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DEVELOPMENT OF AN ON-LINE DAMAGE DETECTION, DISCRIMINATION AND TRACKING SYSTEM FOR THE SPIN RIG FACILITY

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Abstract

The main goal of the work reported here was to expand the capability of the NRC-Aerospace spin rig by adding an on-line damage detection, discrimination and tracking system, and to develop necessary expertise that will allow for optimizing the NDE inspection periods of gas turbine engine components in this facility and minimizing undetected crack nucleation and growth and possibility of catastrophic failures. Passive eddy-current sensors and a data acquisition system able to simultaneously measure blade deflection and tip clearance were selected to monitor health of rotating components. Before application of the system in the spin rig, the system was tested with a rotor rig to check sensor responses to deliberately induced changes in blade tip positions in both radial and circumferential directions. The monitored disc had 12 bolts simulating aerofoils that could be turned into threaded holes to extend or shorten the protruding parts of the bolts. On the other hand, bolt vibration was not excited and analysed during the experiment. Lessons learned on the rotor rig are used to prepare and plan spin tests in vacuum chamber.

Keywords: *disc crack, disc health monitoring, vacuum spin testing, tip timing, tip clearance, low cycle fatigue*

1. Introduction

Damage detection in critical rotating parts of gas turbine engines is a very challenging undertaking, but if performed successfully it can offer great benefits in terms of cost and safety of the engine [6, 7, 9, 27].

A number of approaches to real time monitoring of rotating components in gas turbine engines have been developed in recent years, as described and summarized in [11, 16-18, 22, 23, 27, 29]. Particularly, research in the area of damage detection has been accelerated by the development of new sensing capabilities and new sensors [27].

In the last decade, several non-contact measurement solutions have been developed in the gas turbine industry to avoid use of strain gauges that were traditionally applied to measure strains in both stationary and rotating components. The most advanced and widely used systems are Non-contact Strain Measurement Systems (NSMS), Blade Tip-Timing (BTT) systems, and Blade Vibration Monitoring (BVM) or Blade Health Monitoring (BHM) systems. All these methods generally use various sensors mounted in the rotor casing to monitor behaviour of the blades without contacting them. Out of the many techniques for damage monitoring, the blade tip-timing (BTT) technique has gained popularity in the last decade [8, 10-12, 15, 16, 20, 21, 24-30]. This technique is based on the assumption that fatigue cracks developed in the critical location of rotating components, such as discs or spacers, create a localized deformation which is then magnified through geometric features of the blade and therefore can be detected by a tip-timing system.

A tip-timing system measures time-of-arrival (TOA) for all blades passing the sensors installed. The changes in the crack opening displacement (COD) are reflected in the inter blade spacing (IBS) which can be extracted from the time-of-arrival. Typically, the COD is a function of the crack size and the square of the rotor rotational speed. Consequently, to apply the tip-timing method, the IBS are plotted against the rotor speed and the number of spin rig test cycles to detect a crack and track its progress. For a new disc, in which damage has not developed, the IBS changes from cycle to cycle are minimal. However, for a disc with a crack, the IBS changes with rotating speed and with the cycle count. These changes in the IBS measured by a tip-timing instrument are then translated into crack growth data.

Detection of damage based on direct changes in vibration characteristics of a structure due to cracks is difficult because there are other factors in addition to the presence of a crack that affect the vibrations of the structure. These factors include thermal effects, friction, damping or even rotor handling that involves disassembling and reassembling a rotor. In fact, experience shows that simple vibration characteristics, such as natural frequencies or mode shapes, are insensitive to damage, and changes in the vibration characteristics can be detected only when damage is almost catastrophic, which is too late for the practical application of this approach.

Practical application of BTT or BVM systems to damage detection relies on development of proper sensing techniques and application of robust sensors that can work in the extreme environment of gas turbine. A recent conference [27] summarized various instrumentation used in test cells of gas turbine engines, among them was BTTs.

Before application of damage detection and damage prognosis systems to an entire engine installed on an aircraft, evaluations of these technologies in controlled environments, such as the NRC spin rig, are necessary.

The main goal of the work reported here was to expand the capability of the NRC-Aerospace spin rig by adding an on-line damage detection, discrimination and tracking system, and to develop necessary expertise that will allow for optimizing the NDE inspection periods of gas turbine engine components in this facility and minimizing undetected crack nucleation and growth and consequently avoid possibility of catastrophic failures. The article describes bench tests performed to verify ability of a commercial BVM, Tip-Timing system, to monitor seeded faults in a rotor. In addition, plans of installation of the BVM system in the spin rig environment are presented.

2. Setup of the bench test rig

NRC-Aerospace acquired a commercial tip-timing data acquisition system from Hood Technologies. This instrument allows measuring, recording and analysing tip-timing data from two eddy current probes that record blade passage.

Before application of the BVM system in the spin rig, the system was installed and tested in a room environment. The system was tested in a bench setup with the ultimate goal of installation in the spin rig facility. The objectives of these tests were to check sensor responses to changes in blade tip displacements in both radial and circumferential directions. For this testing, a simulation rotor rig was built as shown in Fig. 1 and 2.

The rotor was powered from the drive system of the NRC-Aerospace burner rig facility, Fig. 1. The test rotor consisted of a 25.4 mm thick and 149 mm diameter disc with 12 bolts that could be turned into the disc threaded holes to extend or shorten the protruding parts of the bolts. These changes in the tip gap also created some change in the time of tip arrival. However, the latter was more difficult to discern and adjust because of the hexagonal head shape of the bolts. The disc and bolts dimensions were chosen in such a way that the external diameter of a rotor with bolts was approximately 200 mm. In this setup, the bolt vibrations were negligible and therefore they were not analysed in the tests.

The major components of the BVM system are shown in Fig. 3, while Fig. 4 illustrate the sensor placements around the rotor. Entire instrumentation shown in Fig. 3 consists of sensors that generate analogue pulses each time a blade passes in front of them; a remotely powered preamplifier, which is located near the test rotor and receives signals from the sensors and a Blade Vibration Sensor Interface (BVSI) unit. The preamplifier receives power and sends buffered signals through a long cable to BVSI. In addition to providing the preamplifier with power, the BVSI also triggers on each blade pulse, creating a digital signal, which is timed.

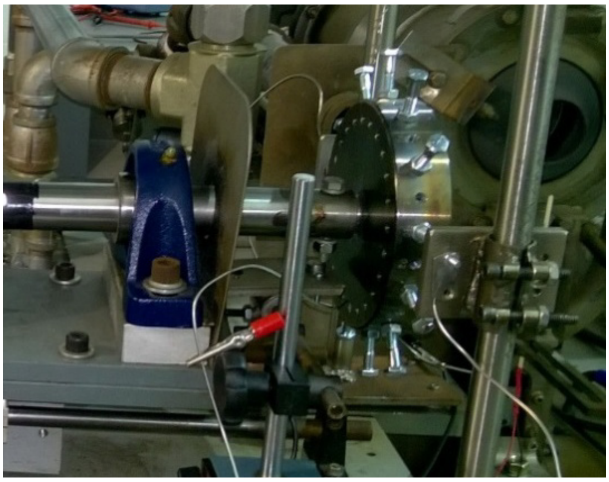

Fig. 1. Test rotor powered from the burner rig rotor

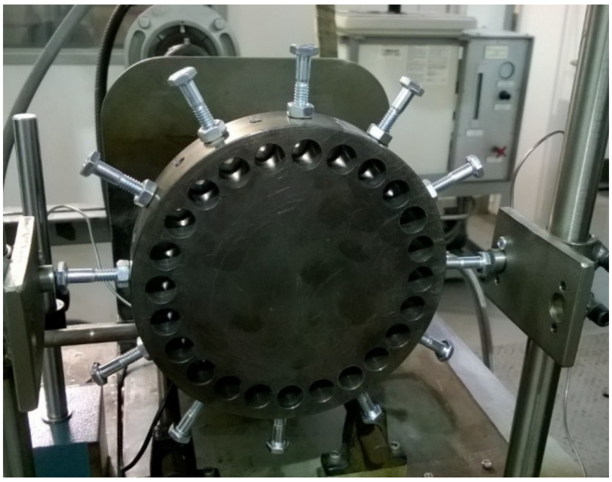

Fig. 2. Disc and bolts of the test system

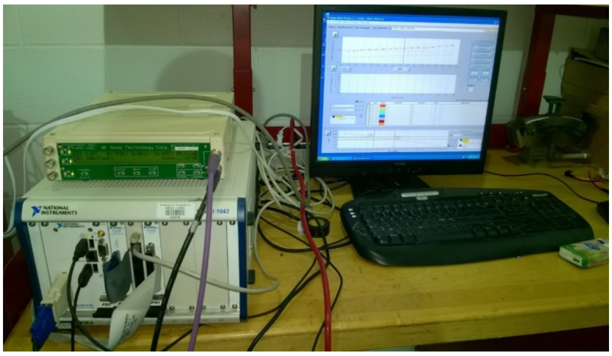

Fig. 3. BVM system at the NRC-Aerospace

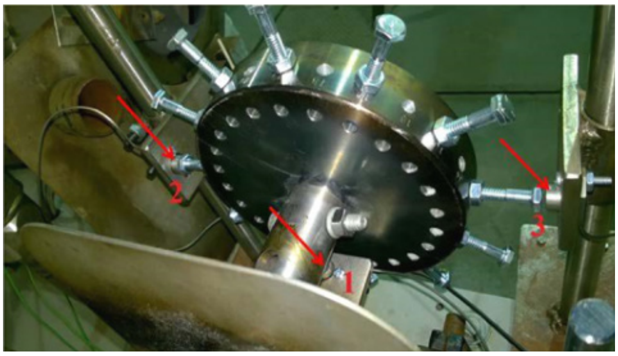

Fig. 4. Sensor placement in proximity to the test rotor: Sensor 1 – one-per-revolution sensor; Sensor 2 and Sensor 3 – tip sensors

The operating console runs proprietary software, Acquire Blade Data. This software allows the user to easily configure the conditioning and triggering parameters of each sensor signal, configure the software to view blade vibration, clearance, and blade stagger and set visual and acoustic alarms.

Sensor 1 shown in Fig. 4 recorded the reference signal. It was installed in such a way that it only recorded one pulse per revolution, while Sensor 2 and Sensor 3 were placed at 180º angle on both sides of the rotor.

3. Blade time of arrival setup

Setting the system trigger limits was critical to measuring TOA and eliminating erroneous results such as a signal that indicates an extra or missing blade [19].

It was observed during the preliminary tests that the eddy current sensors generated double pulses, because of the significant size of the hexagonal heads of the bolt when compared to a typical blade tip thickness. Fig. 5. Therefore, the second pulse had to be removed by using the "Hold Off" time settings. This "Hold Off" setting was useful for removing multiple detections created by the secondary peaks in eddy current sensors depending on the orientation of magnet or magnetic properties of the blade. The hold off period is the period in which system will not re-arm itself. It prevents any blade detection from occurring after a pulse has been triggered. By setting the hold off period to half the inter-blade time, it was assured the unwanted second pulse was eliminated and that only a single triggering per blade happened. In general, the width of the TOA pulse was equal to the hold off period. In the case shown in Fig. 5 the blade edges were represented by the bolt head edges, which were located at much larger distance than a typical blade edge.

In addition, experience with the system showed that reducing the protruding length of one bolt (bolt #3) during trial testing caused a decrease in the impulse amplitude of the output signal, which affected triggering. Therefore, to assure proper triggering, the "Arm" level setting in the Scope tab was decreased ten times from 500 mV to 50 mV.

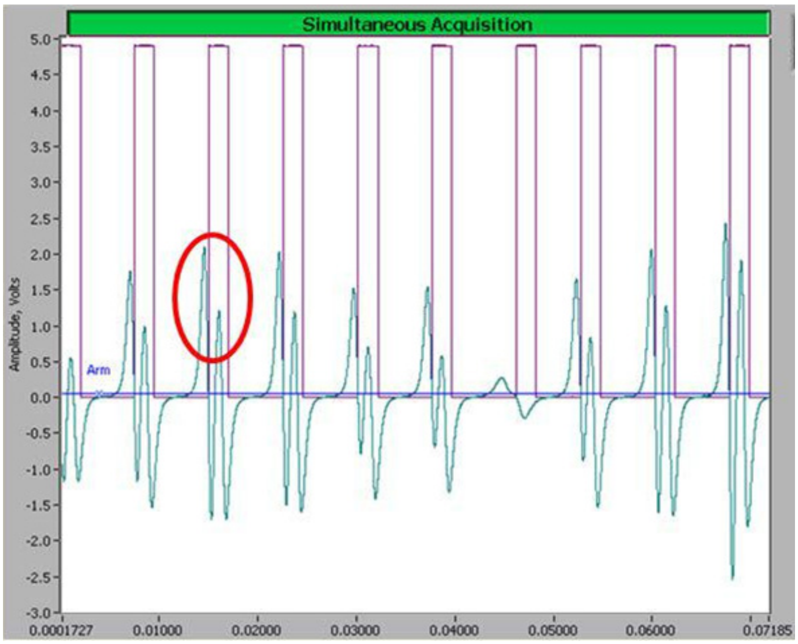

Fig. 5. Double pulses reflecting the bolt head edges

4. Preliminary testing results

Test runs were performed using the test rig shown in Fig. 1-4 to check ability of the BVM system to measure changes of circumferential and radial position of rotating bolts that simulated blades.

The BVM system measured phase and amplitude of pulse signals using counters and the readings were stored in binary files [20]. The analysis software was used to convert the phase from the time unit to the distance unit and export these as circumferential position of bolts to text files. In addition, the amplitudes of pulses representing tip clearance were measured in volts.

A typical profile of the test runs is shown in Fig. 6. In this profile, the rotational speed was increased steadily from 400 to 1000 rpm.

In total eight test runs, also called steps, were performed: the first one to capture reference data (step 0) and following seven steps to capture changes caused by seeded faults. The bolts located on the disc circumference were marked and numbered, starting from bolt #1 to bolt #12. During these preliminary tests, characteristics of bolts #3 and #9 were modified. A notch was cut in bolt #9, so that the bolt could be bent back and forth in the circumferential direction (Fig. 7). In addition, bolt #3 was screwed into the disc one turn per step, total of four turns, which corresponded to total "shortening" the bolt by approximately 5 mm (0.2"). For efficiency, two seeded faults, for blade #3 and blade #9 were applied at the same time. The test steps are summarized in Tab. 1.

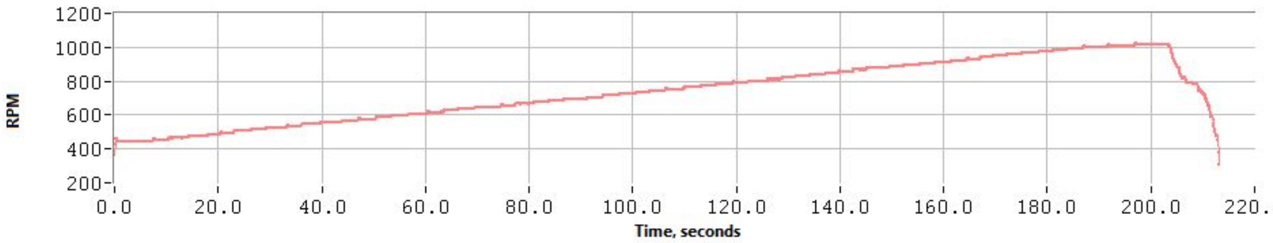

Fig. 6. Profile of the test run

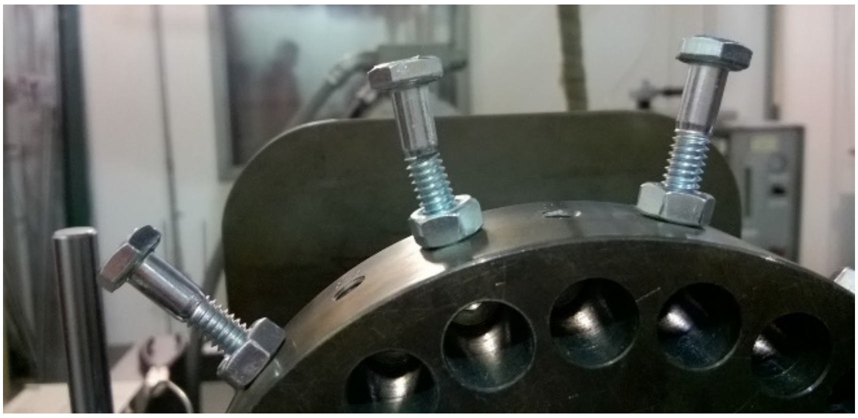

Fig. 7. Bolt #9 notched and bent in the forward direction

Tab. 1. Summary of test runs, called also steps

Step	Recording ID	Bolt #3	Bolt #9
0	_150819_113007	Reference	Reference
1	_150819_113647	Unmodified	Notched and bent forward
2	_150819_114155	Unmodified	Bent back to neutral position
3	_150819_121121	Unmodified	One bolt replaced
4	_150819_121803	Turned in by one turn	Bent backwards
5	_150819_122517	Turned in by one additional turn	Bent forward slightly
6	_150819_123108	Turned in by one additional turn	Bent forward even more
7	_150819_123733	Turned in by one additional turn	Bent forward even more

Figure 8 shows snapshots of the waveforms recorded at the rotational speed of 542 rpm in two time points. These waveforms show that:

– Signals were shifted 180° in phase or by six pulses reflecting the actual sensor placement around the rotor.
– Both sensors represented bolts in a similar way but Sensor 1 produced pulses of amplitude about 30% higher than Sensor 2 as the former one was placed a little closer to the passing bolt heads than the latter.
– Pulses differed in amplitude due to variations in bolt head clearance, that is, variations of distance between the bolt heads and the sensors. In addition, orientation of the bolt heads versus the sensors played a role.

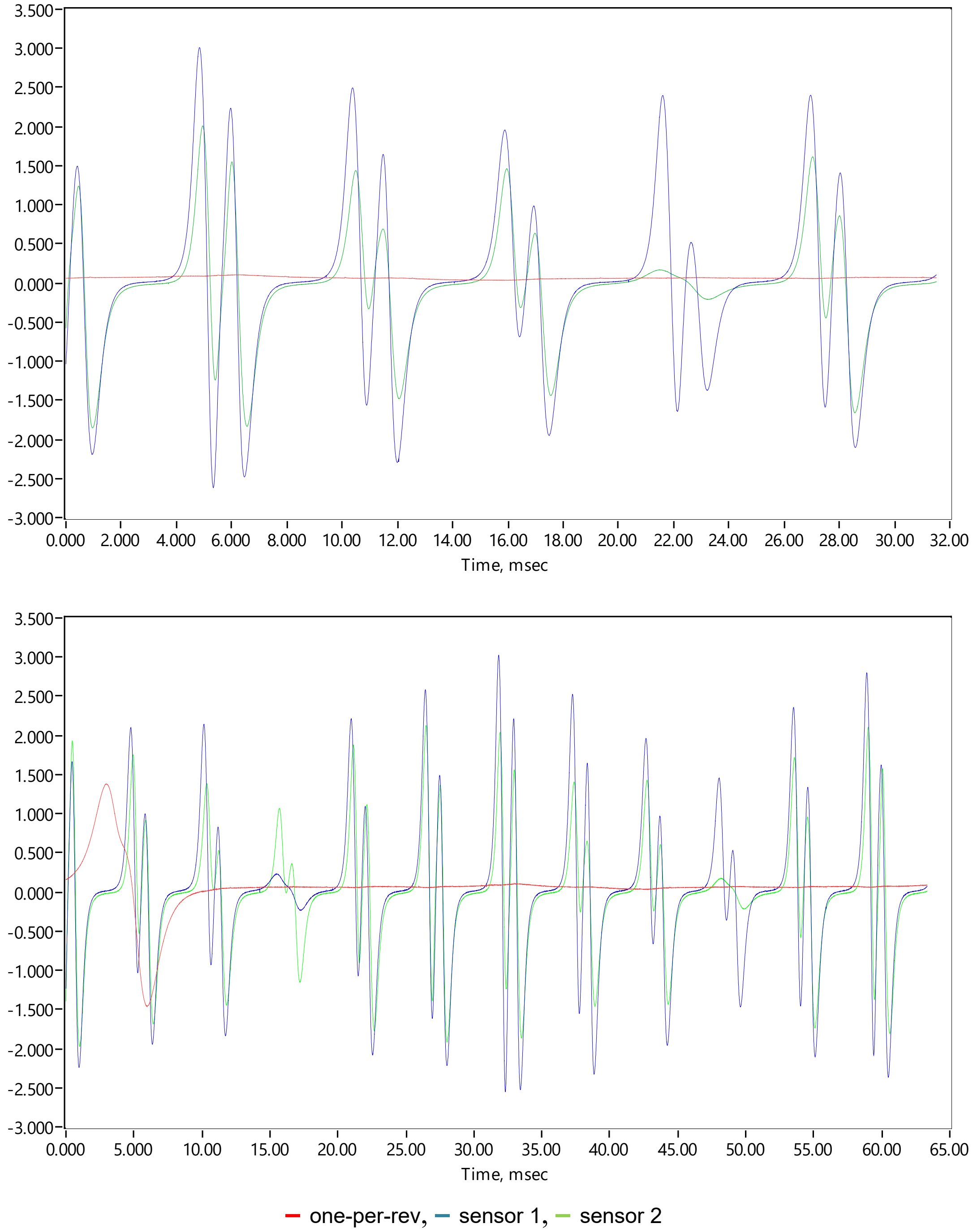

Fig. 8. Signal waveforms taken at 542 rpm on 2015.08.19, 14:40:36 and 14:43:41

– Bolts heads were generally represented by twin pulses because their corners were not sharp like regular rotor blades. This effect was corrected by using the "Hold Off" time feature, as discussed previously.
– Passing of all 12-bolt heads is discernable in the plots. The shapes of pulses generated by passing bolts heads were repeatable in subsequent rotations of the test rotor.
– Signals confirmed that the bolt heads were spaced equidistantly on the rotor circumference.

Please note that in Fig. 10-14 the bolts are denoted as blades.

Figure 9 shows the stack pattern i.e. circumferential positions of each bolt. The plots located in the lower part of the graph represent the signals from Sensor 2 while the plots in the upper part of the graph came from Sensor 1. Different colours of the plots represent different rotational speeds of the test rotor.

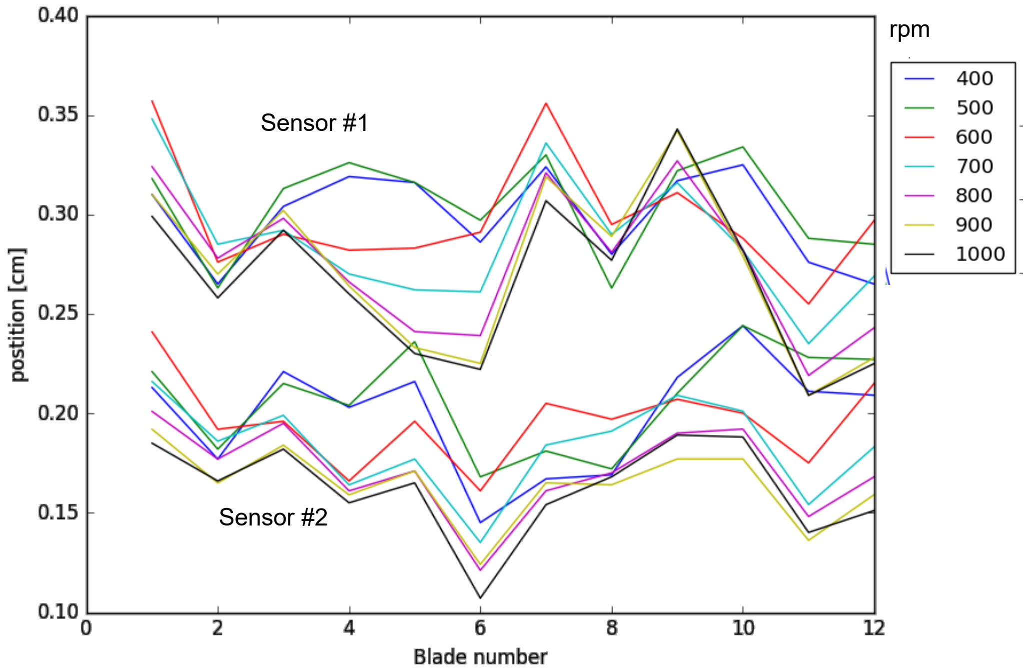

Fig. 9. Reference stack pattern measured by two sensors for different rotor speeds

Figure 10 illustrates the seeded fault effect for bolt #9 for different rotational speeds. This bolt was notched and bent to generate a fault. Delayed arrival of about 2 mm was observed at all speeds in the tested range. In next steps, summarized in Fig. 11, bolt #9 was bent in opposite direction (steps 2-4) and then back (step 6-7). The results confirmed clearly that the system was able to detect and distinguish changes in circumferential position of rotating objects smaller than 1 mm. However, it has to be stressed that bolt heads were not the best reference objects as their shapes were hexagonal and did not represent a typical shape of turbine blade tips. Also screwing-in bolt #3 (in steps 4-7) affected its circumferential position as the bolt head was not precisely set at the previous angle, Fig. 11.

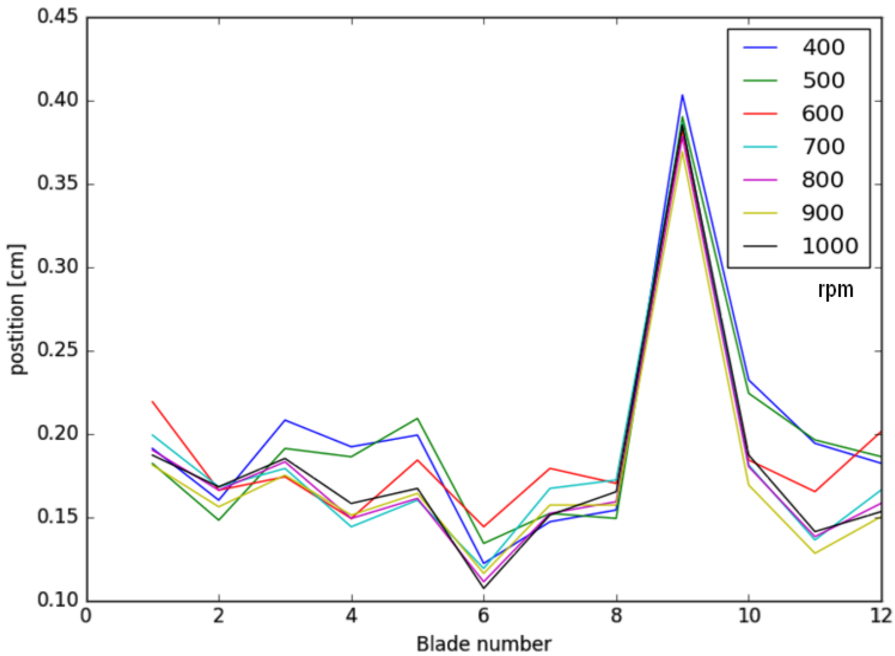

Fig. 10. Stack pattern in the step 1 when the bolt #9 was notched and bent „backwards"

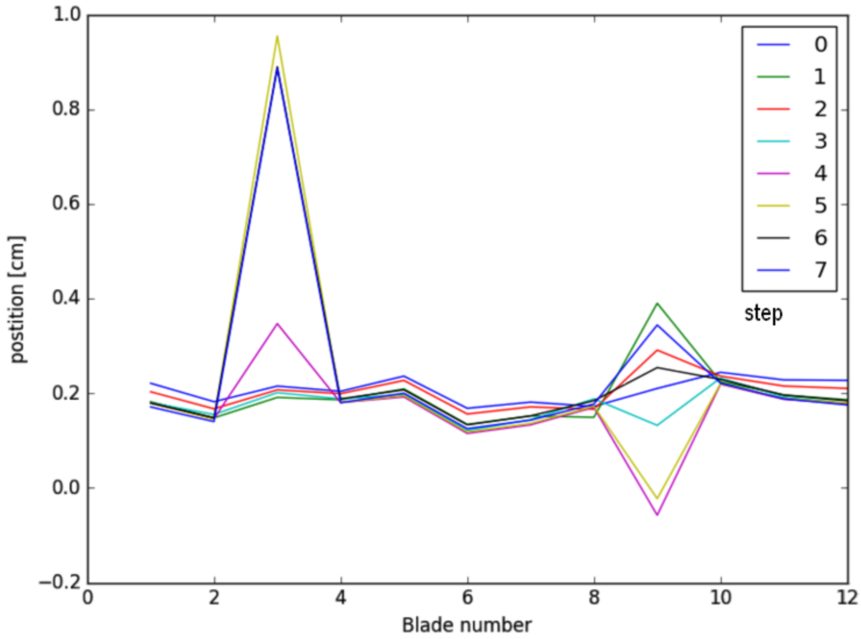

Fig. 11. Stack pattern changed during seeded fault tests for different seeded faults

The theoretical relation between time-of-arrival (phase of pulses) and circumferential position of the objects detected, bolt heads in the reported case, is linear which makes measurement system precise and flexible for measuring blade TOA. However, in the case of radial position, the pulse amplitude depends on the rotor speed and is inversely proportional to the sixth power of the tip clearance as discussed in [25]:

$$V = \frac{K \times tipspeed}{(gap + r)^6} + V_{bias} , \tag{1}$$

where V is the signal voltage, K is the coefficient, r is the radius of the blade, and gap is the distance from the blade tip to the sensor.

This complex relation is the reason that the tip clearance can be efficiently measured only in a limited range of speeds and even in a smaller range of distances. Voltage measurement errors propagate non-linearly, so it may be difficult to obtain acceptable results under certain conditions. However, a value of the clearance measured is an additional signal provided for the analysis with no extra cost, except the effort of calibration. Since cracks that develop in rotating critical components such as turbine or compressor disc are reported to modify both the inter-blade-spacing and tip clearance, both these values should be analysed simultaneously to detect damage.

In the preliminary tests described here, the bolts were used instead of the real turbine blades, so the sensors were not calibrated for measuring absolute tip clearance but only the pulse amplitudes were compared to the qualitatively assessed system response to the seeded faults.

Differences of pulse amplitude as high as 10-15% was observed among bolts (Fig. 12). Screwing in bolt #3 clearly decreased the sensor response (Fig. 13). Bending bolt #9 backward and forward affected the voltage amplitude as the clearance change was an additional effect of bolt bending (Fig. 14).

5. Test plans for spin rig

Spin rigs are used extensively in the turbomachinery industry to evaluate the strength and fatigue life of critical rotating components in a controlled environment. These facilities evaluate gas turbine components by simulating engine conditions and replicating the rotational speeds and temperatures.

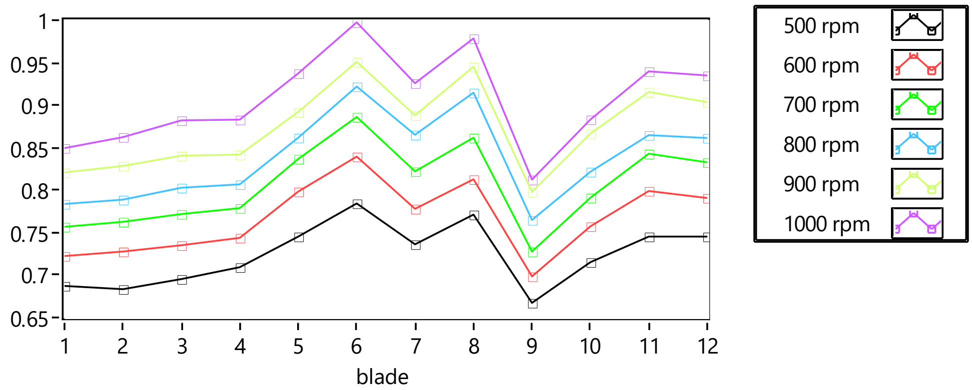

Fig. 12. Reference peak amplitude (step 0) for all bolts

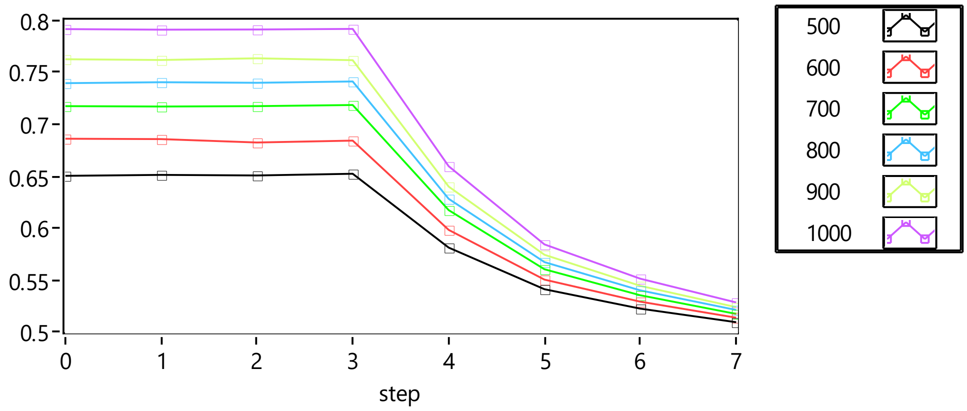

Fig. 13. Peak amplitude for bolt #3, screwed-in (steps 4-7) for different rotational speeds

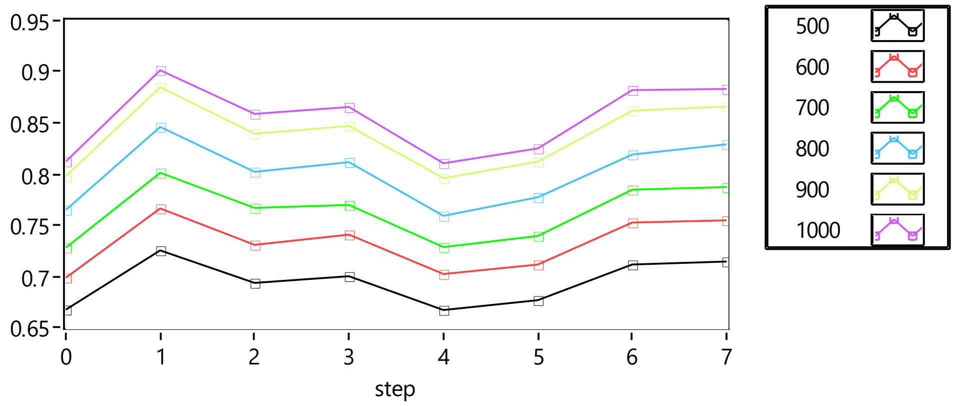

Fig. 14. Peak amplitude for bolt #9 for different rotational speeds

NRC-Aerospace's spin rig test facility shown in Fig. 15 is located in the NRC campus in Ottawa, Ontario, Canada. The rig with a chamber of 1200 mm × 1200 mm in size (48" × 48") allows testing of rotating components in vacuum in elevated temperatures up to 800ºC. Two air turbines allow for exerting rotational speeds up to 40,000 rpm or 100,000 rpm. This rig is used to perform tests of bladed disc assembles with the aim to investigate the process of crack formation and evolution in the critical rotating components. The tip-timing data acquisition system that was bench tested will be installed in this facility to detect incipient cracks and decrease the cost of testing.

Several components of gas turbine engines were tested in the spin rig facility at NRC-Aerospace during the past decade [1-5, 13, 14, 21]. It was found that one of the significant difficulties in designing a test is establishing inspection intervals for components tested. Usually, the test is interrupted at pre-determined intervals, the test rotor is disassembled and the components are subjected to a non-destructive evaluation (NDE). This evaluation involves several NDE techniques, among them an optical examination, liquid penetrant inspection (LPI) or the eddy current (EC) technique. It is clear from NRC's experience in spin rig testing that NDE should be frequent enough so that damage developing in a component can be detected at an early stage. However, each inspection interrupts the test, increases the possibility of damaging the component during disassembly and reassembly of the test rotor, and also incurs additional costs, thus affecting the total cost, schedule and progress of the test. From this point of view, inspections should be performed as infrequently as possible. Nevertheless, extending the period between inspections may lead to missing crack nucleation and growth and result in catastrophic failure of the component. Currently, selection of the inspection interval is based on an educated guess, limited operational data, analytical life predictions or previous experience acquired on tests performed on similar components but under different conditions.

Fig. 15. Spin rig facility in NRC-Aerospace

To assess the condition of a component tested in the spin rig without interrupting the test, on-line damage detection systems that can detect crack formation and evolution in rotating components in vacuum are required and the tip-timing system described in the previous paragraphs will be used for this purpose. As described, the on-line BVM system will continuously monitor blade positions and assess disc health during the test.

A typical test profile used to test a gas turbine disc for low cycle fatigue crack initiation and progression is shown in Fig. 16, while Fig. 17 illustrates a typical fracture surface for a crack generated in the lowest serration of a disc firtree attachment. The crack shown in Fig. 17 was grown naturally in the spin rig environment from a rectangular notch that was artificially introduced using EDM method in the critical location of the firtree attachment, as described in [2]. In this test, spin rig cycling had to be interrupted several times to perform NDE to assure that the artificially generated notch will not grow to a catastrophic size. Application of the BVM system would allow performing this spin rig test much more effectively.

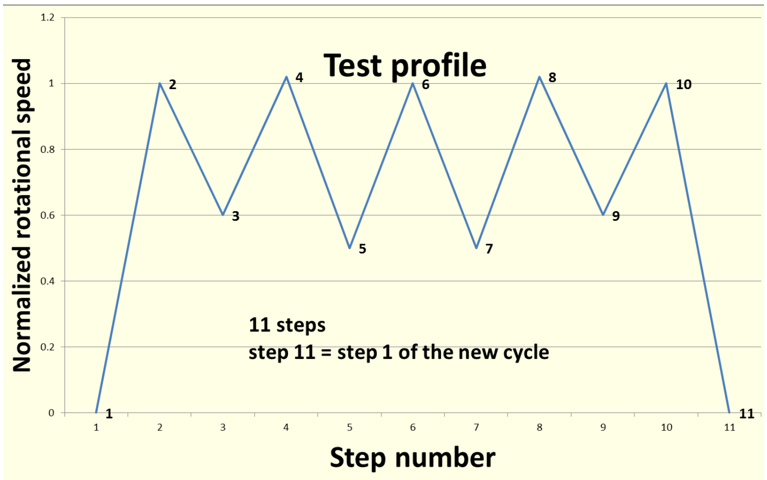

Fig. 16. Typical test profile in the spin rig

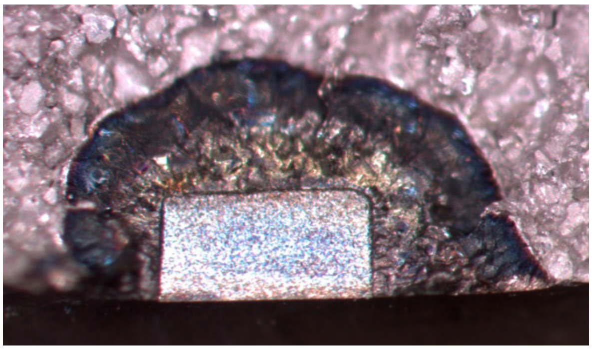

Fig. 17. Typical optical image of a fracture surface for a crack emanating from an EDM notch [2]

6. Summary, conclusions and future work

1. Blade Vibration Monitoring (BVM) system from Hood Technology Corporation was bench tested. The objectives of these tests were to verify sensor response to changes in blade tip displacements in both radial and circumferential directions.
2. The rotor of this test was powered by the carousel stand of the NRC-Aerospace burner rig facility. The test rotor consisted of a disc and 12 equally spaced bolts that could be turned into the threaded holes of the disc to extend or shorten the protruding parts of these bolts.
3. In addition, one of the bolts was notched and then bent into the circumferential direction.
4. Total of eight tests were performed, one to capture the reference data and seven to capture changes caused by seeded faults. In each test, the rotor rotational speed was steadily ramped up from 400 to 1000 rpm.
5. The seeded faults included change in the protruding length of one bolt and also bending of another bolt in the circumferential direction.
6. It was found that the blade vibration measurement system was suitable for monitoring changes of circumferential and radial deflection.
7. Time-of-arrival measurement, visualized on the stack pattern, appeared to be a precise and flexible way to monitor blade circumferential position.
8. Output signal of a passive magnetic sensor depended on the rotational speed, but under certain conditions, it can be calibrated to measure tip clearance.
9. The hexagonal shape of the bolt head made it difficult to monitor its position after height changes were implemented.
10. In the future, the BVM system will be installed in the spin rig facility and testing will be performed using a bladed gas turbine disc.

11. Sensor holders and cable routing for installation in the spin rig environment will be designed and manufactured.
12. Seeded faults using the gas turbine disc are planned to test the ability of the BVM system to detect and discriminate disc damage in the spin rig environment.

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