A NONINTRUSIVE ROTOR BLADE VIBRATION MONITORING SYSTEM*

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ABSTRACT

A technique for measuring turbine engine rotor blade vibrations has been developed as an alternative to conventional strain-gage measurement systems. Light probes are mounted on the periphery of the engine rotor casing to sense the precise blade passing times of each blade in the row. The timing data are processed on-line to identify (1) individual blade vibration amplitudes and frequencies, (2) interblade phases, (3) system modal definitions, and (4) blade static deflection. This technique has been effectively applied to both turbine engine rotors and plant rotating machinery.

BACKGROUND

Introduction

The conventional method of measuring turbine engine rotor blade vibrations during engine operation uses strain gages attached directly to the surfaces of the blades. The strain-gage signals are transmitted from the rotor to stationary signal conditioners through radio telemetry or slip rings. The gages and wiring, located internal to the engine, have a high failure rate and can degrade the engine performance. Repairing strain gages and wiring often requires disassembly of the engine, resulting in test delays and increased costs.

A system for measuring blade-tip deflection as an alternative to using strain gages was developed at AEDC. This system evolved from a technology effort to produce a large, multiple-row Noninterference Stress Measurement system (NSMs). After a full-scale prototype was successfully produced, the need was identified to produce a smaller, more portable and inexpensive system. This later version, now referred to as the NSMS, was developed and installed in a large axial-flow compressor to monitor blade-tip deflections. Additionally, the NSMS has been applied to rotating blades on turbine engine tests, and has been used to characterize torsional static deflections and vibrations of drive motor shaft couplers. Although the new NSMS is specifically tailored for its current application, the system is upgradeable in speed and capacity to meet higher-speed turbine engine applications.

The nonintrusive blade vibrational measurement and analysis technique uses blade-tip sensors, mounted in the engine casing around the periphery of the rotor stage, to sense the arrival of passing blades. These blade passing events are precisely timed and the subsequent data are processed to describe the vibratory characteristics of each of the blades. Blade vibratory frequencies are integrally or nonintegrally related to the rotor rotational frequency. Integral vibration frequencies are more difficult to detect because the signals, sampled at the rotor frequency, are aliased to zero frequency. In general, more blade-tip sensors and unconventional processing techniques are required to extract integral vibration information. Nonintegral vibration frequencies are not integer multiples of the rotor speed; therefore, conventional time-series and frequency analysis techniques can be used in the signal processing.

* The research reported herein was performed by the Arnold Engineering Development Center (AEDC), Air Force Materiel Command. Work and analysis for this research was performed by personnel of Sverdrup Technology, Inc./AEDC Group, technical services contractor. Further reproduction is authorized to satisfy the needs of the U.S. Government.

Presented at the International Gas Turbine and Aeroengine Congress & Exhibition
Birmingham, UK — June 10-13, 1996
The NSMS has proved to be a viable system for measuring rotor blade vibrations. Some of the uses include:

1. Monitoring peak and rms vibration of all blades in each row
2. Detecting individual problems including bent, cracked, resonating, loose, and out-of-tune blades
3. Detecting system modes of vibration while identifying interblade vibration phases, amplitudes and nodal diameters
4. Providing on-line Campbell diagrams relating vibrational resonances to rotor speed
5. Providing archived digital data for all blades.

This report presents the measurement and processing principles of a blade-tip vibration measurement system developed at the Arnold Air Force Base test facilities. The system functional description and application examples for engine and plant rotating machinery are included.

NSMS Concept

The functional operation of the NSMS is shown in Fig. 1. Blade-tip sensors located on the periphery of the engine casing sense blade passing events. A 1/rev (or multiple per rev) sensor provides a synchronization signal for determining rotor shaft speed and blade indexing information. Sensor outputs are conditioned and processed to provide vibration information of all blades in the instrumented blade row.

NSMS DESCRIPTION

Overview

The functional components of the NSMS (Fig. 2) include the blade tip and shaft revolution sensors, on-line monitoring system, and the main processing system. Up to four blade-tip sensors, mounted in the casing along the blade-tip circumferential path, provide measurements of blade passing events. An optional multiple/rev (M/rev) sensor complements the 1/rev sensor in determining rotor shaft speed and acceleration conditions. The monitoring system conditions, processes, stores, and produces near real-time displays for monitoring purposes. The main processor provides more detailed analysis and can optionally support the monitoring system on-line or be used to process data retrieved from data storage.

The major components of the monitor processor are shown in Fig. 3. Optical signals from each blade tip (or optical rev sensors) are detected by a photodiode circuit. Analog pulses from the photodetector are shaped to digital pulses by the pulse shaper and inputted to the pulse-to-digital converter. The pulse-to-digital converter uses digital clocks with programmable clock frequencies to time the blade passing events relative to the 1/rev pulse. Digital data from each of the converters are transferred via the VME bus to the display and recording processor. Unprocessed data, stored in a 1-Gb hard disk, can be off-loaded to a 150-Mb Bernoulli disk for archiving purposes. Unprocessed data are also transmitted via an Ethernet line to a workstation which produces on-line displays of time, frequency and modal analysis results.

The NSMS performance specifications are as follows:

- Maximum rotor speed: 30,000 rpm
- Maximum blade-tip sensor inputs: 4
- Maximum blade rows: 4
- Maximum number of blades per row: 100
- Blade geometry: Unshrouded blade tips
- Blade vibration frequency: > (number of blades/2) x (rpm/60)
- Blade vibration deflection resolution: 0.03 mm peak
- Data acquisition rate: 200 k samples/sec maximum = (no. of blades x rpm/60 x no. of sensors)
- Data storage capacity: 1 Gb before offloading
- Archiving storage capacity = 150 Mb per Bernoulli disk.
Blade-tip sensors required per blade row: 1 to 4, depending on measurement/processing requirements.

Blade-tip sensors light source: 750-mw diode laser for each sensor; 810-nm wavelength

1/Rev sensor: choice of magnetic or optical.

Use of magnetic sensor results in diminished resolution

M/Rev sensor: optical (same as 1/rev optical).

**Sensors**

From one to four blade tip sensors can be installed on up to four blade rows in any combination. Nonintegral data acquisition and processing requires one or two sensors per blade row. Integral data require from one to four sensors per row, depending on the processing techniques and desired results. Sensor circumferential separation distances must be compatible with the range of frequencies to be measured. In general, the sensor spacings must be less than one-half of the blade's vibration cycle in order to maintain accurate vibratory phase information. When traveling wave analysis is required to characterize the rotor-blade system vibratory modes, the sensor spacings allowed are inversely proportional to the number of nodal diameters defined by the array of vibrating blades.

A functional schematic of a blade-tip sensor is shown in Fig. 4. The source light is directed through fibers and focused through a lens into the path of passing blades. Each passing blade reflects a portion of the source light which is then transmitted through receiving optical fibers to a photodetector. State-of-the-art sensors should detect each blade arrival position within 0.03 mm. The 1/rev sensor should have the same measurement resolution as the blade-tip sensor. Some test applications are limited to using a magnetic 1/rev sensor which results in decreased measurement accuracies due to the sensor's slow response time.

The two types of blade-tip sensors usually used are (1) spot focus and (2) line focus. Spot focus sensors (Fig. 4) project a small spot-of-light footprint in the blade-tip path. Used alone, a spot focus sensor cannot resolve the vector components of blade vibration which are necessary if conversion to stress is required. However, the spot focus sensor is smaller, less expensive, and the most commonly used sensor. The line focus sensor is used in defining the blade vibration vector components which are necessary if conversion to blade stress is
A first-order correction for acceleration effects can be accomplished by calculating windows of displacement (Fig. 6) within each revolution where the blade pulses are expected to occur. Pulse signals falling outside the windows are counted as noise; signals within the windows are counted as blade-tip data. The displacement windows are calculated using the 1/rev time, rotor blade-tip circumference, and the blade separation distances around the rotor. Individual blade deflections are calculated as differences between the instantaneous measured blade displacement and the center of the window. An error can occur in the calculation of the displacement windows if the rotor speed is changing (accelerating) within the respective revolution. A first-order correction for acceleration effects can be made by determining the speed change between revolutions using the 1/rev sensor measurements to correct each blade displacement window. If a multiple/rev sensor signal is available in addition to the 1/rev signal, acceleration corrections can be made with improved accuracy.

**Photodetector & Conditioning**

The photodetector has the sensitivity to detect the reflected light, and the response time and stability to define the blade movements within the required resolution. At the current state-of-the-art light probe resolution of 0.03 mm, the response time required at typical blade-tip velocities of 800 m/sec is approximately 37 nsec. Photodetector temperature drift and instability are minimized through temperature compensation circuitry.

Trigger circuitry for converting the photodetector signal to a digitally shaped pulse has adjustable gain and trigger levels and includes hysteresis for noise rejection. Provisions are included for optionally triggering on the photodetector signal rising or falling edges. The pulses are converted to digital words representing the precise times, within the respective rotor revolution, that the blades pass the blade-tip sensor. The digital data must have sufficient resolution (typically 18 to 20 bits) to define the blade-tip measurement within 0.03 mm.

**Monitor Processor**

The monitor processor transfers digital data from the photodetector signal conditioning via the VME bus to an Ethernet controller for transmission to the main processor and to an embedded PC for processing, displaying and storing data. A graphical user interface allows the operator to dynamically select display, and recording functions during data acquisition. Data stored on the 1-Gb hard disk are available for rapid playback or transfer to a removable 150-Mb Bernoulli disk. The monitor processor software is written in C and can be used on other compatible PC's to analyze recorded data.

**Main Processor**

The main processor is an SGI Indigo® workstation with a UNIX operating system. Data inputs to the main processor are received from the monitor processing system across the Ethernet and processed for display and hard copy. A Bernoulli disk is provided for accessing archived data originally recorded by the monitor processor.

**PROCESSING**

**Monitor Processor**

Data received from the sensors are measurements of blade passing time (or 1/rev) and must be converted to blade deflections. This conversion process involves filtering noise, detecting missing blade pulses, and correcting for rotor acceleration effects.

Noise filtering and detecting missing blade pulses are accomplished by calculating windows of displacement (Fig. 6) within each revolution where the blade pulses are expected to occur. Pulse signals falling outside the windows are counted as noise; signals within the windows are counted as blade-tip data. The displacement windows are calculated using the 1/rev time, rotor blade-tip circumference, and the blade separation distances around the rotor. Individual blade deflections are calculated as differences between the instantaneous measured blade displacement and the center of the window. An error can occur in the calculation of the displacement windows if the rotor speed is changing (accelerating) within the respective revolution. A first-order correction for acceleration effects can be made by determining the speed change between revolutions using the 1/rev sensor measurements to correct each blade displacement window. If a multiple/rev sensor signal is available in addition to the 1/rev signal, acceleration corrections can be made with improved accuracy.
The blade deflection data are further processed to determine the vibratory (ac) and static (dc) components. Static deflection is obtained by averaging the displacement values for each blade over a defined number of revolutions. Vibratory deflections are obtained by subtracting the static from the displacement values. Vibratory and static deflections for each blade in the instrumented row are illustrated as shown in Fig. 7.

Main Processor

Processing functions of the main processing system include all capabilities of the monitoring processor plus time and frequency domain analysis to determine individual blade and system modes of vibration. Processing techniques vary accordingly for nonintegral and integral vibrations.

Nonintegral Vibrations. The ac data from nonintegral vibrations are processed using Fast Fourier Transforms (FFTs) in determining the blade vibration characteristics. Two options available for processing nonintegral data are (1) single blade analysis and (2) traveling wave analysis.

Single blade analysis is based on building an ensemble of contiguous data samples from each individual blade. For example, a 1,024-word ensemble requiring 1,024 rotor revolutions would be available for each blade in the row. The FFT of the ensemble will usually result in aliasing the data since the sampling rate of 1/rev would be significantly less than twice the blade vibration frequency. The unaliased frequencies could be identified by having prior knowledge of the rotor vibration characteristics or by adding another sensor located at a different position along the blade-tip path to provide phase difference information. The phase differences between the two sensors' data allow correcting the aliased frequencies.

Traveling wave analysis is used to define the modal characteristics of a bladed disk when they are viewed as a unified vibrating system. Two sensors, spaced a known distance apart, are required to provide amplitude, phase, and frequency information needed in traveling wave analysis. For each sensor, contiguous data from sequential blade samples are used to form an array for FFT analysis. For example, a 64-blade rotor would rotate 16 revolutions to provide enough samples to make up a 1,024-word array used in FFT analysis. The FFT of each sensor's data array identifies frequencies as measured by a stationary sensor. The identified frequencies are transformed from the stationary to the rotational frame of reference using knowledge of the rotor speed measurement and blade-tip sensors' separation distances. Any significant traveling wave vibrational modes are retained and displayed to characterize the bladed disk system's nodal diameters, interblade phases, amplitudes, and frequencies (Fig. 8 and 9).
**Integral Vibrations.** Integral vibrations processing uses the static data acquired from one to four sensors to determine vibration frequencies and amplitudes. Conventional frequency analysis techniques (e.g., Fast Fourier Transforms) cannot be used since integral vibration occur at integer multiples of the rotational speed and are aliased to dc when sampled at the blade passing frequency. One technique is based on the rapid phase and amplitude changes that occur when a blade is excited about its resonant frequency. This approach, referred to as the Single-Degree-of-Freedom (SDOF) oscillator technique, displays the static data from one sensor as a function of engine rpm. When an integral frequency blade resonance occurs as the rotor speed transitions through an integral excitation, the sensor's static deflection measurement has distinctive inflection characteristics which define the resonant peak amplitudes. These inflection characteristics and comparable strain-gage results are illustrated in Fig. 10. Another integral vibration processing technique uses displacement data from four sensors mounted inline along the blade rotating path. Curve fitting techniques and sensor separation distances are used in processing data to define each blade's vibration amplitude, phase, and frequency.

**Additional Processing.** Integral and nonintegral data can be displayed as a function of engine speed, frequency, and vibration amplitude as shown in the modified Campbell Diagram of Fig. 11. Additionally, conversion to stress is possible provided deflection-to-stress conversion transfer functions are available. Stress data could also be displayed in Campbell Diagram format.

**APPLICATIONS**

During the development stages the NSMS has been applied to turbine engine altitude tests, a large axial-flow wind tunnel compressor, and large drive-motor shaft couplers used in plant air supply and exhauster systems. Selected data presentations from each application are included to illustrate a variety of the NSMS processing capabilities.

**Turbine Engine Test**

The NSMS was applied to several turbine engine tests to demonstrate system capabilities and to verify system operation. In one test application, two blade-tip sensors monitored one rotor blade row of a turbine engine fan, providing measurements of non-flutter and flutter conditions as shown in the time series sampled data of Fig. 12. The same data in Campbell Diagram form (Fig. 13) provide a good description of nonintegral order blade resonance as a function of engine speed.

**Wind Tunnel Compressor**

An NSMS prototype was used to investigate rotor blade problems on the third stage of a large (7.3 m-diam) supersonic wind tunnel compressor. Four sensors, circumferentially located around the rotor shell, provided blade data characterizing blade static and vibrational deflections. Blade-tip data were acquired between startup and synchronous (0 to 600 rpm) speeds to investigate blade cracking problems. An example of blade-tip static deflection due to centrifugal and air loading of a selected blade is illustrated in Fig. 14. An example of integral order analysis using the SDOF technique, requiring only one blade-tip sensor, was shown in Fig. 10. The NSMS prototype used in this application provided the basis for the current
Plant Motor Coupler

The AEDC Engine Test Facility is equipped with many air supply and exhauster compressors which are driven by large synchronous motors. A nonsynchronous motor, attached to each synchronous motor through an inline flexible shaft coupler (Fig. 15), drives the system to synchronous speed for normal operation. When a coupler failure occurred, the NSMS was readily adapted to investigate the motor coupler problem. Twelve strips of reflective tape were placed around the rotor shaft on one side of the coupler while a single 1/rev reflective tape was located on the rotor shaft on the other side of the coupler (Fig. 15). The reflective tape strips simulated 12 rotor blades and a 1/rev marker, allowing the NSMS to accomplish the measurement with a single blade-tip sensor and a 1/rev sensor. Data from the sensors were processed, using normal blade analysis software, to describe the torsional static and vibrational deflections. Further insight into characterizing the coupler loads was provided through an axial deflection measurement. One of the 12 strips of reflective tape was oriented at a 45-deg angle relative to the axial orientation of the remaining 11 strips. This arrangement provided a direct indication of shaft axial displacement, as illustrated in Fig. 16. Examples of data presentations produced in the investigations are shown in Figs. 17 and 18.

SUMMARY

The NSMS has been developed as an alternative to the strain gage to monitor rotor blade vibrations in rotating machinery. The NSMS uses light probes mounted through the rotor casing to monitor all blades of an instrumented blade row. The blade-tip signals for both integral and nonintegral vibrations...
are processed on-line to display single blade deflections, as well as system vibration modal analysis for all blades. The NSMS has been successfully applied to turbine engines, a plant rotating compressor, and motor rotating shaft couplers.

The NSMS, using PC technology and a VME bus for system integration, stores data on a Bernoulli disk which can be accessed for playback and analysis by any PC with installed software and compatible disk hardware. The main processor workstation provides comprehensive time and frequency domain analyses to identify individual blade and system traveling wave vibration components.

Efforts identified for future development include improving blade-tip sensors, implementing conversion from blade-tip displacement to blade stress, and combining strain-gage and blade-tip vibration measurements in the data processing algorithms. The synergistic advantages of using both strain-gage and blade-tip measurements in the analysis include improved frequency information (strain gages) and complete coverage to all blades (NSMS).