TECHNOLOGY DEVELOPMENT FOR SHAFT CRACK DETECTION IN ROTATING EQUIPMENT

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Abstract

A non-intrusive torsional vibration method for monitoring and tracking small changes in shaft crack growth during normal machinery operations of rotating equipment is under development. This method resolves and tracks characteristic changes in the natural torsional vibration frequencies that are associated with shaft crack propagation. The method is generally applicable to many types of rotating equipment, including, reactor coolant pumps, centrifugal charging pumps, condensate and feed water pumps. The focus of this effort is to develop and apply the torsional vibration shaft cracking monitoring technique on a Westinghouse 93A reactor coolant pump.

A laboratory scale rotor test bed was developed to investigate shaft cracking detection techniques under controlled conditions. The test bed provided a mechanism to evaluate sensing technologies and algorithm development. For accurate knowledge of the crack characteristics (crack depth and front), a sample shaft was seeded with a crack that was propagated using a three point bending process. Following each crack growth step, the specimen was evaluated using ultrasonic inspection techniques. This was followed by installation of the shaft in the rotor test bed and the observation of the change in shaft torsional vibration features.

The torsional vibration measurement method has demonstrated the ability to reliably detect the first natural shaft frequency in the range of 0.1 to 0.2 Hz. This shows the potential to enable online structural health diagnostics and ultimately the prevention of shaft failure due to crack growth.
Introduction

The importance of shaft crack detection in nuclear power plants is apparent when considering the impact of past failures. For example, Primary Coolant Pumps (PCPs) have experienced shaft cracking and subsequent failure, often with little or no warning from state-of-the-art crack detection systems. The financial loss associated with a forced outage caused by such a shaft failure is substantial. Recently, pre-1974 Westinghouse Reactor Coolant Pumps (RCPs) have come under particular scrutiny, as at least five have experienced significant cracking. A root cause analysis indicated that Model 93A pumps that are operated in counterclockwise Reactor Coolant System (RCS) flow loops are particularly susceptible to developing shaft cracks [1].

In late 2000, Tennessee Valley Authority (TVA) Sequoyah Unit 1, RCP 4 experienced severe cracking that resulted in an extended forced outage. The crack detection system on the RCP provided no warning of substantial crack growth. After shutdown, inspection revealed a circumferential crack of 252º, and only one-third of the cross-sectional area remaining. Note that similar pumps are found at the following US plants: Beaver Valley, Prairie Island, Diablo Canyon, Three Mile Island, D C Cook, Oconee 1, Farley, and Sequoyah.

The unexpected loss of a Steam Generator Feed Pump (SGFP) in a Pressurized Water Reactor (PWR) or a Reactor Feed Pump (RFP) in a Boiling Water Reactor (BWR) often results in a unit trip and subsequent operation at reduced power. For instance, the loss of a SGFP due to turbine shaft cracking occurred at Plant Vogtle (Southern Nuclear) in the mid-90s. The result was a unit trip, and the usual 3-4 days to return to full operation. In addition, the unit operated at reduced power (~70%) for approximately one week to facilitate turbine repair resulting in a substantial monetary loss.

In addition, PCPs in BWRs have had shaft-cracking problems. Recently, for instance, Plant Hatch (Southern Nuclear) has replaced several PCPs due to potential shaft cracking problems identified by the vendor.

Other pumps that have experience shaft cracking include Condensate Pumps and Centrifugal Charging Pumps (20 shaft failures of current design used in PWRs in the USA). Although the failure of these pumps due to shaft cracking does not generally result in unit trips or reduced power operation, the unexpected failure can create maintenance scheduling problems and increased safety risk.

To address the shaft cracking issue, a health monitoring technique based upon the torsional vibration signature is currently under development with EPRI sponsorship. The proposed system will identify characteristic changes in the torsional vibration of the shaft that are associated with a propagating crack. This method appears to be less sensitive to changes in the pump rotor context (e.g., seals, oil film, and supports) than the existing crack detection systems. The method has recently been installed and used successfully in hydro plants for maintenance and health monitoring [2]. Based on laboratory and field experience, to date, the approach has the potential to provide a robust measure of the shaft structural integrity.

The overall objectives of the multi year project discussed in this paper are twofold:

1. To demonstrate the feasibility of using torsional vibration as a diagnostic method for shaft cracking detection and monitoring in rotating equipment in nuclear power plants;
2. To develop and install a prototype shaft crack detection system for a Westinghouse Model 93A reactor coolant pump at TVA’s Sequoyah Nuclear Power Plant.

This paper will present the research to date toward meeting these objectives. A laboratory subscale shaft was fabricated and a seeded crack fault placed in the shaft. The crack was initiated and grown by fatiguing the shaft for a specified number of cycles. The crack was then nondestructively characterized. The shaft was installed in the torsional test rig and operated to extract the torsional vibration signature. The shaft was then subject to additional fatigue cycling and the inspection process repeated. The torsional vibration signature was used in conjunction with the crack characterization to examine the sensitivity of the method to monitor the shaft’s structural health.

Modeling efforts are being conducted in parallel to understand the effects of shaft crack growth on the torsional and lateral vibration. Finite element models of the subscale shaft have been developed to simulate both the static and dynamic response. Attention focuses on the ability of the models to replicate the torsional and flexural vibration features that are found to be sensitive to crack growth. Modeling efforts are underway to extend the application to an RCP (Westinghouse 93A). The analysis will examine the effects that shaft crack development and growth will have on the vibration signature. The RCP modeling effort is being performed jointly between Penn State and EDF (Electricité de France) team members.

**Torsional Vibration as a Rotating Machinery Diagnostic**

A system to measure torsional vibration of a rotating shafting is shown in Figure 1 [3,4]. Signal detection involves three main aspects, shaft encoding, transduction data discretization and demodulation. The shaft encoding system can use a variety of approaches including a timing gear or optical encoder. Depending on the shaft encoding device a number of transducers are viable, including infrared reflective intensity fiber optic sensors and Hall effect transducers.

The detection of the passing times from the multiple pulse-per-revolution shafts encoders is used to measure the torsional vibrations. A number of variations of the basic measurement scheme have been used previously, including both analog [2] and more recently entirely digital processing methods.

Digital methods of measuring torsional vibrations are becoming viable and cost effective alternatives to the analog hardware due to the rapid increases in digital clock speeds and computing power. Vance describes a prototype system called the TIMS (time interval measurement system) [3] in which a digital tachometer circuit is able to record the passing times of each line on the encoding device. The passage times are then converted to angular...
shaft velocity. Various investigators have addressed a number of issues and proposed enhancements to this approach [7,8,9,10]. The torsional measurement scheme used in this work is based upon the TIMS approach. The basic technique has been further advanced by work at Penn State to allow for correction of transducer imperfections and the removal of fixed order components. This refined torsional vibration measurement approach is used in the current effort.

Recent applications of the method have shown the effectiveness of using torsional vibration in monitoring simulated turbine shaft-blade coupled torsional vibrations [5,6]. By monitoring blade natural frequencies, it is possible to determine shifts due to cracking and other mechanisms. Beyond the laboratory investigations, the approach has been used in several field applications including hydro-electric equipment [2] and with a variety of other types of rotating equipment [6].

**Torsional Vibration Experiments with a (Progressively Grown Fatigue) Cracked Shaft**

A test was performed on a shaft with a fatigue crack grown sequentially to eight different stages. The characteristics of the shaft and crack were evaluated in multiple fashions at each growth increment. The torsional vibration signature of the shaft at each cracked state was determined in laboratory tests. The test sequence is intended to correlate the changing torsional vibration signature to the growth of a fatigue crack under controlled laboratory conditions. The test hardware and procedures follow.

**Fatigue Crack Growth** - The test specimen shaft material was 0.625 inch diameter ANSI 316 L stainless steel. To initiate a crack, a 0.010 inch deep notch was machined into the midlength of the shaft specimen with the edge of a milling machine tool (per ASTM E399 specifications for fatigue precracks). The specimen was mounted on an MTS 642.10B 3-point bend fixture and cyclic loading was applied with a servohydraulic MTS 810 test stand operated by a MTS 458.20 electronic controller. The fatigue test hardware is shown in Figure 2. Tests were performed to determine the cyclic loading parameters needed to grow the crack to a specified depth without causing permanent deformation. These parameters were used to accurately control the crack growth process.

**Crack Characterization** - Upon completion of a cyclic loading sequence the fatigue crack was quantified using both a visual inspection and an ultrasonic NDE method. The visual inspection entailed viewing the crack with a telescope and measuring the fatigue crack surface length while the shaft was under a constant lateral load in the 3-point bending fixture. Note that the crack was closed in the unloaded configuration.

Two nondestructive evaluation procedures using ultrasonic waves
Figure 3. Typical shaft section beach marks.

were applied to map the crack front.

One method used a conventional ultrasonic inspection technique with longitudinal waves to estimate the uncracked shaft cross section. The second method used a novel wedge transducer that emits both surface and shear waves.

At the completion of the fatigue cycling a destructive crack evaluation was performed. The shaft was sectioned and the cracked cross-section viewed with a metallograph to help correlate the NDE results with actual crack characteristics as seen in Figure 3. The crack metric ($a/D$) is expressed as the distance from the shaft surface to the extreme location of elliptical crack front along a diametric line as shown in Figure 3.

**Torsional Rigidity Measurement** – After each fatigue cycling increment, an MTS 319 Axial-Torsion test machine was used to measure the torsional rigidity, $GJ$, relative to the uncracked condition. Two fully reversed cycles of a triangular torque waveform were applied at a rate of 20 lb-in/s and torque and angle of twist were measured. Linear regression was employed to determine torque-angle relationship and the torsional rigidity calculated.

**Torsional Vibration Test Stand** - A test rig was constructed to measure the torsional vibration of the cracked rotating shaft under controlled laboratory conditions and is shown in Figure 4. The shaft specimen was mounted in Rulon-J non-metallic flanged sleeve bearings and rotated by a variable speed Perske motor.

An encoding wheel was constructed to sense the torsional vibration with an outer diameter of 3.575 inches and 180 teeth with a 0.125 inch tooth depth. An infrared fiber optic intensity reflective transducer was used to sense the wheel tooth passage as shown in Figure 5. The tooth passage times were sensed and recorded with a National Instruments PCI-6602 Timer/Counter Board using an 80MHz clock reference.
Torsional Vibration Analysis - Once recorded, the encoding tooth passage times were processed with a customized torsional vibration algorithm developed at Penn State. The routine ultimately produces a spectrum of the torsional vibration. The routine can compensate for artifacts from the encoding device and remove order content from the signal, thus improving the signal-to-noise ratio [4].

Testing of a Shaft with a Progressively Grown Fatigue Crack – A test sequence was performed that evaluated the torsional vibration signature of a shaft with a fatigue crack grown progressively to nine different stages. The crack was located one half the axial distance along the shaft. The following test sequence was performed.

1. A new shaft, with a milled crack initiation notch, was tested in the torsional test rig to establish the baseline signature.
2. The fatigue crack was grown as closely as possible to a specified depth.
3. The crack was nondestructively inspected and the torsional rigidity tested.
4. The shaft was tested in the torsional test rig to determine the torsional natural frequency. The vibration signature was measured with eight to ten complete disassemblies and reassemblies of the shaft in the torsional test stands. The multiple tests were necessary to statistically establish the system natural frequency due to errors induced by the assembly-disassembly process.
5. Steps 2-4 were repeated eight times.
6. The shaft was destructively sectioned to evaluate the crack front at each fatigue test increment as apparent from the beach marks.
Test Results – The torsional vibration spectra around the first natural frequency for four tests increments spanning the test range are shown in Figure 6. A reduction in system natural frequency as the crack grows is apparent. Figure 7 shows the shaft system’s torsional natural frequency as a function of the fatigue crack. The results show that there is a gradual decrease in the shaft natural frequency with approximately a 1.5 Hz drop observed for a crack depth of $a/D = 60\%$.

The torsional vibration tests with the progressively grown fatigue crack show:

1. There is an identifiable natural frequency change that can be tracked in relation to the seeded fault condition of the shaft.
2. The torsional rigidity ($GJ$) showed a measurable decrease in relation to the crack growth.
3. A decrease in the first torsional natural frequency was observed as the crack grew.
4. When high quality data was acquired, changes in natural frequency as low as 0.1 Hz were identifiable by inspection of the spectrum.

Figure 6. Torsional vibration spectrum from the laboratory test rig with four different fatigue crack depths.

Figure 7. First torsional natural frequencies versus fatigue crack depths.

FEM of Torsional Test Stand with Cracked Shafts

The goal of the rotor modeling is to analytically predict the natural frequencies of the system in the presence of a growing crack. For the uncracked case, this was accomplished using a beam model, and extracting natural frequencies in the torsional domain. A torsional spring was
introduced to model the crack effects on the shafting system’s natural frequencies. Four methods were used to determine the equivalent spring torsional stiffness. The objective is to determine an approach that accurately estimates the torsional spring stiffness required to replicate the measured natural frequencies shifts as a function of fatigue crack depth.

**Model Geometry and Properties** - A finite element model of the experimental rotor system was developed using ANSYS as shown in Figure 8. Beam elements were used for the flexible members and lumped inertial elements for the motor. The model inputs were calculated based on dimensions and properties. The motor properties were based on shaft drawings and rotor weights and dimensions from the manufacturer, augmented by some external measurements.

**Cracked Shaft Modeling** - A torsional spring was introduced into the shaft model at the location of the crack to evaluate the dynamic effects due to crack growth as depicted in Figure 9. The torsional spring stiffness to model a particular depth crack was calculated by four methods. Two methods were analytically based, while two methods used the previously acquired experimental results to estimate the stiffness.

1. **Localized Crack FEM** - The crack front is idealized to be straight and it is assumed that no friction exists between the crack faces. The crack is modeled by unconstraining the nodes that correspond to a particular crack front. One end of the shaft is completely constrained, while the other end is constrained to allow only planar angular deflections. A torque of 1000 lb-in was applied as a couple and the corresponding angular deflections computed. The equivalent torsional spring stiffness was then computed.

2. **An energy based solution** – The torsional spring stiffness is the inverse of the local flexibility induced by a straight open crack, which is computed using the stress intensity factor and Castigliano’s theorem as given by Papadopoulos [11].

3. **Torsional rigidity tests** – The equivalent torsional spring needed to produce the angular rotation measured in torsional rigidity tests was computed for each fatigue crack state. The

**Figure 8.** FEM of laboratory torsional test stand.

**Figure 9.** Dynamic modeling of shaft crack with a torsional spring.
torsional rigidity tests had a relatively high variance; hence the computed spring rates also tend to show a large variation.

4. **Torsional vibration test results** – The shaft model shown in Figure 9 was placed in the test stand FEM (Figure 8). The torsional spring constant used to model the crack was adjusted so that the natural frequency coincided with the measured value. This analysis was performed at each fatigue crack increment.

The equivalent torsional spring stiffness computed by the four methods as a function of crack depth is shown in Figure 10. The four methods do not produce consistent results. There is reasonable agreement between the localized FEM and the solution presented in [11]. There is also some general agreement between the rigidity and dynamic test results. However, the analytical and computational approaches predict a greater flexibility than either experimental method.

The accurate modeling of the crack is important for 1) to assess the method’s applicability to various rotating equipment, and; 2) to evaluate the dynamic torsional vibration signature in relation to the shaft’s structural integrity. The modeling of the fatigue crack’s effects on the torsional dynamics remains a topic of investigation and is presently being further analyzed.
Figure 11. Cut away view of Westinghouse 93A-1 Reactor Coolant Pump (Source: http://www.mhi.co.jp/atom/hq/atom_e/03/08.html) and ANSYS torsional line shaft finite element model of a 93A RCP.

Torsional Vibration Monitoring of a Reactor Coolant Pump

A prototype torsional vibration package has been developed for a Westinghouse 93A RCP at TVA Sequoyah. The instrumentation is to be installed in the fourth quarter of 2003 and the online monitoring of the pump will commence. The initial goal is to capture the torsional vibration signature and thoroughly examine its features for diagnostic purposes. The lateral vibration signatures will also be acquired and evaluated in conjunction with algorithms developed at Electricité de France for shaft crack monitoring. Depending on the results, data fusion between the lateral and torsional vibration analysis methods may be implemented. A cutaway view of a 93A-1 pump is shown in Figure 11. A finite element model of the pump has been developed jointly between Penn State and EDF. A torsional line shaft model of a 93A pump is also shown in Figure 11. The models will ultimately be used to examine the effects of crack growth in the shaft on the pump’s torsional dynamics. This work is continuing.
Summary

The objective of the work is to demonstrate the feasibility of using torsional vibration as a potential diagnostic method for shaft crack detection and monitoring in nuclear power plant rotating equipment. To this end, a series of experimental and modeling studies have been performed. The major accomplishments of the effort can be summarized as:

1. Techniques have been developed to initiate and grow fatigue cracks in a shaft under a controlled and predictable fashion.
2. Inspection techniques were developed and applied to characterize both the localized crack and its effect on shaft stiffness.
   a. An ultrasonic inspection method was developed to quantify the crack front internal to the shaft.
   b. Torsional rigidity tests were performed on the shafts to statically measure the effect that a crack has on the shaft shear rigidity ($GJ$).
3. Fatigue cracks ranging in depth from approximately 20-65% of a 0.625” diameter stainless steel shaft were created with no significant permanent deformation.
4. A table top scale test stand was designed and fabricated for torsional vibration testing of the shafts with fatigue cracks.
5. Digital signal processing methods were established to allow identification of the shaft system’s first torsional natural frequency from data acquired from the test stand.
6. A test sequence involving the sequential fatigue crack growth, inspection and torsional vibration evaluation was performed and showed:
   a. The torsional rigidity showed a measurable decrease in relation to the crack growth.
   b. A decrease in the first torsional natural frequency was observed as the crack grew.
   c. Changes in natural frequency in the range of 0.1 to 0.2 Hz were identifiable by a visual inspection of the spectrum.
7. The shaft rigidity results from the localized crack finite element model were incorporated into the dynamic model to predict natural frequency changes with respect to crack growth.

Potential for Crack Detection on Nuclear Power Rotating Equipment - The torsional vibration measurement method has demonstrated the ability to reliably detect natural frequency shifts in the range of 0.1 - 0.2 Hz. This frequency shift is within the range of frequency shifts caused by shaft cracks and hence, shows the potential to enable online diagnostics and prevention of shaft failure due to crack growth. Furthermore, natural frequency trending is a rudimentary machinery diagnostic feature. The torsional vibration may possess other features that may provide an even more sensitive indicator for early shaft crack detection and monitoring purposes.
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