NASA / TM-2000-210303
ARL-TR-2244

Field Measurement of the Acoustic Nonlinearity Parameter in Turbine Blades

Yolanda L. Hinton
U.S. Army Research Laboratory
Vehicle Technology Directorate
Langley Research Center, Hampton, Virginia

Jeong K. Na
Energy Services Group, Williamsburg, Virginia

William T. Yost
Langley Research Center, Hampton, Virginia

Gregory L. Kessel
Virginia Power, Glen Allen, Virginia

September 2000

The NASA STI Program Office ... in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the lead center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers, but having less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results ... even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at ***http://www.sti.nasa.gov***

- E-mail your question via the Internet to help@sti.nasa.gov

- Fax your question to the NASA STI Help Desk at (301) 621-0134

- Phone the NASA STI Help Desk at (301) 621-0390

- Write to:
  NASA STI Help Desk
  NASA Center for AeroSpace Information
  7121 Standard Drive
  Hanover, MD 21076-1320

NASA/TM-2000-210303
ARL-TR-2244

Field Measurement of the Acoustic Nonlinearity Parameter in Turbine Blades

Yolanda L. Hinton
U.S. Army Research Laboratory
Vehicle Technology Directorate
Langley Research Center, Hampton, Virginia

Jeong K. Na
Energy Services Group, Williamsburg, Virginia

William T. Yost
Langley Research Center, Hampton, Virginia

Gregory L. Kessel
Virginia Power, Glen Allen, Virginia

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

September 2000

Available from:

NASA Center for AeroSpace Information (CASI)
7121 Standard Drive
Hanover, MD 21076-1320
(301) 621-0390

National Technical Information Service (NTIS)
5285 Port Royal Road
Springfield, VA 22161-2171
(703) 605-6000

INTRODUCTION

As an acoustic wave passes through a material, nonlinearities in the material produce harmonics of the acoustic wave. The amplitudes of the incident wave and the harmonics are related by the acoustic nonlinearity parameter. The acoustic nonlinearity parameter, β, is influenced by crystal structure, fatigue state, dislocation dipole density, precipitates and their phases, coherency strains, and other material conditions. The nonlinearity parameter has been shown to be sensitive to fatigue in stainless steel turbine blades [1].

The acoustic nonlinearity parameter is defined by the nonlinear form of the classic wave equation:

$$\frac{\partial^2 u}{\partial t^2} = c^2\left(1 - \beta \frac{\partial u}{\partial a}\right)\frac{\partial^2 u}{\partial a^2} \qquad (1)$$

where u is particle displacement, a is a Lagrangian coordinate, and c is the infinitesimal wave speed. β is a material property, described by

$$\beta = \left(\frac{A_2}{A_1^2}\right)\frac{8c^2}{\omega^2 a} \qquad (2)$$

where A_1 and A_s are the particle displacement amplitudes of the fundamental and second harmonic acoustic waves respectively, and ω is the angular frequency of the fundamental wave. Yost and Cantrell [2] proposed a substitutional technique for measuring β using resonant ultrasonic transducers rather than absolute displacement transducers. In the case that β is known for a given reference material, β′ may be measured for another specimen by measuring the voltage output from resonant transducers for both materials and using the equation

$$\beta' = \left(\frac{c'}{c}\right)^2\left(\frac{d}{d'}\right)\left(\frac{V'_2 / V'^2_1}{V_2 / V_1^2}\right)\beta \qquad (3)$$

where V_1 and V_2 are the peak output voltages for the fundamental and second harmonic waves, c is longitudinal wave speed, and d is the distance traveled (the specimen thickness). The primed values refer to the unknown specimen and the unprimed values refer to the reference specimen. It is necessary that the same measurement system be used to measure both materials, and that the specimens be of the same acoustic impedance.

EXPERIMENTAL PROCEDURES

The acoustic nonlinearity parameter was measured in turbine blades made of 403 stainless steel on Unit 5 at Virginia Power's Chesterfield Power Station during a maintenance outage. These blades were designed for a forty-year life and had been in service 34 years. Measurements were taken by holding two transducers in contact with and on opposite sides of the turbine blades. The transducers were placed and gently rocked back and forth until the amplitude of the received signal was maximized, in order to compensate for the curvature of the blades. A Harisonic 5 MHz, 0.5 inch diameter, damped PZT ultrasonic transducer was used to transmit a 5 MHz signal through the blades. The signal was generated by a system designed for nonlinear acoustics, with a 5 MHz, three-cycle tone burst, and passed through a 5 MHz low pass filter. The fundamental signal was detected with a 10 MHz single crystal, non-resonant lithium niobate transducer, passed though a 20 dB pre-amplifier and the nonlinear acoustics system receiver with 22 dB gain. The second harmonic signal was detected with the same 10 MHz lithium niobate transducer, passed through a 9.8 MHz high pass filter, a 40 dB preamplifier and the system receiver with 22 dB gain. One thousand samples of each of the fundamental and second harmonic signals were captured and averaged by a digital oscilloscope. The amplitudes were recorded from the oscilloscope display. The measurements were made at three locations on each of several turbine blades: near the outer tie wire, on the boss at the inner tie wire, and midway between the two tie wires. These are the areas of highest stress that we can reach, and where failures are most likely to occur. The measurement was repeated four or more times at each location. The blade root is another region of high stress and likely failures, but it is not accessible for this measurement. Figure 1 is a photograph of the turbine blades, showing the inner and outer tie wires and the region between them.

The measurement technique was replicated in the laboratory on specimens of aluminum 2024 and 410Cb stainless steel on which β had previously been measured. This allowed the nonlinearity parameter of the turbine blades to be calculated by the substitutional technique. The 410Cb stainless steel specimen, with β=7.2, was used as a reference for subsequent measurements because its structure and acoustic impedance are similar to the 403 stainless steel used in the turbine blades.

The measured amplitude of the acoustic wave is dependent upon the angle between the wave and the surface of the transducer, and the surface roughness. Therefore, a series of specimens with varying angles between the surfaces were fabricated of 410Cb stainless and finished to a surface roughness of about 63 rms, the roughness of the blades at installation, in order to study these effects. The acoustic nonlinearity parameter was measured in these canted specimens and the results are shown in Figure 2. A retired blade from another unit at the Chesterfield power station was cut at the measurement location and used to measure the angle between the surfaces at the boss near the tie wire, and at an area comparable to the midspan region where measurements were taken on the Chesterfield-5 blades. In both cases the angle between the surfaces was about 12^{o}. The correction factor for this angle and surface roughness was determined from the data in figure 1 to be 201% and was applied to the data. The measurements for other angles and surface finishes are reported elsewhere.

The nonlinearity parameter was also measured in ten-year old blades of 17-4Ph stainless steel at the Mt. Storm, West Virginia Power Plant for comparison with the data from the Chesterfield plant.

Figure 1. Turbine blades at Chesterfield plant. Measurements were taken near tie wires and midway between them. Turbine blades are approximately 85 centimeters long; tie wires are about 20 centimeters apart.

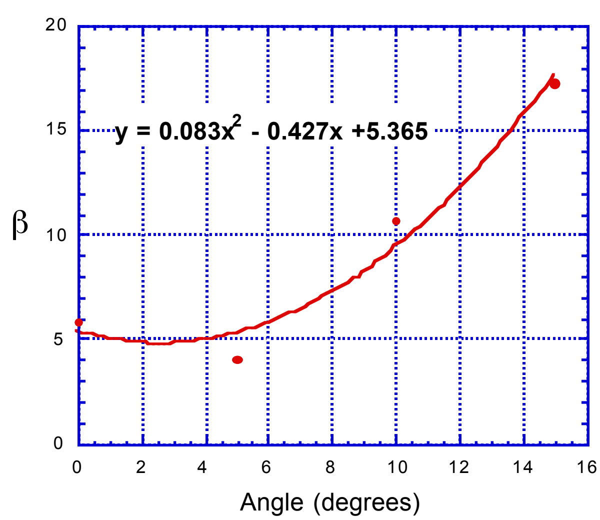

Figure 2. The effect of surface canting on the nonlinearity parameter of 410Cb stainless steel at a surface finish of rms 63.

EXPERIMENTAL RESULTS

The nonlinearity parameter was measured for 14 blades. The results are shown in figures 3-4. Figure 3 shows β for fourteen blades, corrected for the angle between the transducers. Five or more measurements at each location on each blade were taken, and the standard deviations calculated with two exceptions: only one measurement was taken at the inner tie wire on blade 44, and none on blade 98 due to limited access to the measurement location. The standard deviations are shown by the error bars. In most cases, the standard deviations were small, demonstrating the measurement is repeatable. The standard deviations on blades 2 and 29 at the inner tie wire were larger than most of the other measurements, indicating most likely an instability in transducer mounting. This measurement was taken on the boss at the tie wire. Placing the transducers near the edge of or on the radius of the boss causes some of the uncertainty in this measurement. A high standard deviation was seen in blade 1 at the point midway between the two tie wires. This is an area where the curvature of the blade is greatest and there is no distinguishing physical characteristic guiding placement of the transducers. In this case, the measurements may not have been taken exactly at the same location on the blade.

Figure 4a shows the average of all measurements made on the fourteen blades, with error bars indicating one standard deviation. The average β near the outer tie wire is 41.3, an increase of 474% over β of the virgin material. Near the inner tie wire, β is 27.3 and midway between the two tie wires β is 32.2, increases of 280 and 347% over the original value. This indicates that the region around the outer tie wire has experienced more fatigue induced damage than have the other two regions. The tie wires reduce the amount of flexural bending in the turbine blades during operation. The region around the inner tie wire would experience less bending due to constraints by the rest of the blade. In addition, the boss area around the tie wire is of greater thickness, increasing the flexural stiffness and further reducing bending. The area between the two tie wires is slightly less restrained and able to bend more, and would, therefore, see more fatigue loading. The standard deviations of these measurements indicate that the values of β at the inner tie wire and the midspan may be even closer than the mean values indicate.

The measurements from blades at Mt. Storm are shown in figure 4b. The nonlinearity parameter in these ten-year old blades was found to have increased by about 242% when compared to unfatigued material.

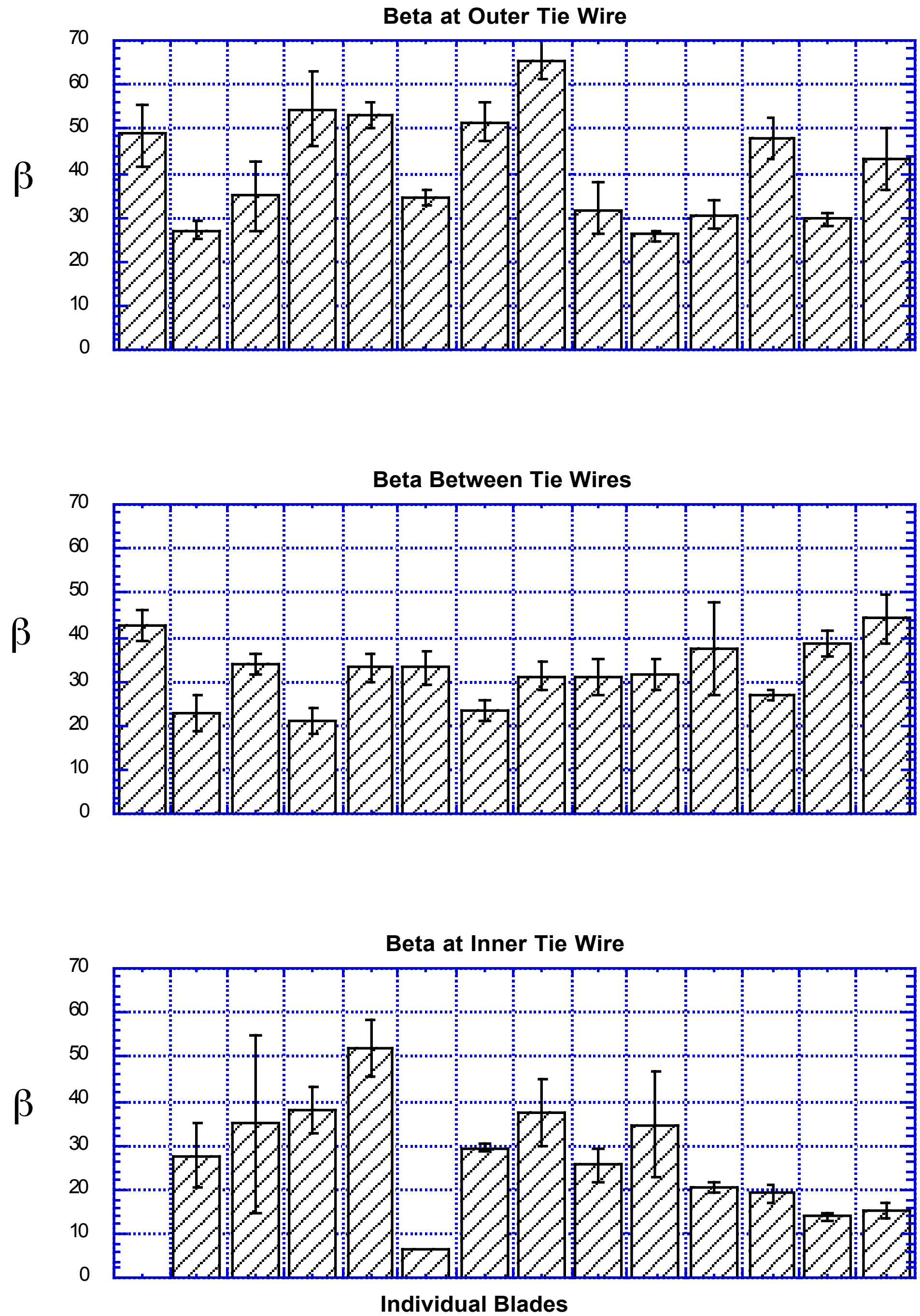

Figure 3. Beta measured at three locations on each of fourteen blades. Error bars indicate one standard deviation.

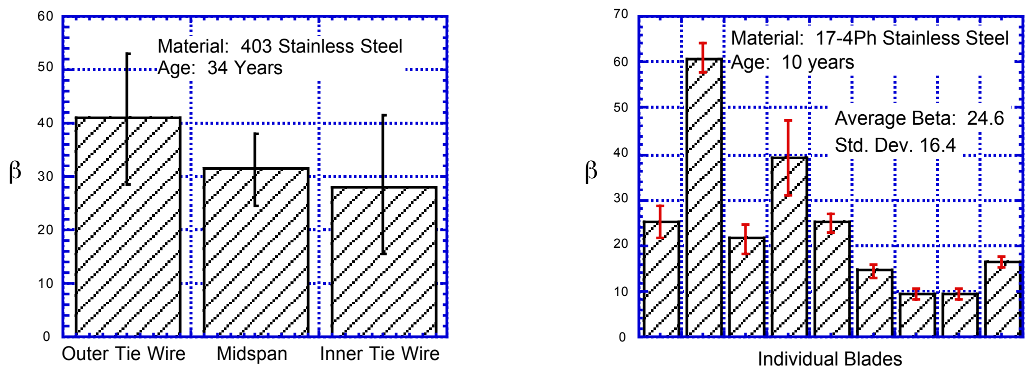

Figure 4. a. Average beta at three locations in 34-year old Chesterfield blades. b. Beta measured in 10-year old turbine blades at Mt. Storm Power Plant. Error bars indicate one standard deviation.

DISCUSSION

Precise placement of the transducers for measurement of β was found to be difficult. The physical space between blades is very small, making it difficult to hold the transducers in place. The amplitude of the ultrasonic signals will be greatest when the wave has a direct path from one transducer to the other. The transducers must be positioned on opposite sides of the blade with centers aligned. Because the blade surfaces are not flat, compensation must be made for the curvature of the blades. In most cases, several measurements were made while attempting to hold the transducers in the same locations. For these measurements, the amplitudes were repeatable. In cases where the transducers were removed from the blade surfaces and repositioned, the standard deviations are higher, and the measurements less repeatable. This indicates that the reproducibility in location of the transducers on the blade surface is the more critical factor, implying that we have a transducer positioning error or that we have a substantial point-to-point variation in β.

The data were corrected for the effect of the angle between the surfaces of the transmitting and receiving transducers. This angle was measured on a retired blade from another unit at Chesterfield, and was of a different design than those on the Chesterfield-5 unit. In the future, the angle will be measured at the time and location the beta measurements are made.

CONCLUSIONS

The acoustic nonlinearity parameter β was measured on fourteen L-0 turbine blades at the Chesterfield Power Station Unit 5 and eleven blades at Mt. Storm Unit 3. β was found to have increased in the Chesterfield turbine blades from that of the virgin material by as much as 474%. β is greatest at outer tie wire, less at inner tie wire. Midway between tie wires, β is slightly greater than at inner tie wire. This suggests that the region of the blade near the outer tie wire has been subjected to higher fatigue loads and experienced more fatigue damage than have the other two regions where measurements were taken. These values must be compared to values in failed blades to determine residual life. The increase in β for the Mt. Storm blades was 242%. These blades have been in service for only ten years, whereas the Chesterfield blades are 34 years old, and have been subjected to many more fatigue cycles.

The effects of surface angle and surface roughness were included in the measurements. The surface angle was estimated from measurements on a blade of similar, though not identical, design. The thickness of the blades, corresponding to the distance between the transducers, was measured with a micrometer. This measurement is not accurate because of the curvature of the blades. A more precise measure is needed for accurate measurement of β. It was assumed that the surface roughness of the blades had not changed since installation. This needs to be validated. The difficulty of making the measurements repeatably due to limited access and manual placement of the transducers needs to be addressed by designing and implementing a mechanical device that will also measure thickness and surface angle.

REFERENCES

1. Na, Jeong K., Cantrell, John H. and Yost, William T. in, *Review of Progress in Quantitative Nondestructive Evaluation,* Vol 15, (Plenum, New York, 1996), p. 1347.
2. Yost, William T. and Cantrell, John H., in *Review of Progress in Quantitative Nondestructive Evaluation,* Vol 18B, (Plenum, New York, 1999), p. 2345.
3. Na, Jeong K., Yost, W. T. and Cantrell, J. H., in *Review of Progress in Quantitative Nondestructive Evaluation,* Vol 19, (Plenum, New York, 2000).

REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	September 2000	Technical Memorandum

4. TITLE AND SUBTITLE
Field Measurement of the Acousitc Nonlinearity Parameter in Turbine Blades

5. FUNDING NUMBERS
WU 706-12-21-01

6. AUTHOR(S)
Yolanda L. Hinton, Jeong K. Na, William T. Yost, and Gregory L. Kessel

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Langley Research Center
Hampton, VA 23681-2199

U.S. Army Research Laboratory
Vehicle Technology Directorate
NASA Langley Research Center
Hampton, VA 23681-2199

8. PERFORMING ORGANIZATION REPORT NUMBER
L-17972

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001
and
U.S. Army Research Laboratory
Adelphi, MD 20783-1145

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA/TM-2000-210303
ARL-TR-2244

11. SUPPLEMENTARY NOTES
Hinton: U.S. Army Research Laboratory, Vehicle Technology Directorate, Langley Research Center, Hampton, VA; Na: Energy Services Group, Williamsburg, VA; Yost: Langley Research Center, Hampton, VA; and Kessel: Virginia Power, Glen Allen, VA

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Category 70 Distribution: Nonstandard
Availability: NASA CASI (301) 621-0390

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)
Nonlinear acoustics techniques were used to measure fatigue in turbine blades in a power generation plant. The measurements were made in the field using a reference based measurement technique, and a reference sample previously measured in the laboratory. The acoustic nonlinearity parameter showed significant increase with fatigue in the blades, as indicated by service age and areas of increased stress. The technique shows promise for effectively measuring fatigue in field applications and predicting subsequent failures.

14. SUBJECT TERMS
nondestructive evaluation; nonlinear acoustics; nonlinear ultrasonics; metal fatigue; field testing

15. NUMBER OF PAGES
12

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL