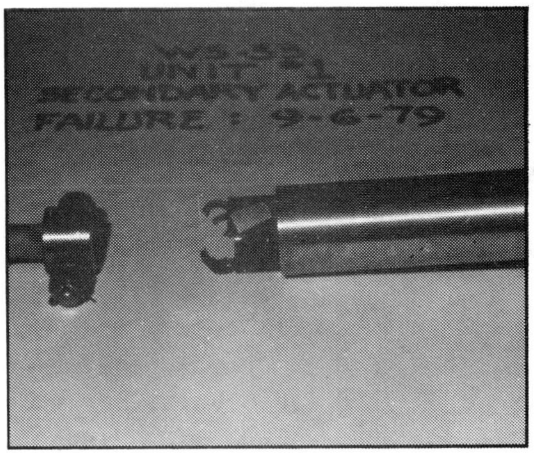


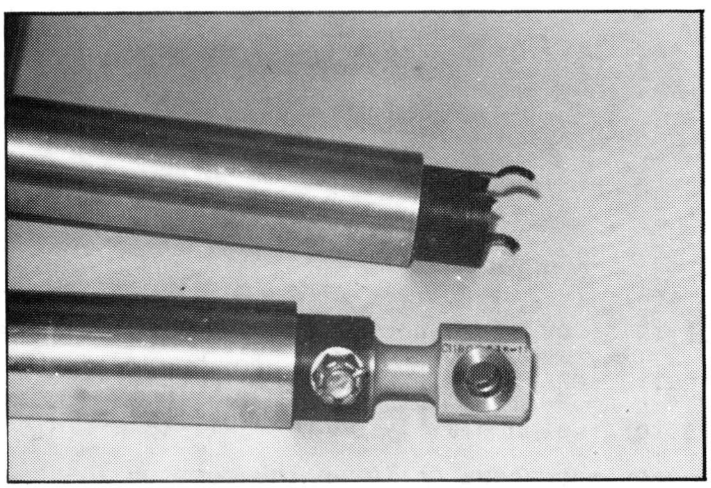
Figure 18 Secondary Actuator Load vs Elongation Measured at Hub Holes



TEST SPECIMEN FAILURE



NO. 1 UNIT FAILURE



FAILED TEST SPECIMEN WITH
LOAD DEFLECTION SPECIMEN

Figure 19 Secondary Actuator - Specimens

1. Temporarily restrict any operation of the unit above 35 mph winds. (Above 35 mph the blades will be pitched to 55° from the plane of rotation.)

2. Install strain gauges on the secondary actuator rod end to (a) investigate load reversals on the system (b) determine the level of these loads.

5.0 COST ANALYSIS

5.1 COST ANALYSIS UPDATE

Phase II activities did not lead to any major changes in hardware or production cost estimates. Therefore, the costs presented in the Phase I report are representative of the production costs in 1978 dollars. Updating these costs to 1980 dollars using inflation rates of 10% for 1979 and 10% for 1980 yields the following:

	1,000 Units Per Year	
	1978	1980
Production Cost	$11,010	$13,322
Transportation, Dealer Fees (50%)	5,505	6,661
Installation	3,800	4,600
Installed Cost	$20,315	$24,583

The cost of this, or any other mechanism of equivalent size and complexity, is quite sensitive to production rates. In addition, several other factors weigh heavily on the ability of this industry to reach the production necessary to lower the costs. These are:

- Cost of money (Prime Rate)
- Skilled labor availability
- Critical component lead time
- Heavy machine time availability
- Facility start up costs

As these additional non-recurring costs and factors will be applied to any machine manufactured, optimizing the production rate to meet the demand will be critical.

APPENDIX A

8 kW PROTOTYPE INSPECTION PROCEDURE

I. Pivot Bearing Installation (Garlock 68DU32)

a. check bearing #1
b. clean bearing #1
c. lube bearing #1
d. install bearing #1

Stamp ________

e. check bearing #2
f. clean bearing #2
g. lube bearing #2
h. install bearing #2

Stamp ________

II. Pivot Shaft Installation (C11B06031-1)

a. lubricate pivot shaft
b. retaining pin installation (C11B06134-11)
c. washer and cotter pin installation
d. retainer (C11B06131-11)
e. retainer assembly (C11B06130-1)
f. thrust bearing (Andrews XW -4-½)
g. retainer (C11B06139-11)
h. align 3 holes in retainer
i. install 3 bolts/washers
j. lock wire installation
k. lubricate thrust bearing

Stamp ________

III. Pivot Bearing Retainer Installation

a. pivot bearing retainer (C11B06140-11)
b. shim (C11B06029-11)
c. pivot shaft retainer (C11B06133-11)
d. align 3 holes in retainer
e. install 3 bolts/washers
f. lock wire installation

Stamp ________

IV. Rotor Shaft Installation

a. position aft bearing (Dodge SFB1000E-11/16)
b. position fwd bearing (Dodge FB950-3-7/16)
c. position rotor shaft (C11B06016-1)
d. align shaft to strongback
e. clamp and drill fwd bearing
f. install and torque fwd bearing hardware
g. clamp and drill aft bearing
h. install and torque aft bearing hardware
i. locate shaft in fwd and aft bearings
j. install thrust washer (C11B06103-1)

Stamp ________

V. Gear Box Installation

a. lubricate and install key in rotor shaft (C11B06120-17)
b. lubricate shaft
c. align key/shaft to gear box and install gear box
d. position bracket (Dodge 247248)
e. drill and bolt bracket
f. install and bolt link (C11B06110-11)
g. install lock washer (FMC W17) and lock nut (FMC AN17) to shaft
h. torque and secure lock washer tab
i. position fwd and aft bearing collor on rotor shaft and tighten set screws
j. tighten set screws on gear box collars

Stamp __________

VI. Generator/Shaft Installation

a. position key (C11B06003-13) bushing (Dodge 2517-2-3/16) and coupling half (Dodge 2WFR) on gear box high speed shaft
b. position coupler with spacer gage and lock in place
c. lubricate generator mounting pads (DEMA FRAME No. 284T)
d. position generator on strongback with 4 bolts in position (DO NOT SECURE)
e. install pully assemble (Dodge TL60L050) to generator shaft, position with spacer gage and secure
f. lubricate and slide key (C11B06003-11), bushing (Dodge 2012-1-1/8) and coupling half (Dodge 2WFR-1-7/8) into generator shaft
g. position coupler with spacer gage and lock in place
h. position (2 each) gaskets (Dodge) and disc brake with bolts to one end of the shaft half coupling
i. position (3 each) belts (Dodge 510L050) over pully and eye bolt
j. position bolts in second coupling half and install gasket (Dodge)
k. position shaft subassembly on gear box side
l. position coupling/brake disc to generator
m. align generator with gear box coupling
n. secure generator bolts (4 each)
o. secure (2 each) couplings with 6 each bolts per coupling

Stamp __________

VII. Rotor Pitch Actuator Rod/Brake Actuator Arm Assembly/Brake Caliper Installation

a. lubricate and position rotor pitch actuator rod (C11B06104-11) in rotor shaft
b. position swivel fitting nut, needle bearing, spacer, thrust bearing, spacer and washer onto actuator rod
c. install nut on actuator rod to complete installation of swivel details on rod
d. lubricate and install swivel fitting (C11B06018-1) secure nut to fitting

Stamp __________

VII. (cont.)

e. locate brake caliper assembly (C11B06014-1) on strongback
f. align to brake disc and secure with 4 each bolts
g. attach brake actuator arm (C11B06020-1) to bracket and swivel with hardware
h. assemble pully and hardware
i. secure nut/washers on high speed shaft coupling
j. secure nuts/washers on generator attaching bolts
k. lubricate swivel bearings

Stamp ________

VIII. Assemble Primary/Secondary Pitch Actuator

a. install brake cable assembly (C11B06025-1) secure to brake caliper and actuator are DO NOT ADJUST TURN BUCKLE
b. install bushings (2 each) (AMPLEX FF-1102-6) with bolt into crank (C11B06026-11) and secure to strongback
c. install secondary pitch actuator (Duff-Norton) to crank and strongback, secure with bolt/nut
d. install primary pitch actuator (Motion System MP-A-641) to crank and swivel, secure with bolt/nut
e. position PM generator assembly (3820) on strongback
f. adjust tension/alignment with previously mounted belt and secure with 4 each bolts

Stamp ________

IX. Hub Installation

a. clean shaft and hub
b. lubricate shaft & hub
c. install key (C11B06120-15) on shaft
d. position nylon sleeve onto pitch rod
e. align/install hub (C11B06007) on shaft
i. install
   - o washer (AM1257160)
   - o lock washer (FMC W14)
   - o lock nut (FMC N14)
   - o torque nut
   - o secure lock washer

j. install washer (AN960-1616) on rotor pitch actuator
k. position yoke (C11B06127-11) with blade shaft links and secure to rotor pitch actuator rod (3 bolts)
l. install torque arm assembly (C11B0602401) to yoke/pitch rod with washers/nuts and secure
m. install switch/bracket subassemblies (C11B06042-15/-17/-19) on strongback fitting with (8) screws and nuts

Stamp ________

X. Switch Adjustment

a. set up hub gages
b. connect cable to test equipment and switches
c. plug in adjusting test cable ends to bracket switches (3 places)
d. adjust switches per procedure noted on dwg. C11B06041 and adjust brake cable
e. remove hub gages

XI. Bulkhead and Frames Installation

a. install fwd bulkhead (C11B06019-1) to strongback with bolts
b. install frame #1 (C11B06017-1) to strongback, bolt (4) places
c. install frame #2 (C11B06017-1) to strongback bolt (4) places
d. install eye bolts to underside of strongback

Stamp ________

XII. Tower Cable and Slip Ring Installation

a. feed tower cable assembly (C11A06007) thru pivot shaft
b. position retainer and connect cable to slip ring
c. secure slip ring and retainer
d. position adapter plate (C11B06123-11) and install with slip ring brush assembly
e. coil up cable under dolly

Stamp ________

XIII. Nacelle Harness and Junction Box Installation

a. position nacelle junction box assembly (C11A06006-1) and fasten with screws to strongback
b. connect harness terminals (C11A06002) to nacelle junction box terminals, wires from switches and plug-in connections on pitch actuator assemblies
c. connect harness terminals to fwd bulkhead components
d. connect harness terminals to generator and PM generator
e. position main harness (C11A06002) on strongback and secure with damp and screws
f. connect harness terminals to slip ring brush assembly
g. connect second harness assembly to slip brush assembly and nacelle junction box

Stamp ________

XIV. Functional Test

a. plug in anemometer to test stand, position control box on test stand
b. connect tower cable to test bench
c. position hub in protection screen
d. conduct functional run-up and stop test program (generator/ motor, gear box, pitch control and brake)
e. disconnect cables remove control box and anemometer
f. box control box and anemometer

Stamp ________

XV. Fairing, Tower, Cap and Slip Ring Covers Installation

a. install cover (C11B06101-15) on underside of strongback
b. install fwd fairing (C11B06143-11)
c. install slip ring covers
d. install fwd louver (C11B06039)
e. install hub cap (C11B06124-11) with O-Ring and fasteners, safety wire heads

Stamp ________

XVI. Forward/Mid/Aft Cover Installation

a. position, fwd/mid/aft covers (C11B06004-1,-3,-5)
b. check in between gaps
c. install fasteners
d. check opening and closing

Stamp ________

XVII. Turntable Install

a. check location -13, -15 & -16
b. check .490-.500 CSK holes for rivnut installation (19) places
c. check lock wire of AN6H12A (19) places
d. check location -11
e. check .500-.503 holes in -13, -15 & -16 (12) places
f. check installation of AN8-32 (12) places
g. check location of post assembly and turntable bearing assembly
h. check installation of AN8-41 (11) places
i. check installation of AN8-36 (1) places
j. check installation of AN8-34 (20) places