NASA/TM—2001-210812

# Neural-Net Processed Characteristic Patterns for Measurement of Structural Integrity of Pressure Cycled Components

A.J. Decker
Glenn Research Center, Cleveland, Ohio

March 2001

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's counterpart of peer-reviewed formal professional papers but has 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 cosponsored 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 data bases, 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 Access Help Desk at 301–621–0134

- Telephone the NASA Access Help Desk at 301–621–0390

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

NASA/TM—2001-210812

# Neural-Net Processed Characteristic Patterns for Measurement of Structural Integrity of Pressure Cycled Components

A.J. Decker
Glenn Research Center, Cleveland, Ohio

Prepared for the
12th Nondestructive Evaluation Subcommittee, 21st Rocket Nozzle Technology Subcommittee and 34th Structures and Mechanical Behavior Subcommittee Joint Meeting sponsored by the Joint Army, Navy, NASA Air Force Interagency Propulsion Committee
Cocoa Beach, Florida, March 26–30, 2001

National Aeronautics and
Space Administration

Glenn Research Center

March 2001

Available from

NASA Center for Aerospace Information
7121 Standard Drive
Hanover, MD 21076
Price Code: A03

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22100
Price Code: A03

Available electronically at http://gltrs.grc.nasa.gov/GLTRS

# NEURAL-NET PROCESSED CHARACTERISTIC PATTERNS FOR MEASUREMENT OF STRUCTURAL INTEGRITY OF PRESSURE CYCLED COMPONENTS

A.J. Decker
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

## ABSTRACT

A neural-net inspection process has been combined with a bootstrap training procedure and electronic holography to detect changes or damage in a pressure-cycled International Space Station cold plate to be used for cooling instrumentation. The cold plate was excited to vibrate in a normal mode at low amplitude, and the neural net was trained by example to flag small changes in the mode shape. The NDE (non-destructive-evaluation) technique is straightforward but in its infancy; its applications are ad-hoc and un-calibrated. Nevertheless previous research has shown that the neural net can detect displacement changes to better than 1/100 the maximum displacement amplitude. Development efforts that support the NDE technique are mentioned briefly, followed by descriptions of electronic holography and neural-net processing. The bootstrap training procedure and its application to detection of damage in a pressure-cycled cold plate are discussed. Suggestions for calibrating and quantifying the NDE procedure are presented.

## INTRODUCTION

Artificial neural networks have been demonstrated at NASA Glenn Research Center for some interesting potential applications to optical diagnostics of flows, structures and instrument alignment.[1-3] But the successful practical application of neural nets has been the detection of small variations in images caused by structural changes or damage.[4] That application used neural nets in an attempt to detect pressure-cycle induced damage in an International Space Station (ISS) instrumentation cold plate. The images used for NDE (non-destructive-evaluation) were the characteristic patterns or mode shapes generated by electronic time-average holography. Electronic time-average holography (sometime called television holography or electronic speckle pattern interferometry with a smooth reference beam) is described in many publications[5-7] and has been available commercially in one form or another for many years. For electronic time-average holography, the structure for NDE is excited to vibrate with a siren or shaker. The excitation may be broadband noise or at a single frequency to excite a single normal mode of vibration, but the vibration amplitude is very small. The amplitude is measured in wavelengths of visible light (typically $2\times10^{-5}$ in. or 500 nm). The simplest output image is a so-called Bessel fringe pattern that clearly displays the vibration mode shape as well as information about the vibration amplitude distribution. A vibration mode shape at low frequencies depends critically on boundary conditions and on the internal composition of the structure. The mode shapes can be monitored visually in an attempt to detect structural changes, but our new neural-net software add-on now allows them to be monitored automatically. The software uses artificial neural networks to flag small, gradual variations that might remain undetected by the eye. The current procedure requires only the recording of a few mode shapes generated experimentally from the structure before other tests are performed. Hence the effects on a mode shape can be monitored where the structural changes are induced by another test.

This paper is concerned mainly with the neural-net training procedure for NDE and approaches to calibrating that procedure. However, the paper begins in the next section by presenting a brief background on projects to develop the software and hardware needed for the procedure. Then electronic holography and neural-net processing are discussed in more detail, followed by the training procedure itself, under Apparatus. Finally the application to the Space Station Cold Plate is discussed followed by approaches to calibrating the NDE procedure.

## ADDITIONAL BACKGROUND

Development efforts encompass neural-net technology, structural and optical modeling, optical instrumentation, calibration and consistency with NASA standards. Developments of calibration and consistency with NASA standards[8-9] are most relevant to the NDE approach discussed in this paper. However, other development efforts are introduced briefly here for completeness. Some background on the development of the neural-net software is first presented, including a brief description of neural nets, structural and optical modeling and the necessary optical instrumentation

### *NEURAL NET TECHNOLOGY*

The most useful definition of an artificial neural network technology is any system whose input-output response is instantiated with a training set of exemplars.[10-11] The inputs to our nets consist of speckled Bessel fringe patterns generated from a vibrating structure. Figure 1 shows the Bessel fringe pattern from a vibrating blade. Outputs at different times have included model-generated distributions of vibration displacement (modified by some optical effects) and model-generated distributions of surface strain (also modified by some optical effects). But the most straightforward output is simply an indicator. The indicator flags significant changes in the Bessel characteristic fringe pattern. Determining the sensitivity to change and level of significance is part of the calibration problem. Using neural nets effectively requires the selection of an optimum training set, the selection of a neural-net algorithm or architecture, and the conditioning of the input data for optimum training of that architecture. The creation of optimum training sets is an on-going research problem in statistical decision theory.[12-13] A general objective is to create a generally noisy training set of input-output pairs that will provide optimum interpolation and some extrapolation regardless of the neural-net architecture while training the net to ignore irrelevant effects. Typically we actually use feed-forward nets trained with a version of the so-called back-propagation algorithm. We also use nets occasionally based on Adaptive Resonance Theory, but feed-forward nets are the most compact in software. The feed-forward net is described briefly below. Neural-net algorithms or architectures are discussed in books on neural networks.[10-11,14] Finally the format of the input data may need to be conditioned or altered for the particular neural-net architecture. Conditioning will be discussed in a reference.[15]

Figure 1—Bessel Characteristic Fringe Pattern.

### *STRUCTURAL AND OPTICAL MODELING*

The easiest way to create training sets is from model-generated data using finite-element models for the structures and optical models of electronic holography. The optical model is quite effective,[16] but sample-to-sample variations in structural mode shapes and the effects of boundary conditions have made the use of finite-element models less effective.[3] A hope is that the use of probabilistic finite-element models will ameliorate this situation somewhat. Model-generated modes however permit different neural-net strategies to be tested effectively.

### *OPTICAL INSTRUMENTATION*

We are continuing to develop electronic holography to record the characteristic patterns to be processed by the neural networks. As stated electronic holography is well developed for applications in the NDE laboratory and is supported by commercially available equipment. The challenge is to use electronic holography in the field for NDE of stationary and moving structures. Fiberscopes can be used to record electronic holograms of structures in generally inaccessible places. Figure 2 shows a mode shape of the vibrating fan blade depicted in fig. 1, but this time recorded through a fiberscope. It can be seen that the pattern recorded through the fiberscope is acceptable although closer examination would show some degradation. A more challenging problem is to record electronic holograms of objects that are moving. Examples include objects subjected to excessive environmental disturbances or the rotating components of a jet engine. Pulsed lasers can be used to freeze the motion of the object. Another approach, which has been tested at Glenn, is to use gated image intensifiers with continuous-wave lasers. Intensifiers unfortunately are noisy and have low spatial resolution. Magnifying the holograms prior to their amplification by the intensifier can be used to compensate for the low resolution, but reduces the portion of the object that can be inspected at one time. Figure 3 shows a square inch of a 50 kHz mode recorded from 200 microsecond exposures through a gated image intensifier showing that intensifiers can be used for electronic holography. Exposure times as short as 20 microseconds have been recorded. But exposures 2 orders of magnitude shorter (200 nanoseconds) are required at the tips of rotating fan blades. That level of performance would be achievable with frame-straddled double-exposure electronic holography implemented with a modern Nd:YAG laser and a frame straddling CCD camera. Such electronic holography has been conducted with an old-model laser with poor spatial matching of the double exposures, and the performance has been poor.

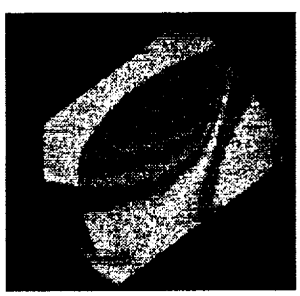

Figure 2—Bessel Fringes Through Fiberscope.

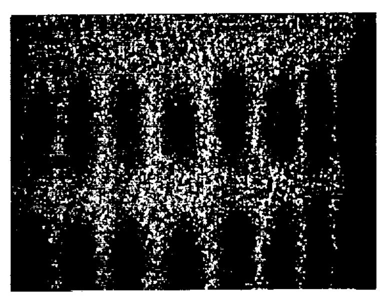

Figure 3—Bessel Fringes at 50 kHz From Image-Intensified Holograms.

The hardware and software necessary to perform neural-net NDE with electronic holography are now described. A measure of the sensitivity for damage detection is presented. Then a straightforward procedure is described for acquiring and instantiating the training sets. An application of that procedure to inspection of a pressure-cycled cold plate is discussed. The need for, and direction of, calibration activities are then discussed.

## APPARATUS

### *ELECTRONIC HOLOGRAPHY*

Electronic holograms are recorded with a CCD camera, or intensified CCD camera, frame-grabber combination. The holograms are processed in a computer to generate the so-called characteristic patterns shown in figs. 1, 2 and 3. A single hologram can be used to visualize a vibration characteristic pattern, but the fringe contrast is poor. In practice, tens, hundreds, or even thousands of holograms may be recorded to increase contrast, reduce electronic noise, reduce speckle-effect noise and extract quantitative displacement data. Figure 3, using an intensified CCD camera, required averaging 100 characteristic patterns. But the simplest contrast-increasing step only two holograms as shown below. Then the vibration characteristic patterns can be sampled as much as 30 times per second. Hence, our neural-net inspections generally have been performed with hologram pairs.

An electronic hologram is an interference pattern formed between an image of a laser-illuminated object and a coaxial reference beam. The interference pattern is formed on the CCD array or on the intensifier. It may be necessary to magnify or scale the interference pattern for a low-resolution intensifier as was done for the mode in fig. 3. The instantaneous value of the interference pattern for a structure vibrating in a normal mode is given by

$$I_1 + I_2 \cos(\varphi - 2\pi\mathbf{K}\bullet\delta)$$

where $I_1$, $I_2$, and $\varphi$ are random variables associated with the laser speckle effect. However, $\delta$ is the instantaneous displacement at a point on the vibrating structure. The vector **K** is called the sensitivity vector and is a parameter of the illumination and imaging system.

If two identical holograms with identical speckle patterns are recorded at the same displacement value, but shifted in phase by $\pi$, and if the holograms are subtracted, then only the so-called cross-interference term

$$2\, I_2 \cos(\varphi - 2\pi\mathbf{K}\bullet\delta)$$

is the remainder. This step is the simplest contrast enhancement step in electronic holography.

In fact, the structure vibrates during the exposure. If the structure vibrates for one or more complete cycles, then the cross-interference term is given by

$$I_3\, J_0(2\pi\mathbf{K}\bullet\delta)$$

where $I_3$ is a random variable encoding the laser speckle effect and $J_0$ is the zero-order Bessel function of the first kind. Here $\delta$ is the displacement amplitude. The absolute value of this Bessel fringe pattern is displayed in figs. 1 and 2. Figure 3 in fact averages 100 such patterns.

In a laboratory, electronic holography can be performed with an ordinary interlaced TV camera. The pair of holograms is recorded in adjacent frames of the camera, and the phase is shifted by $\pi$ between frames. This technique needs to be modified outside the laboratory at least to minimize the effects of environmental disturbances. Then so-called frame straddling is employed. As a first step, the exposure time needed to record the hologram is minimized. (For example, the shortest time to time-average a1000 Hz mode is 1 millisecond.) In frame straddling, one hologram is recorded at the very end of a frame and the second hologram of the pair is recorded at the very beginning of the next frame. The inter-frame time is less than 1.0 microsecond for some cameras; thereby the time between holograms for extraneous environmental disturbances is minimized. A second application of frame straddling is double-exposure holography performed with a double-pulse laser. Double-exposure holography can be performed without phase shifting, if the structure moves between the two exposures. Subtracting the two holograms yields a characteristic pattern given by

$$I_2 \, Cos(\varphi - 2\pi \mathbf{K} \bullet \delta_2) \; - \; I_2 \, Cos(\varphi - 2\pi \mathbf{K} \bullet \delta_1)$$

where a point on the vibrating structure is at different displacements for the exposures. An interlaced camera can be used for frame straddling, but adjacent video fields must be subtracted resulting in a significant reduction in quality. Frame transfer cameras have been developed for frame straddling in particle velocimetry. One discussion of the frame straddling technique in particle velocimetry is given in a reference.[17]

The remainder of this paper assumes Bessel characteristic patterns. The assumption is that at least one complete vibration cycle is recorded in each frame.

## *NEURAL-NET PROCESSING*

A neural-net application as stated is defined by a training set of input-output exemplars. The training set is used to train an architecture or algorithm embedded in software (or hardware). The simplest example is to use characteristic patterns such as shown in figs. 1, 2 and 3 to train a neural net to distinguish un-cracked specimens from those that develop a particular kind of crack. This example has been studied using simulations and then tested on actual structures.[18-19] These simulations produce estimates of the sensitivity of the NDE method discussed herein. The simulations in the references used finite element models and a model of the electronic holography process to calculate vibration characteristic patterns for cracked and un-cracked versions of cantilevers and fan blades. The minimum detectable difference in the displacement distribution between the cracked and the un-cracked structures was then determined. In fact, electronic holography estimates the distribution of the quantity $\mathbf{K} \bullet \boldsymbol{\delta}$. But the vectors **K** and $\delta$ are often nearly parallel thereby yielding the distribution of $\delta$. Cases where **K** varies significantly are harder to handle. Then one must arrange the most favorable view of the region most likely to be damaged.

The neural nets developed for the referenced studies have been able to detect changes in the characteristic patterns corresponding to displacement amplitude changes smaller than 1 percent of the maximum displacement amplitude. It is to be noted that a crack at a single location affects the characteristic pattern over much of the structure. Hence the damage is communicated to the net at several pixels and therefore at several inputs.

Briefly, the following specific properties defined the neural-net training sets and the neural nets used for the referenced studies. First, the resolutions of the characteristic-pattern inputs were reduced to the extent that the number of pixels equaled the number of finite elements in the simulations. Figure 4 shows a finite-element-resolution characteristic pattern of a blade vibrating in its first mode. This pattern involved some conditioning.[15] The model depicted here used 903 finite elements. One advantage of the lower resolution is that the CCD and computer combination responded at 30 frames per second. Second, the training sets contained independent examples of the speckle pattern. Previous research has shown that the number of independent speckle patterns must constitute about 10 percent of the number of pixels which equals the number of finite elements.[16] About 100 patterns are required for the 903 finite elements. The output most simply consisted of 2 or 3 classification nodes. The simplest case contains the cracked or un-cracked classes. The third case adds an unrecognized class where the patterns represent neither the cracked or un-cracked training examples. The third case might represent conditions where the vibration amplitude is out of range.

Figure 4—Finite-Element-Model Pattern
at Finite-Element Resolution.

The neural-net architecture which is most compact in software is the feedforward net depicted in fig. 5. The nodes or neurons in the net sum their inputs, transform the sums nonlinearly, and fan the outputs to nodes in the next layer. Training is accomplished by various versions of the so-called back propagation algorithm.[10-11] There are three objectives for a net. It should learn the training set; it should generalize by handling legitimate cases not found in the training set; and it should learn quickly. The neural-net technology used for NDE satisfies these criteria. The details are part of the neural-net-technology aspect of this work and are discussed in the references.

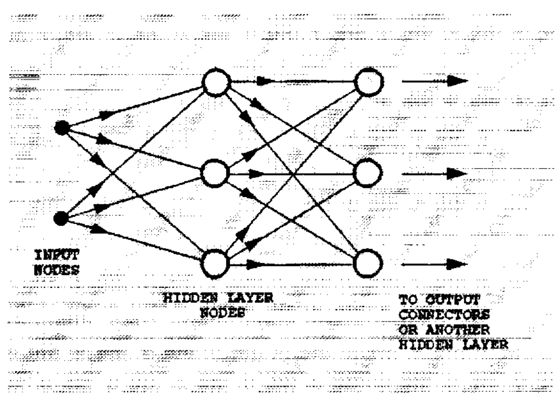


Figure 5—Diagram of Feedforward Neural Network.

The training procedure used for NDE of the ISS cold plate differs in some details from the procedures used to develop the neural-net technology and to test for sensitivity. That procedure is described in the next section.

## TRAINING FOR NDE

The training procedure is a bootstrap procedure and strictly ad-hoc at this stage of development. Four experimentally visualized vibration modes and 4 associated characteristic patterns were selected. One of these patterns was the un-excited pattern, where only environmental effects were present. One of the remaining patterns was selected as the pattern to be monitored for structural changes. The other two vibration patterns as well as the un-excited pattern were selected as examples of significantly changed patterns. The pattern to be monitored for changes was assigned a particular output coding. All the other patterns were assigned another code. A code is contained in 2 or 3 output nodes. For training, a node is assigned the value 0.2 or 0.8 (the values differ from 0 and 1 because of the normalization requirements of the net architecture). The only other requirement for adequate training is that each mode has enough independent speckle patterns to impart speckle pattern immunity. Independent speckle patterns are easy to generate; since the net requires fewer pixels than recorded by the camera. Each pixel retained is considered to be a large pixel containing many of the smaller camera pixels. One small pixel is selected at random for each large pixel to generate a sample pattern. The process is continued until enough samples have been recorded for each mode. As stated previously, the required number of samples is about 10 percent of the number of large pixels. Calculating the correlation coefficients between samples of the same mode is used to check the effectiveness of the process.

Executing the training process for a feedforward net consists of minimizing the rms error between the training outputs and the net-generated outputs. A typical rms error is 0.01. The output values generated by the net are not exactly 0.2 or 0.8, and some tolerance must be assigned.

The procedure described so far has been a formula procedure: Select 4 modes; select one mode to be monitored; assign a code to that mode and a code to the remaining 3 modes; record enough uncorrelated speckle patterns for each mode; and train the neural net. Unfortunately the selection of the modes, the accompanying adjustment of sensitivity and the selection of neural-net tolerances are not formula procedures at this time. This ad-hoc nature of the bootstrap procedure is discussed next.

First, different sets of 4 training-modes-per-set do not perform the same for showing a particular structural effect. Boundary conditions, affected for example by setting mounting-bolt torques, always have a very significant effect on the neural-net response for lower frequency modes. But maximizing the response of the net for changes at a particular location on a structure is a trial-and-error procedure. Currently that location is perturbed in some way (by application of a light point load for example) to test sensitivity. The mode mixture is adjusted for best sensitivity. The net needs to be trained and tested for each candidate set of modes to test for best sensitivity.

Second, the output of the neural net must be interpreted. Thresholds must be set. The output of a feed forward net does not and should not change abruptly as the inputs differ from the training set. Environmental disturbances such as air currents and extraneous vibrations have an effect that must be discounted in setting the threshold. An advantage of the feedforward net is its insensitivity to optical effects such as contrast changes and brightness changes. But there is some degradation of the outputs in response to these optical effects. Graceful degradation is the objective. In the absence of a statistically correct methodology for setting thresholds, the criterion has been arbitrary. Typically, outputs larger than 0.65 or 0.7 are declared to differ insignificantly from the training output 0.8. Another criterion is that high outputs in the 2-or-3-node codes for two different classes differ by at least 0.2, although that distinction has not been required in practice.

A result of using the existing ad-hoc NDE procedure is discussed next followed by a discussion of approaches to calibrating the technique.

## RESULTS AND DISCUSSION

### *USE OF NDE PROCEDURE FOR A COLD PLATE TEST*

The ad-hoc NDE procedure is exemplified by a discussion of its application to a test of an ISS instrumentation cold plate.[4] A cold plate was bolted to a frame through several of the holes intended for mounting instrumentation to the cold plate. Bolt torque was quite critical for this test; since modes shapes are very sensitive to the boundary conditions. The objective was to pressure cycle the plate, with its cooling passages filled with water, to test for structural integrity. Neural-net-processed electronic holography was used to inspect the plate for structural changes before, during and after pressure cycling. Both the entire plate and a suspicious zoomed region between 4 bolt holes were tested at different times. Different mode mixtures were used for the two tests. A total test procedure, which employed both classical silver-halide-emulsion holography and electronic holography, is discussed in the reference. Only the application of neural-net-processed electronic holography between the 4 bolt holes is discussed as an example of the NDE procedure.

The test was conducted in a laboratory on a vibration-isolation table. Electronic holography does not require the full vibration-isolation of the table, but silver-halide-emulsion holography does. The bolt holes were on 4 in. (10 cm.) centers. A zoomed electronic holography test was performed on a suspicious region (visualized previously with an ultrasonic C-scan) between 4 holes. The zoomed test actually followed an inspection of the entire plate performed during 2000 pressure cycles. The 4 steps of the application to the cold plate of the general ad-hoc procedure are stated specifically.

First 4 training modes were selected. The large-pixel zero-amplitude pattern is shown in fig. 6, where the neural-net input consisted of 40x54 large pixels. The 3 vibration modes had frequencies of 2310 Hz, 780 Hz and 1597 Hz and are shown at full resolution in fig. 7 along with 2 additional modes that were also evaluated in the trial-and-error procedure.

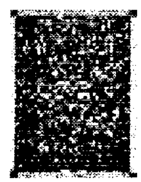

Figure 6—Large-Pixel Zero-Amplitude Pattern of Cold-Plate Segment.

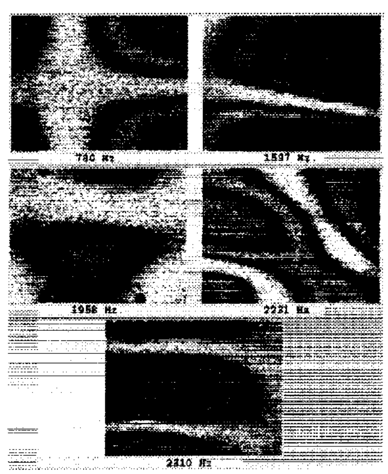


Figure 7—Modes that Contain Cold-Plate Training Mixture.

Second trial-and-error training indicated that the mode at 2310 Hz was most sensitive to perturbations, and that mode was selected for inspection. The zero-amplitude pattern and the modes at 780 Hz and 1597 Hz were selected as training examples of changed patterns. According to the 10-percent formula mentioned previously, 216 independent speckle patterns were acquired for each mode. Software automatically directed the acquisition of these speckle patterns.

Third, the neural-net outputs corresponding to the modes were encoded and interpreted as stated above. The output of the net was immediately converted by software into colored large-pixel characteristic patterns to make visualization easier. Patterns measured as unchanged from the training pattern at 2310 Hz were colored green. Otherwise the patterns were colored yellow.

Fourth, the net was trained and used for inspection. Training to a rms error of 0.01 occurs in a few minutes.

The execution of these four steps and the use of the trained net for inspection constituted the ad-hoc NDE procedure. The cold plate was pressure-cycled 1000 times during the application of the procedure and simultaneously excited to vibrate at 2310 Hz. Pressure cycling proceeded at 0.2 Hz, and the plate was continuously monitored with the holography, neural-net combination. The test was also interrupted every 250 cycles to record 20 neural-net-processed characteristic patterns at the pressure-relaxed condition. The test showed no neural-net detectable changes in the characteristic pattern at the pressure-relaxed condition. However, the net did flag the mode shape of the pressurized plate as different. Figure 8 shows the large pixel output of the holography, neural-net combination for the relaxed and pressurized conditions. Figure 8 can be compared with fig. 7 that shows the full-resolution characteristic pattern. As can be seen, the full-resolution pattern extends outside the region that was inspected shown in fig. 8.

Figure 8—Net-Colorized Characteristic Patterns for
Relaxed and Pressurized Cold-Plate Segments.

The neural net detected no significant changes in the characteristic pattern during or after 3000 pressure cycles to 120 psig (827 kPa). The 20-pattern sets recorded of the region between the 4 bolts showed no indication of a change. Some of the patterns recorded of the whole cold plate were flagged as changed, but these changes were associated with a period of instability of some of the electronic accessories the holography setup. That instability caused a large decrease in contrast of some of the characteristic patterns.

### *CALIBRATION AND QUANTIFICATION OF THE PROCEDURE*

So far the NDE procedure has been straightforward but only semi-quantitative. That is, only simulations have proven that pattern changes equivalent to displacement-amplitude changes of 1 percent or less of the maximum displacement amplitude are detected. These simulations have involved fan blades rather than complex structures like the cold plates. Three approaches have been proposed for full quantification of the NDE procedure.

The first approach uses deterministic finite-element modeling for the structure to be tested. The patterns predicted from deterministic finite-element models have been found to be generally not accurate enough to train a neural net for inspections of an actual sample of a physical structure.[3] But the modes predicted may be accurate enough to test the net for sensitivity as a function of training-mode mixture, if the structural damage can also be modeled or if the displacement distribution can be perturbed by known amounts. This approach was used to evaluate neural-net sensitivity for detecting blade cracks and is the source of the 1 percent estimate of sensitivity.

The second approach would use probabilistic finite-element modeling techniques. Then a range of patterns would be generated including some patterns that were "out-of-range". The net would be trained to ignore normal structural variations and to flag out-of-range patterns that might indicate structural damage. Stochastic variations in the environment and electronic holography can also be added to create a neural-net detection of a limit state.

The third approach would attach the new neural-net, holography NDE to existing vibration testing procedures[8-9] making it perhaps more acceptable to the NDE community. Out-of-range conditions would be specified with displacement, strain or force gages. The neural-net NDE would be performed periodically during the normal test procedures. This approach has the advantage that the calibration or quantification procedure would be developed in cooperation with personnel who normally do the vibration testing.

The second and third approaches have been included in proposals directed to NASA project offices.

## SUMMARY AND CONCLUSIONS

A NDE procedure has been developed at Glenn to use artificial neural networks to detect structural damage or structural changes from the characteristic patterns or mode shapes recorded using electronic holography. The electronic holograms have been recorded using CCD and intensified-CCD technology directly and through fiberscopes. The electronic-holography visualization technique is sensitive to the vibration-displacement distribution of the structure. The procedure is a simple 4-step procedure, but so far is un-calibrated. Nevertheless, the procedure's sensitivity has been estimated by using finite-element-model simulations and laboratory tests. The procedure has been applied to inspection of a ISS cold plate for pressure-cycle-induced damage or changes. The cold plate passed the test in that significant damage or changes were not detected.

Perhaps the major conclusion is that artificial neural nets definitely can be used to automate the sometimes-tedious inspection of structural images for changes.

The 4-step procedure is easy to apply and permits the performance of whole- surface inspections for structural damage or changes. The inspections can be performed in real time (30 frames per second using standard video cameras). But the procedure is ad-hoc. Four vibration modes must be selected for training the neural net and the sensitivity must be adjusted by varying the mode selection. That sensitivity adjustment is currently a matter of judgment based on the characteristics of the sample. Hence efforts have been proposed to calibrate or quantify the procedure. These efforts will apply: finite element models, probabilistic finite element models, or correlations with sensor readings used in implementing existing NASA standards.

## REFERENCES

1. A.J. Decker and A.E. Buggele, "Automation of Some Operations of a Wind Tunnel Using Artificial Neural Networks," *AIAA J. 34,* pp. 421–423, 1996.
2. A.J. Decker, "Self-Aligning Optical Measurement Systems," *Applied Optics 31,* pp. 433–4340, 1992.
3. A.J. Decker, "Neural-Net Processing of Characteristic Patterns," *Topics on Nondestructive Evaluation Series, Volume 4, Automation, Miniature Robotics and Sensors for Nondestructive Evaluation and Testing,* Yoseph Bar-Cohen, Technical Editor (The American Society for Nondestructive Testing, Inc., 2000), Chapter 7.1.
4. A.J. Decker, M.E. Melis and K.E. Weiland, "Inspection of Space Station Cold Plate Using Visual and Automated Holographic Techniques," NASA/TM—1999-209388, Aug. 1999.
5. K.A. Stetson and W.R. Brohinsky, "Fringe-Shifting Technique for Numerical Analysis of Time-Average Holograms of Vibrating Objects," *Journal of the Optical Society of America A5.* pp. 1472–1476, 1988.
6. S. Nakadate, "Vibration Measurement Using Phase-Shifting Speckle-Pattern Interferometry," *Applied Optics 25,* pp. 4162–4167,1986.
7. K.A. Stetson and W.R. Brohinsky, "Electro-Optic Holography System for Vibration Analysis and Nondestructive Testing," *Optical Engineering 26,* pp. 1234–1239, 1987.
8. "Dynamic Environmental Criteria," *NASA–HDBK–7005,* 2000.
9. "Payload Vibroacoustic Test Criteria," *NASA–STD–7001, Jun. 1996.*
10. Yoh-Han Pao, *Adaptive Pattern Recognition and Neural Networks.* Addison-Wesley, New York, 1989.
11. B.D. Ripley, *Pattern Recognition and Neural Networks.* Cambridge University Press, New York, 1996.
12. M.T. Manry, et al., "Cramer Rao Maximum A-Posteriori Bounds on Neural Network Training Error for Non-Gaussian Signals and Parameters," *International Journal of Intelligent Control and Systems 1,* pp. 381–391, 1996.

13. M.T. Manry, S.J. Apollo and Q. Yu, "Minimum Mean Square Estimation and Neural Networks," *Neurocomputing 13,* pp. 59–74, 1996.

14. D.E. Rumelhart, et al., *PARALLEL DISTRIBUTED PROCESSING, Explorations in the Microstructure of Cognition, Volume 1: Foundations.* MIT Press, Cambridge, 1988.

15. A.J. Decker, "Optimization of Training Sets for Neural-Net Processing of Characteristic Patterns from Vibrating Solids," to be published in SPIE Proceedings.

16. A.J. Decker, E.B. Fite, Oral Mehmed and S.A. Thorp, "Processing Speckle Patterns With Model Trained Neural Networks," *Optical Technology in Fluid, Thermal, and Combustion Flow III, Proc. SPIE 3172,* pp. 285–293, 1997.

17. M.P. Wernet, "Particle Displacement Tracking Applied to Air Flows," *NASA TM–104481,* Aug. 1991.

18. A.J. Decker, E.B. Fite, O. Mehmed and S.A. Thorp: "Vibrational Analysis of Engine Components Using Neural-Net Processing and electronic Holography," *Advanced Non-Intrusive Instrumentation for Propulsion Engines, AGARD–CP–598,* pp. 33-1–33-6, May 1998.

19. A.J. Decker, E.B. Fite, S.A. Thorp. and O. Mehmed "Comparison of computational-model and experimental-example trained neural networks for processing speckled fringe patterns," *International Conference on Optical Technology and Image Processing Fluid, Thermal, and Combustion Flow, Proceedings of VSJ–SPIE '98,* **on compact disc in pdf, paper AB002,** December 1998.

# REPORT DOCUMENTATION PAGE

*Form Approved*
*OMB No. 0704-0188*

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

| 1. AGENCY USE ONLY *(Leave blank)* | 2. REPORT DATE | 3. REPORT TYPE AND DATES COVERED |
|---|---|---|
| | March 2001 | Technical Memorandum |

**4. TITLE AND SUBTITLE**

Neural-Net Processed Characteristic Patterns for Measurement of Structural Integrity of Pressure Cycled Components

**5. FUNDING NUMBERS**

WU–323–78–00–00

**6. AUTHOR(S)**

A.J. Decker

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**

National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135–3191

**8. PERFORMING ORGANIZATION REPORT NUMBER**

E–12727

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**

National Aeronautics and Space Administration
Washington, DC 20546–0001

**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**

NASA TM—2001-210812

**11. SUPPLEMENTARY NOTES**

Prepared for the 12th Nondestructive Evaluation Subcommittee, 21st Rocket Nozzle Technology Subcommittee and 34th Structures and Mechanical Behavior Subcommittee Joint Meeting, sponsored by the Joint Army, Navy, NASA Air Force Interagency Propulsion Committee, Cocoa Beach, Florida, March 26–30, 2001. Reponsible person, A.J. Decker, organization code 5520, 216–433–3639.

**12a. DISTRIBUTION/AVAILABILITY STATEMENT**

Unclassified - Unlimited
Subject Categories: 35 and 38 Distribution: Nonstandard

Available electronically at http://gltrs.grc.nasa.gov/GLTRS
This publication is available from the NASA Center for AeroSpace Information, 301–621–0390.

**12b. DISTRIBUTION CODE**

**13. ABSTRACT** ***(Maximum 200 words)***

A neural-net inspection process has been combined with a bootstrap training procedure and electronic holography to detect changes or damage in a pressure-cycled International Space Station cold plate to be used for cooling instrumentation. The cold plate was excited to vibrate in a normal mode at low amplitude, and the neural net was trained by example to flag small changes in the mode shape. The NDE (nondestructive-evaluation) technique is straightforward but in its infancy; its applications are adhoc and uncalibrated. Nevertheless previous research has shown that the neural net can detect displacement changes to better than 1/100 the maximum displacement amplitude. Development efforts that support the NDE technique are mentioned briefly, followed by descriptions of electronic holography and neural-net processing. The bootstrap training procedure and its application to detection of damage in a pressure-cycled cold plate are discussed. Suggestions for calibrating and quantifying the NDE procedure are presented.

**14. SUBJECT TERMS**

Neural networks; Nondestructive evaluation; Electronic holography

**15. NUMBER OF PAGES**

17

**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 | |

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102