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Pinson C2E Wind Turbine Generator Failure Analysis and Corrective Design Modification

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ABSTRACT

On December 4, 1978, wind speeds at the Rocky Flats Small Wind Systems Test Center reached 42 m/s (94 mph). During a routine inspection of all wind machines following this windstorm, two failures were observed on the Pinson C2E Wind Turbine Generator. One failure was fatigue cracks which formed on plates welded to the rotor shaft. The second failure was a number of cracks in the skin of all three blades. Although the possibility exists that the high winds of December 4, 1978 contributed to these failures, no conclusive data exist substantiating this theory. In fact, the C2E's feathering mechanism functioned normally during the windstorm; thereby, controlling rotor overspeed, a potential cause of damage.

The Rocky Flats Physical Metallurgy Laboratory determined that cracks in the plates on the rotor shaft formed at points of high stress concentration during vertical deflections of the plates. It should be noted, however, that vibration testing indicated WTG/tower interaction was at least a partial cause of this failure. As a result, the support structure of the C2E was changed, and the plates on which the cracks occurred were redesigned with an emphasis on improved fatigue life.

Metallurgical analyses also indicated that the cracks in the blade skins (the second failure) were due to the design of a joint (on each blade) that caused high stresses to be applied to a sharp-cornered hole. This determination resulted in the redesign of these joints, incorporating rounded corners.

NOTE: This report does not present nor discuss the costs of purchase, installation, maintenance, or other costs of operation of the Pinson C2E Wind Turbine Generator. Questions regarding actual or estimated costs of these items should be addressed directly to the manufacturer and/or its representatives.

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LIST OF ABBREVIATIONS

A or amp	- ampere
ac	- alternating current
cm	- centimeter
dc	- direct current
ft	- foot
hp	- horsepower
Hz	- Hertz
in.	- inch
ITDC	- Intensive Test Data Collection
kg	- kilogram
kVA	- kilovolt-ampere
kW	- kilowatt (1000 watts)
kWh	- kilowatt hour
lb	- pounds
LTDC	- Long Term Data Collection
m	- meter
mV	- milli-volt
mph	- miles per hour
m/s	- meters per second
RI	- Rockwell International
rpm	- revolutions per minute
SWECS	- Small Wind Energy Conversion Systems
V	- volt
W	- watt
WSTC	- Wind Systems Test Center
WTG	- wind turbine generator
°	- degrees

1.0 INTRODUCTION

Manufactured and distributed by the Pinson Energy Corporation, Marston Mills, Massachusetts, the Pinson C2E small wind energy conversion system (SWECS) is designed to provide electrical or mechanical output for a variety of residential or small business applications. The machine began its testing program at the Rocky Flats (RF) Small Wind Systems Test Center (WSTC) during August 1978 and is currently undergoing atmospheric testing. Testing of the machine will be completed when sufficient amounts of performance data have been collected to develop a reliable power curve, and the machine has experienced at least one wind storm with velocities of 38 m/s (85 mph) or greater.

On December 4, 1978, wind speeds reached 42 m/s (94 mph) at the WSTC. During a poststorm inspection of the C2E, cracks were observed in plates welded to the rotor shaft and on the skin of all three blades. The machine had been operating for approximately six weeks when the cracks were found. Subsequent vibration testing made it necessary to keep the machine on its tower for an additional eight weeks. However, the machine's blades were not permitted to turn during this period. Once the machine was removed from its tower, a preliminary examination indicated that the two types of cracks were not related, so each was analyzed separately.

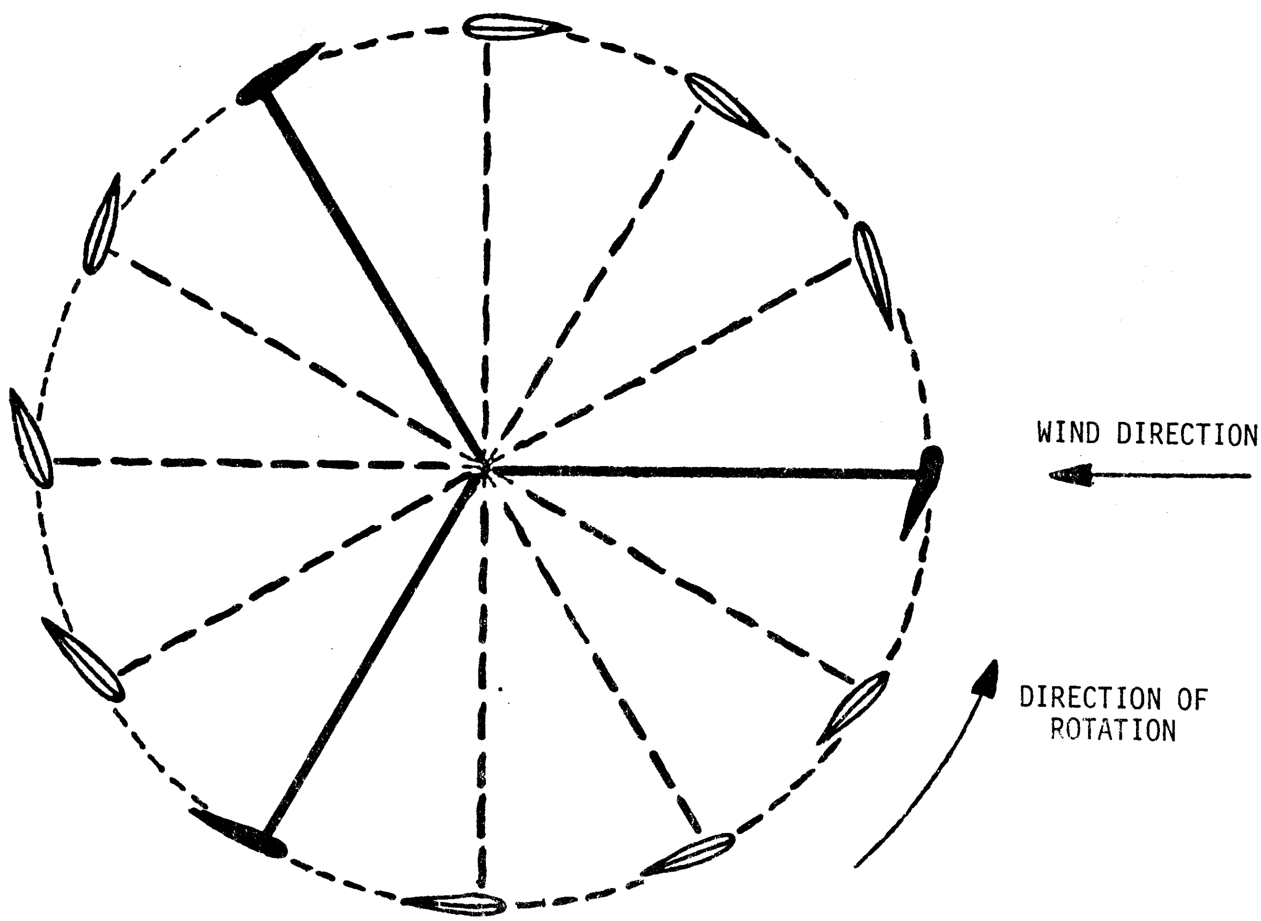
It is the purpose of this report to present the failure analyses performed on the cracks described above and investigate the WTG/tower interaction.

2.0 MACHINE OVERVIEW

The Pinson C2E is a vertical-axis, vertically straight-bladed wind turbine with cyclically-pitched blades (See Figure 2). The cycloturbine differs from the classic vertical axis Darrieus rotor in that its blades do not remain at a fixed "flat" angle, but follow a preset schedule of angle (See Figure 1), allowing more favorable use of aerodynamic force on the blades. The amount and timing of pitch change is determined by a cam device mounted atop the main shaft, actuating the blades via pull rods. A tail vane affixed to the cam programs correct orientation relative to the wind direction.

The overspeed control system is a mechanical, centrifugally activated force balance. When the centrifugal force reaches a specified amount, a tilt box is tripped, which drives the blades to a feathered condition.

Figure 1
A Representation of the Operation of the Pinson C2E



The original support structure was a Rohn SSV sections 6 and 7 with an octahedron extension. The centerline of the rotor was at a height of 16.8 m (55 ft).

The power generated from the C2E is dissipated into four 1 kW resistive loads for heating. The manufacturer's control box is a 2 step device. At startup, the alternator sees the two 1 kW loads. As the machine picks up speed and the alternator output reaches 120 V, the control box switches in the remaining two 1 kW loads, making the total load 4kW.

3.0 ANALYSIS OF CRACKS AT WELDS IN PLATES ON THE ROTOR SHAFT

Results of Visual Inspection

Two cracks were found on plates welded to the central rotor shaft of the Pinson C2E WTG. Figure 3 shows a close-up of one of the cracks, which both ran along the welds between a mild steel plate (1/4" thick) and a mild steel tube (1/4" wall thickness). Two such cracks were found. Both were located on the rotor plates in the area where the struts for the No. 2 blade were attached. The cracks appeared to be similar in nature, and only the crack in the upper plate was analyzed further.

The section of the plate containing the crack was "bandsawed" out of the rotor shaft (Figure 4 and 5). The crack was located along the edges of the two fillet welds joining the plate to the tube. It appeared that the crack extended through the plate and was similar in extent on both sides of the plate. A section from the center of the crack (A in Figure 4) was carefully sawed free (Figures 6 and 7), at which time it fell into two pieces because the crack went completely through the plate. The fracture surface was slightly rusty but clearly showed beachmarks typical of fatigue. The presence of a linear feature running along the centerline of the fracture, coupled with the

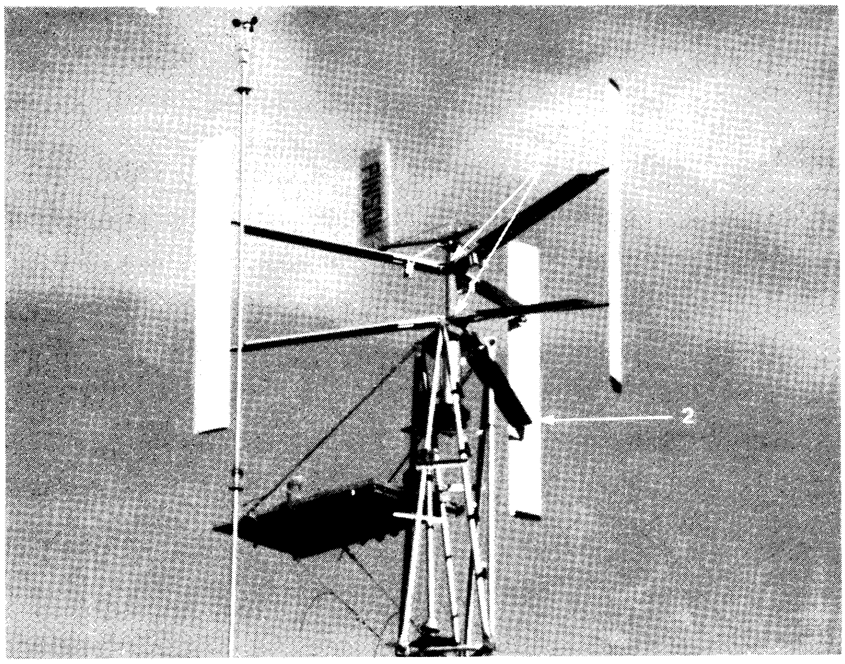


Figure 2

Overall view of the Pinson C2E Wind Turbine Generator
(1 = Rotor Shaft; 2 = Strut Attachment Point)

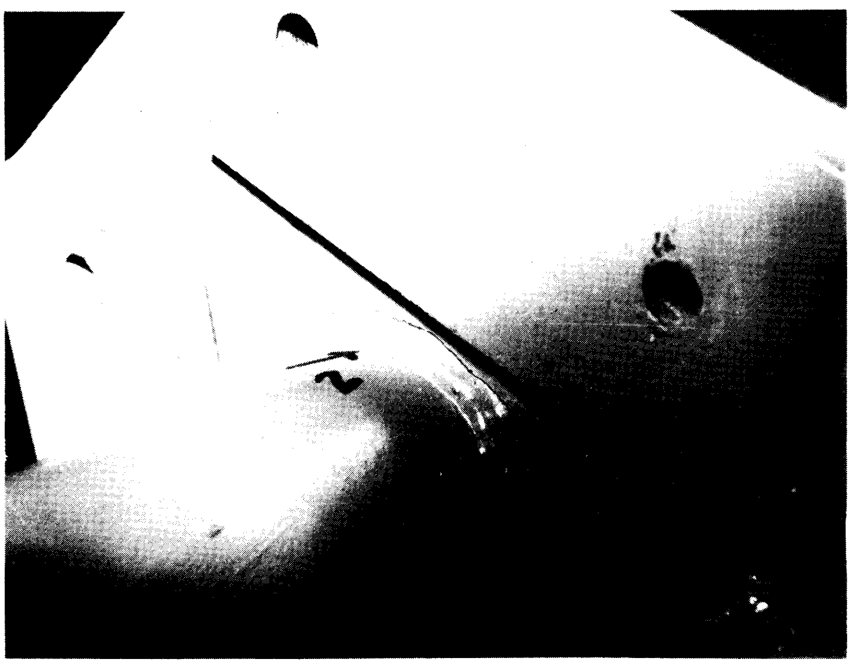


Figure 3

Overall View of One of the Cracks in a Plate of the Rotor Shaft

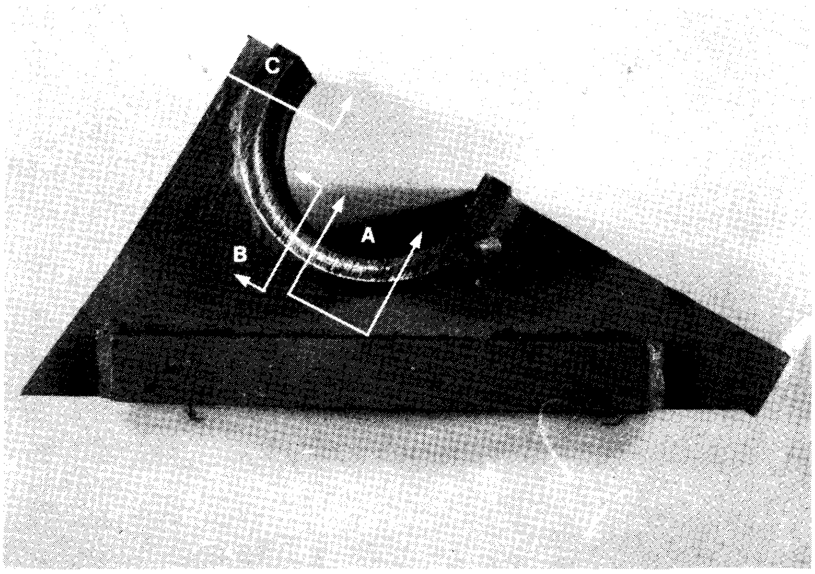


Figure 4

Section of the Cracked Rotor Shaft Plate Showing the Location of the Subsequent Samples

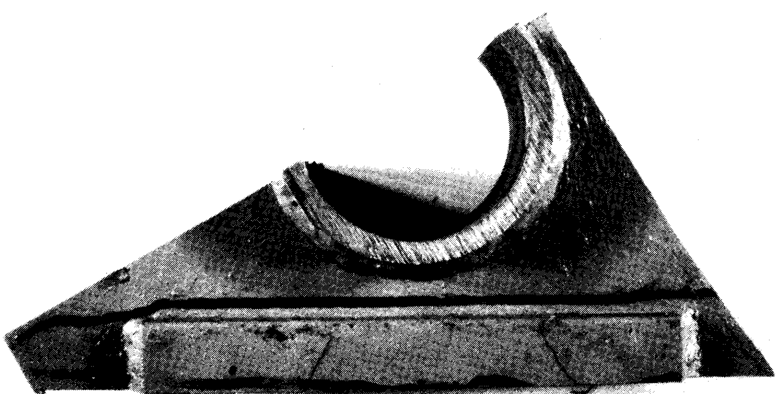


Figure 5

Reverse View of Figure 4 Showing Similar Extent of Cracking

Figure 6

(A) Mating Half of the Fracture Surface of Section A in Figure 4

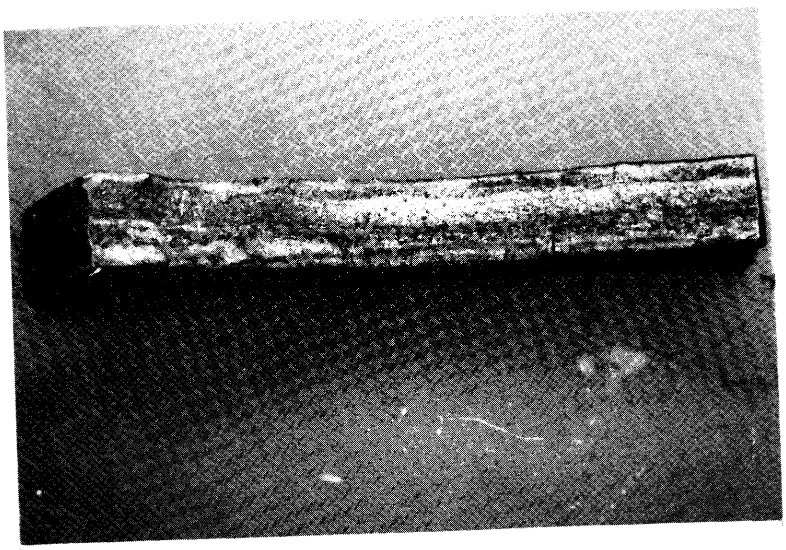


Figure 7

(B) Mating Half of the Fracture Surface of Section A in Figure 4 orientation of the beachmarks, indicate that this plate was loaded in reversed bending due to vertical cantilever deflections of this plate. This was an observed vibrational mode in which the blades attached to the rotor plate by struts displace vertically, parallel to the central shaft, while in operation.

The stepped shape of the edges of the fracture surface indicate that the fatigue crack had many initiation sites, which subsequently grew together into two large cracks which met at the center line.

Results of Microscopic Examination

The piece shown in Figure 7 was examined in the Scanning Electron Microscope (SEM). Figure 8 is an overall view of an area of the fracture surface showing three areas selected for closer viewing. Figures 9 and 10 show an area in the beachmarks near the edge of the piece. Fatigue striations in this area have a spacing of about 0.5 μ/striation. Figure 11 shows an area near the middle where the spacing of striations is about 0.3μ/striation. Figure 12 shows striations found near the opposite edge. Again the spacing of striations was similar to the other locations, about 0.4μ/striation. These measurements represent upper limits on the spacing of striations on this surface; finer striations may exist below the resolution limit of the SEM.

A cross section of the cracked area (B in Figure 4) was mounted, polished and etched with 2% nital. The crack was seen to start at the toes of the two fillet welds and to run completely through the plate (Figure 13).

A second cross section from an uncracked area (C in Figure 4) was similarly mounted, polished and etched. Cracks were again found in the plate near the toes of the filler welds (Figures 14 and 15). These cracks emanated from notches due to slag (Figure 15) and ran only partially through the plate.

Other than those cracks, the quality of the welds was good in terms of structure and soundness. The base materials (plate and tube) appeared typical of hot-worked steel, with the plate material showing practically no pearlite due to its low carbon content (plate - 0.06%; tube - 0.19%).[1]

Discussion

Fatigue failures in welded structures of this type are not uncommon.[2] They generally occur, as did this one, at the toe of the weld because of natural stress concentration at that point. In these welds, there was additional stress concentration due to the notches caused by the slag generated during welding. The carbon content of the plate material was low (0.06%) which means that the yield and ultimate strengths were also low (24 ksiσ_y; 43 ksiσ_t for hot-rolled 1006 steel). Fatigue strength is roughly proportional to the ultimate strength, so this material, being comparatively weak, is also low in its ability to resist fatigue. Overall then, it appears that this part failed due to the initiation and propagation of a fatigue crack which started at the points of highest stress concentration in relatively weak material. That is, the stresses encountered during testing exceeded the fatigue load bearing capability of this part. Methods for improving the fatigue strength of welded assemblies such as this are discussed in detail in Reference 2.

Conclusions

1. The crack observed on the plate of the rotor shaft was a fatigue crack.
2. The loading under which this part failed was reversed bending caused by vertical deflections of the plate.

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1 K. Kirchner, Analytical Laboratories, Rocky Flats Plant, Bldg. 881, Report No M79-532.

2 K.G. Richards, "Fatigue Strength of Welded Structures," The Welding Institute, Abington Hall, Cambridge, England, May 1969.

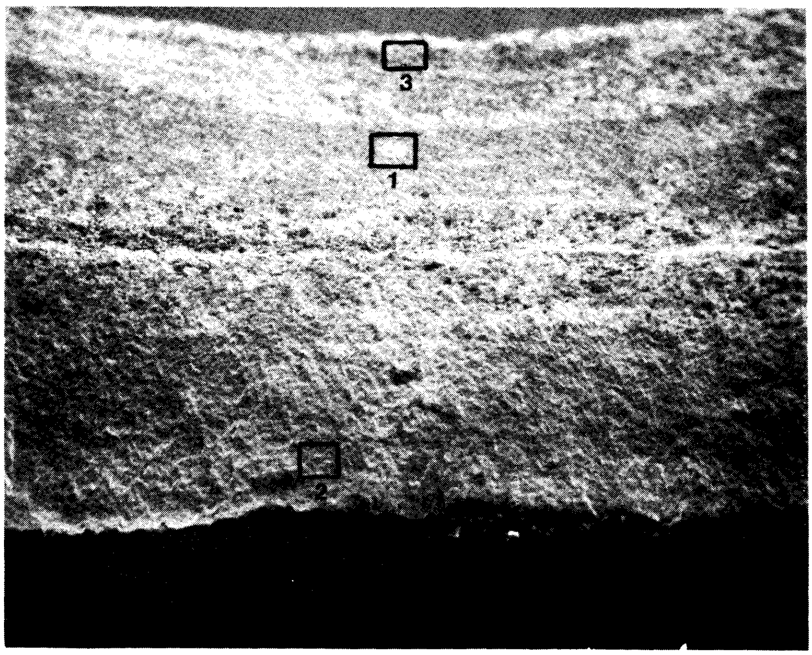


Figure 8

SEM Micrograph of the Fracture Surface Shown in Figure 7. Subsequent Micrographs were taken near the Numbered Areas. (20X)

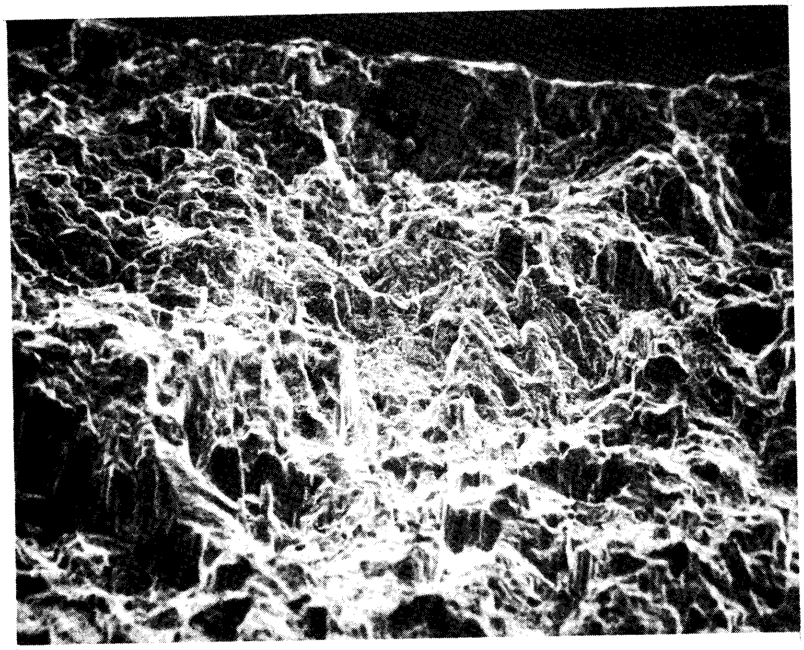


Figure 9

Area 3 in Figure 8 (400X)

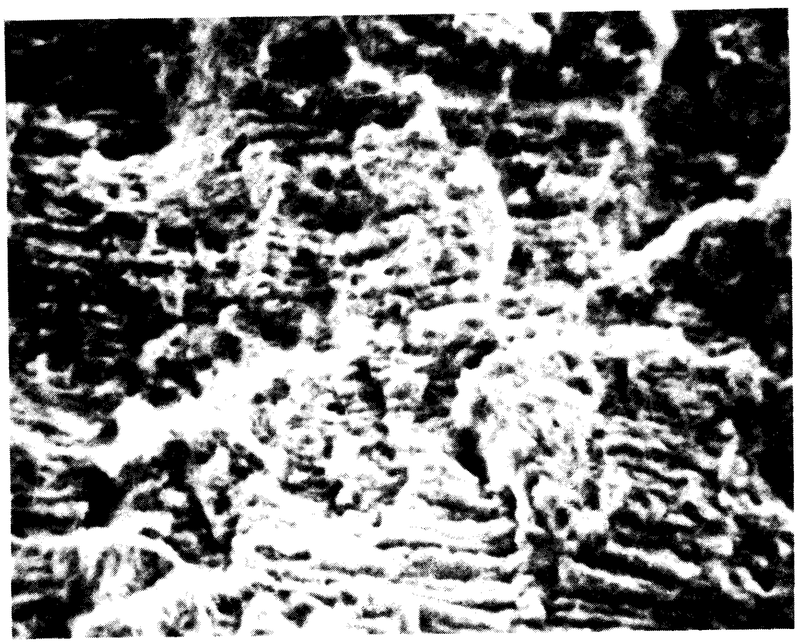


Figure 10

Higher Magnification of the Center of Figure 9 Showing Fatique Striations (oxidized) (4000 X)

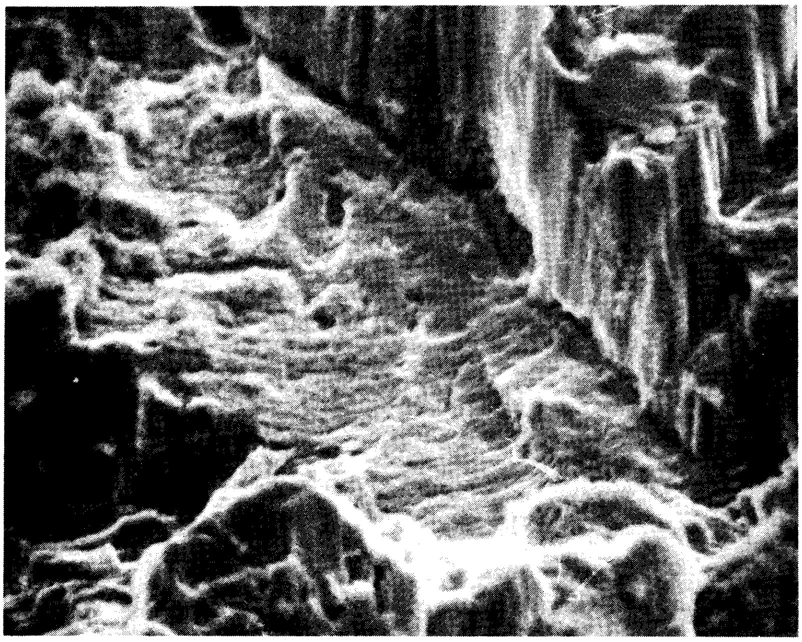


Figure 11
Fatigue Striations near No. 1 in Figure 8 (4500X)

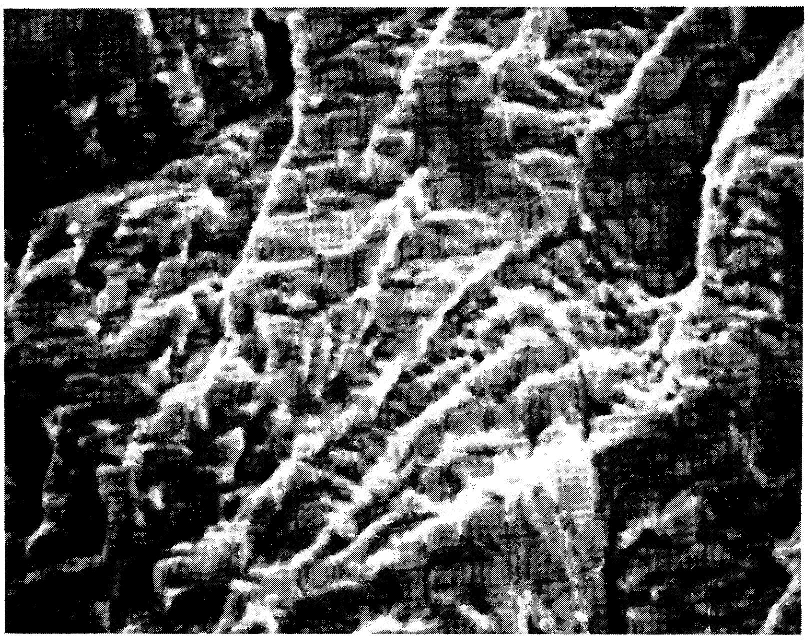


Figure 12
Fatigue Striations near No. 2 in Figure 8 (5000X)

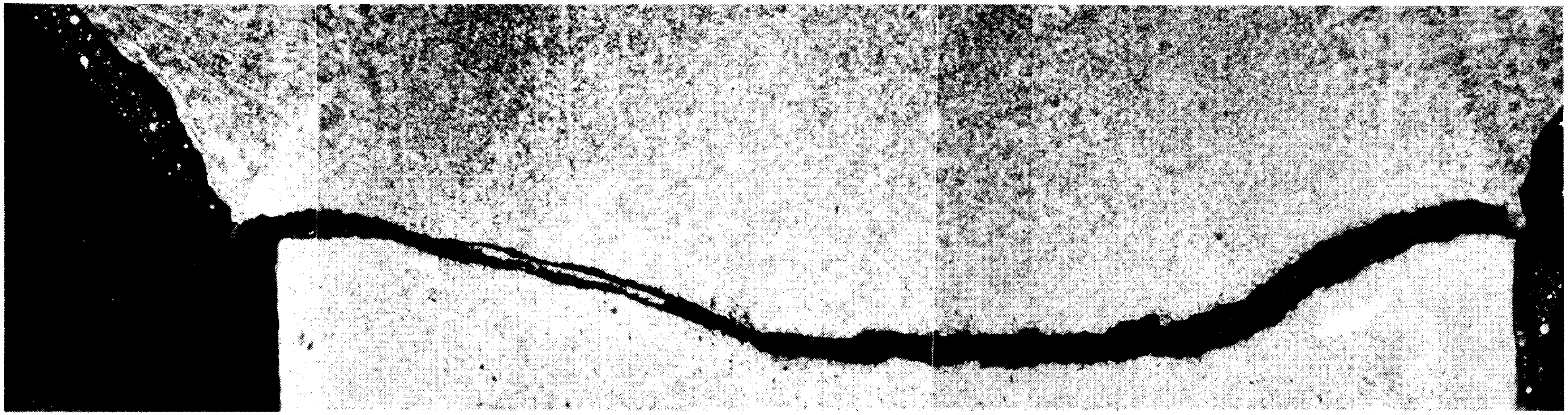


Figure 13

Optical Micrograph showing the Crack Traversing

Section B in Figure 4 (40 X)

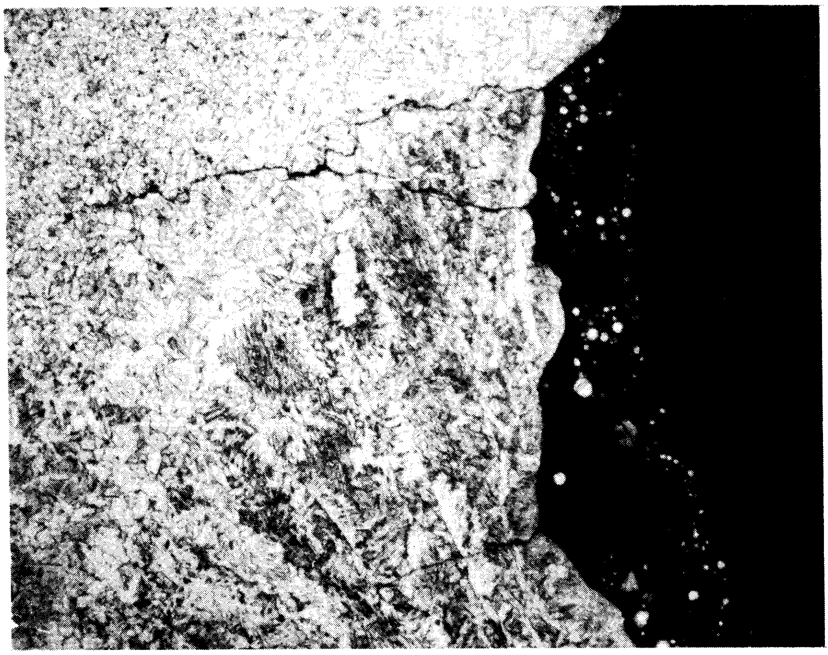


Figure 14

Fatigue Cracks Found in Area C of
Figure 4, an "Uncracked" Area. (80 X)

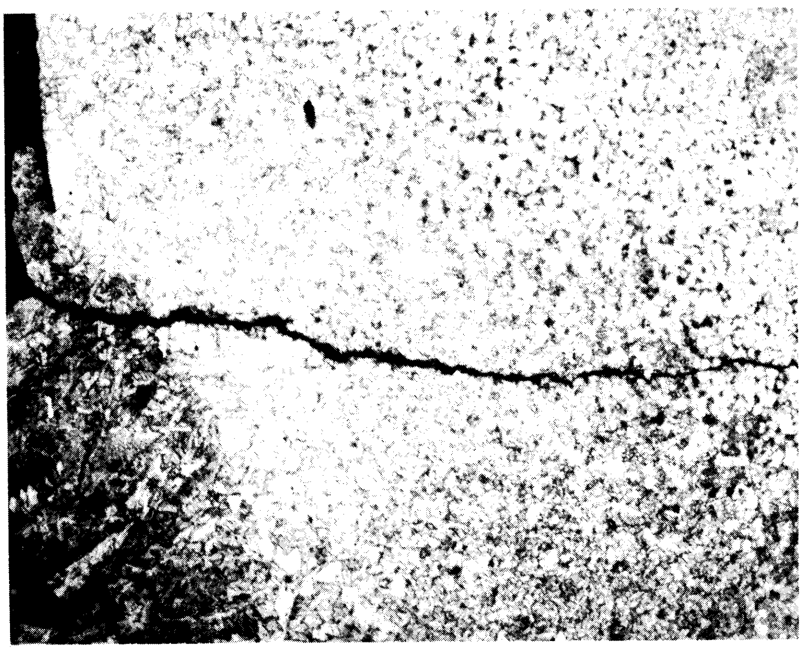


Figure 15

Fatigue Cracks Found in Area C of
Figure 4, an "Uncracked" Area. (80 X)

3. The cracks initiated in notches were caused by slag adhering to the surface of the weld, at the toe of the filler weld joining the plate to the rotor shaft (tube). Under normal loading, this is the area of highest stress concentration in the part.
4. The welds were generally of good quality with respect to structure and soundness. The steel used to make the plate contained 0.06% carbon; the steel used to make the tube contained 0.19% carbon. Both steels had normal hot-worked structures and are relatively free from inclusions.
5. Redesign of the failed part, with emphasis on improving the fatigue life of the unit, should be considered if this unit is to be rebuilt.

4.0 ANALYSIS OF CRACKS IN THE SURFACE OF THE BLADES AT THE POINTS WHERE THE STRUTS ARE ATTACHED

Results of Visual Inspection

Cracks were observed in the skin material covering the blades, at five of the six places where the struts were attached (Figure 2). The cracks were located at the sharp corners of a square hole cut in the skin, through which two anchor points for the strut protruded. Figure 16 shows one such area with four cracks, one running out from each corner of the hole. The blades were generally of a riveted sheet construction. A manufacturer's label was found on an unpainted interior area indicating that the sheet was 6061-T6 aluminum. Therefore, it is assumed that all the sheet stock is 6061-T6.

The skin sheet was removed from the backside of the blade (Figure 17). This showed that the main loading on the blade was borne by a tubular strut, to which was welded a box section tube. The strut attachment points were welded to this box section tube. A square bottomed "u-shaped" piece was positioned in the square hole and riveted to the skin in order to roughly seal the remaining open area around the hole.

The arrangement of these parts was such that when tension was applied at the strut attachment points, the skin was bowed outward. The cracks which were observed appeared to have initiated at the sharp corners of the square hole and run outward in response to this loading.

Results of SEM Examination

The crack labeled No. 2 in Figure 16 was carefully excised and then pulled open so that the fracture surface could be observed. Much of the fracture surface showed signs of rubbing, particularly near the origin, and so was useless for fractography. However, a few areas were found which clearly showed fatigue striations (Figure 18) with spacings of about 0.6μ/striation. Little or no reduction in area was observed at the crack, which is also a sign of a fatigue since this material is ductile and normally shows some necking prior to failure.

Discussion

The cracks in the skin of the blades were fatigue cracks which propagated out from the sharp corners of square holes cut in the skin to past the attachment points for the struts. The sharpness of the corners is probably the primary cause of these cracks, coupled with the overall design of the joint which causes the skin to be pushed outward at the hole. Redesign of the joint with consideration for its service in a fatigue environment (i.e., rounded corners, no load on skin) should be considered when this piece is replaced.

Conclusions

1. The cracks in the skin of the blades were fatigue cracks.

2. The cracks were due to the design of a joint which caused high stresses to be applied at the sharp corners of a square hole.

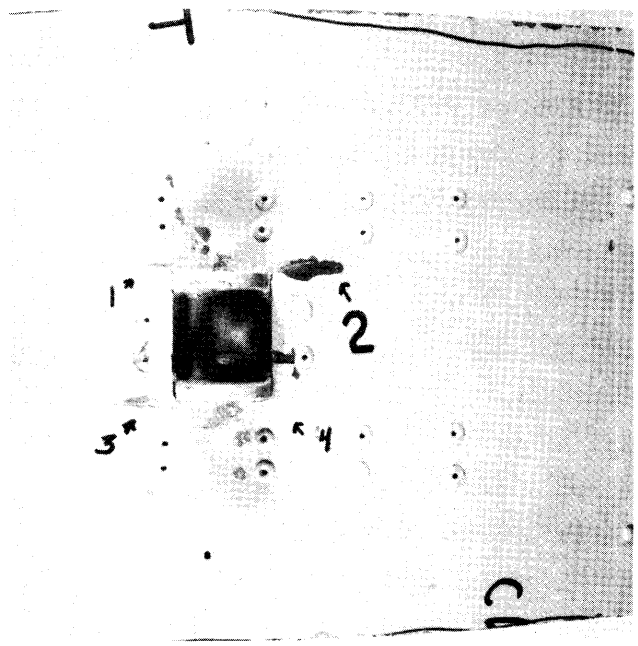


Figure 16

Overall View of Cracks in the Skin of a Blade. The Numbers Indicate the Cracks.

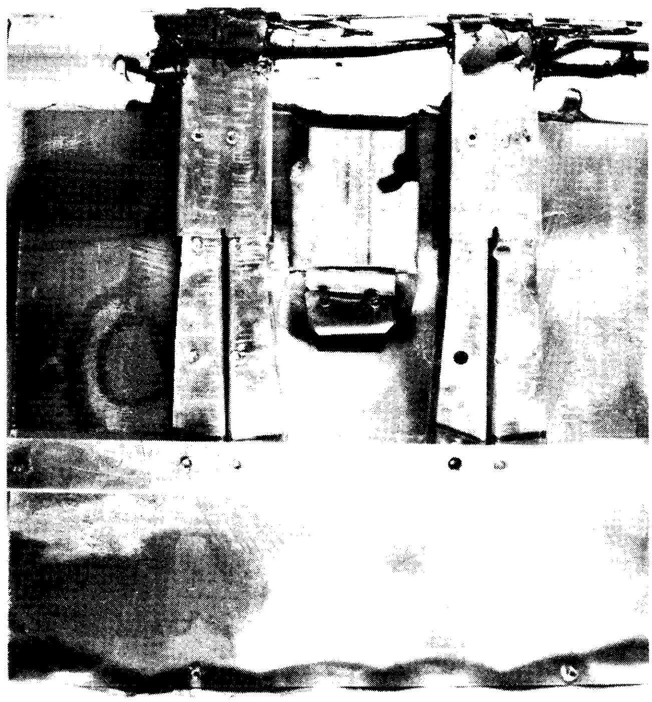


Figure 17

Reverse View of Figure 16 with the Skin Removed, Showing Interior Construction

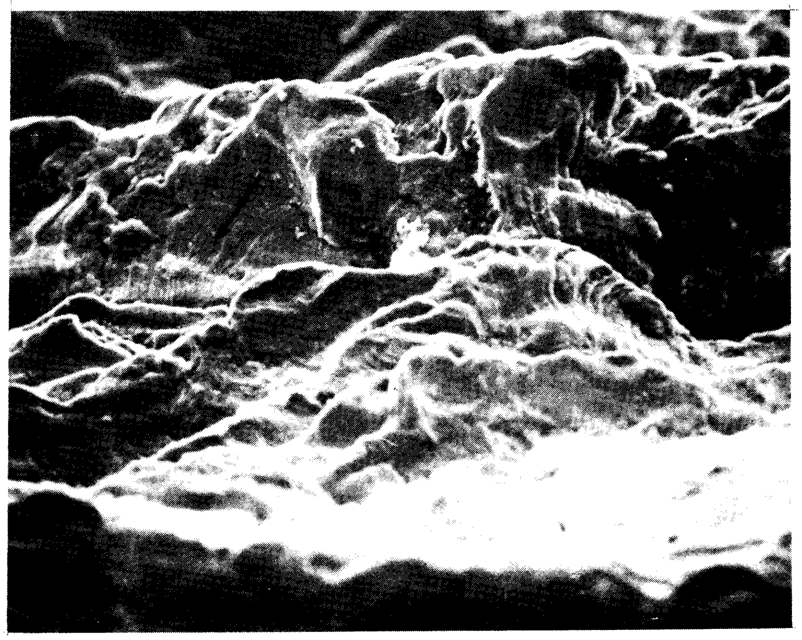


Figure 18

SEM Micrograph of Fracture Surface of Crack No. 2 in Figure 16 Showing Fatigue Striations Found 3 mm from the Origin. (1000 X)

5.0 RESULTS OF VIBRATION TESTING

Vibration tests on the Pinson C2E and its tower were conducted to determine the possible cause of cracks which appeared in the hub plates and blade skins. Instrumentation used for vibration testing of the Pinson C2E was owned by Rockwell/DOE and is listed below:

- Accelerometer (Piezoresistive) Endevco Model 2262C-25
- Signal Conditioning - Cyber Systems Model 9320
- Analog Tape Recorder/Reproducer - Honeywell Model 101
- Digital Analyzer - Hewlett-Packard HP 5420A
- Plotter - Hewlett-Packard HP 9872A

Two different system configurations were used for vibration testing of the Pinson C2E WTG. System (1) consisted of the C2E mounted on a Rohn SSV Sections 6 and 7 with an octahedron extension. System (2) consisted of the C2E mounted on octahedron sections 2, 3, 4 and 5 with an octahedron extension that is not a standard section. Both of these tower configurations brought the centerline of the rotor to a height of 16.8 m (55 ft).

Test Results

The natural frequency (first mode bending) of System 1 was determined to be 4.5 Hz (Figure 19). The time history of the response is presented in Figure 20. The natural frequency of System 2 was found to be 2.5 Hz as shown in the auto spectrum in Figure 21. Figure 22 depicts the time history of the response for System 2. A summary of vibration test results is presented in Table I.

TABLE I

SUMMARY OF VIBRATION TEST RESULTS

System	Natural Frequency First Mode Bending
(1)	
WTG atop a Rohn SSV Sections 6NW and 7NW with an octaheron extension	4.5 Hz

(2) WTG atop an octahedron tower Sections 2, 3, 4 and 5 with an octahedron extension (specified tower configuration after the machine's failure	2.5 Hz

Discussion

Cyclic loading is a characteristic of the Pinson C2E that stems from a 3P excitation. Therefore, System (1) with a natural frequency of 4.5 Hz will be excited at a rotor speed of 90 rpm, while System (2), the current configuration, will be excited at 50 rpm.

Vibration test results indicate the WTG/tower interaction of System 1 was a partial cause of the failure due to passing through resonance at 90 rpm. The 90 rpm represents a higher energy input that does 50 rpm, due to the corresponding winds at the two rotor speeds. System (1), while in operation, was seen to go through "violent" vibrations at 90 rpm, while System (2) goes through a rather gentle "rocking" motion at 50 rpm. It must be noted, however, that if a 1P excitation was experienced for any reason (icing, rotor imbalance, etc.), System (2) would go through resonance at 150 rpm, which is close to the rated rpm of the C2E. The manufacturer has been notified of this situation. This possiblility (a 1P Excitation) will be closely monitored.

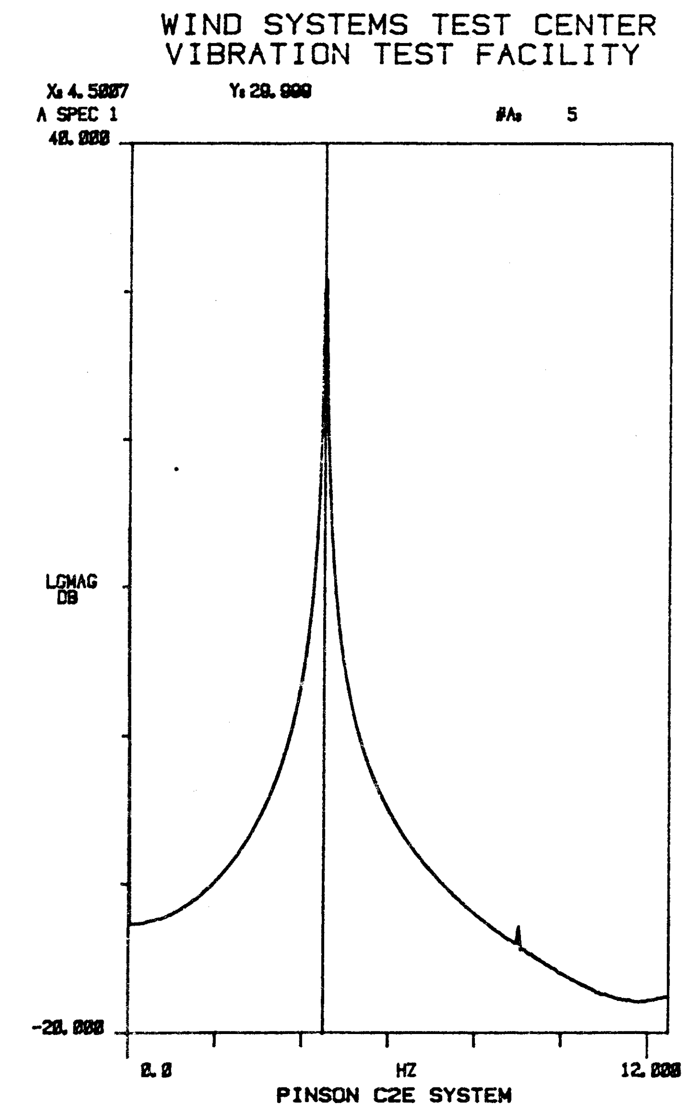
6.0 CORRECTIVE DESIGN MODIFICATIONS

Replacement parts for the Pinson C2E were received on 2/13/79, and the machine was put back into operation on the octahedron tower (System 2) on 4/18/79. Equipment and operational problems were responsible for the delay in the reinstallation. A summary of modifications based on data presented in this "Failure Analysis" and RF/manufacturer experiences is contained in Table II.

TABLE II

MODIFICATIONS OF THE PINSON C2E

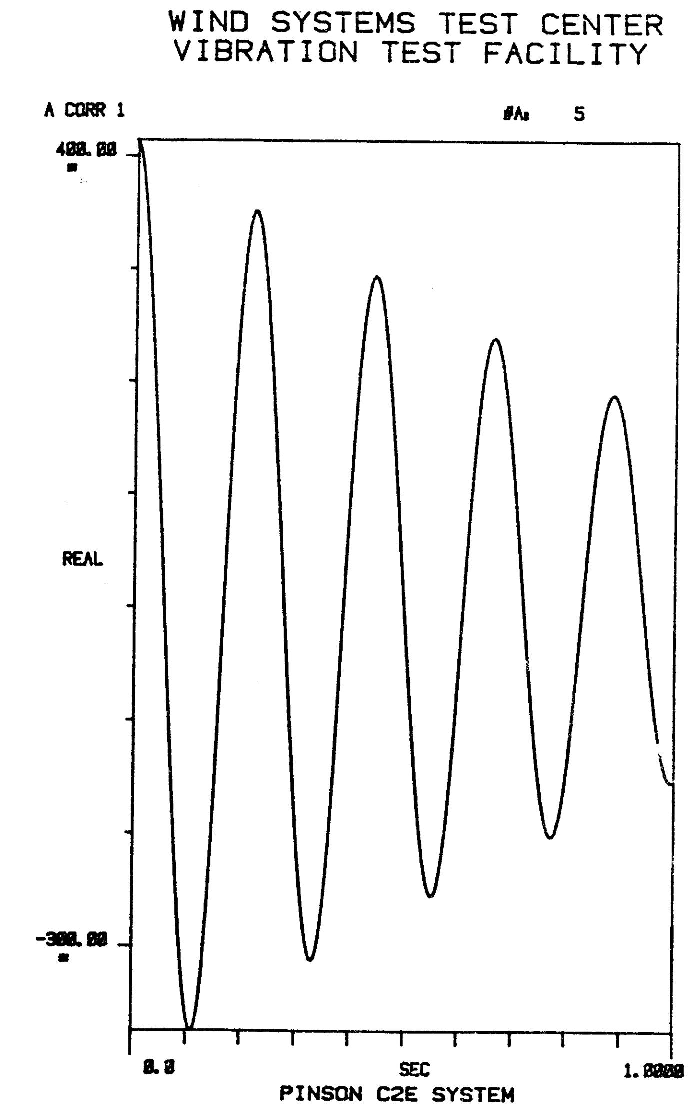
Part	Original Specification	Corrective Modification
Hub Plate	6.5mm (1/4")	25.5mm (1")
Blade Cut-Outs	Square Corners	Rounded Corners
Tower	Rohn SSV 6NW & 7NW with octahedron extension 16.8 m (55 ft) in height	Octahedron tower sections 2, 3, 4 and 5 with an octahedron extension; 12.9 m (42.5 ft) in height



TYPE OF EXCITATION HAND SHAKE
LOCATION OF INPUT TOWER TOP
LOCATION OF RESPONSE XDCR TOWER TOP
1/5/79

Figure 19

Natural Frequency (first mode bending) of the Pinson C2E System (1)



TYPE OF EXCITATION HAND SHAKE
LOCATION OF INPUT TOWER TOP
LOCATION OF RESPONSE XDCR TOWER TOP
1/5/79

Figure 20

Time History of the System Response for the Pinson C2E System (1)

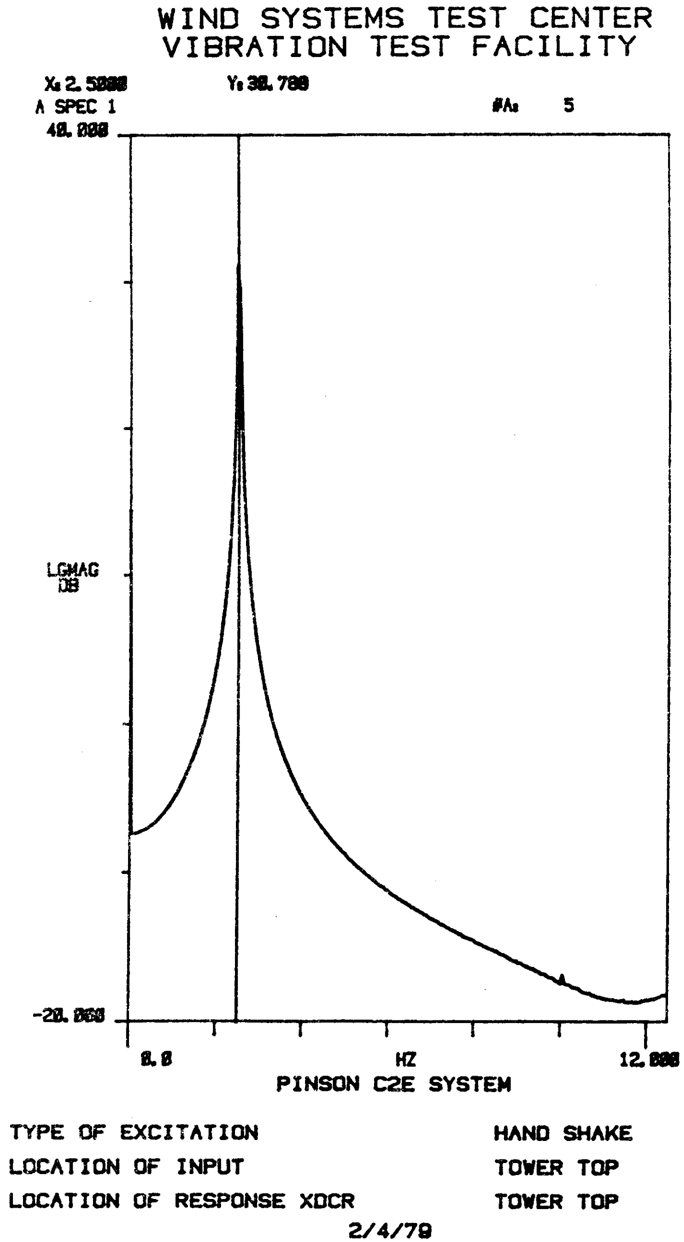


Figure 21

Natural Frequency (first mode bending) of the Pinson C2E System (2)

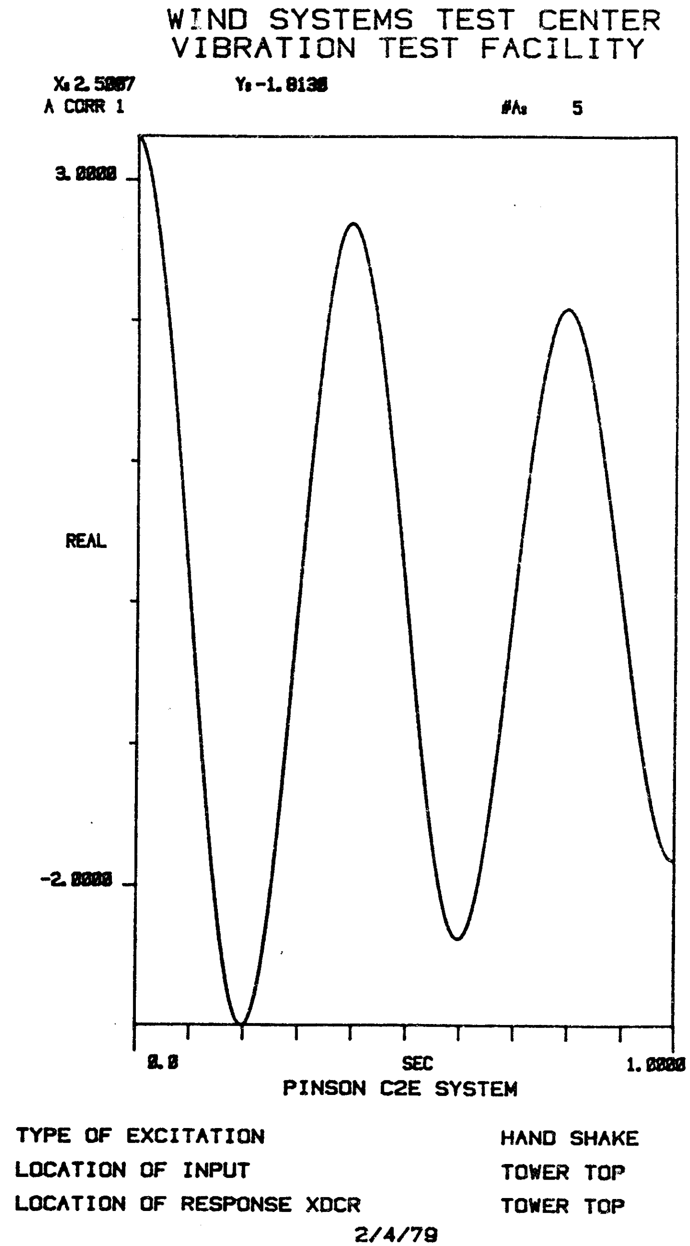


Figure 22

Time History of the System Response for the Pinson C2E System (2)