The effect of sensor characteristics on blade tip timing measurements

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ABSTRACT

Blade Tip Timing is a contactless method used to monitor the vibration of blades in rotating machinery. The blade vibration and the blade clearance are potentially important diagnostic features for condition monitoring, including the detection of blade cracks. Eddy current sensors are considered in this paper. The key requirement is the accuracy of the timing measurement, which depends on the blade deformation and clearance. These effects are much greater for eddy current sensors. Hence a detailed quasi-static finite element model of the electromagnetic field is presented in this paper to understand the integrated measured output. As an example, the effect of the tip clearance and blade velocity on a simplified blade geometry is investigated.

KEYWORDS: contactless diagnostic method, blade tip timing, eddy current sensor, electromagnetic field, blade cracks.

1. INTRODUCTION

Rotor blade failure caused by High Cycle Fatigue (HCF) has been known to produce significant damage during both development and engine operation, which can lead to catastrophic failures in the entire engine. This results in an increase in maintenance cost and increased downtime. To ensure safety and to achieve the predicted remaining life of the equipment in the engine, an in-service health monitoring system is critical to detect and identify unexpected events that lead to HCF. In recent years, contact measurement and data processing techniques have been proposed to monitor the vibration of blades in the rotating frame. One of the basic contact methods is the strain-gauge system which appeared in the 1960s [1]. This approach involves mechanically attaching transducers to the selected blades to provide vibration measurements. This method has several shortcomings; it is time consuming and fragile to the gas turbine environment. Therefore, many investigators have considered contactless diagnostic systems to monitor blade vibrations in the rotating frame due to the non-intrusive and easy installation of sensors which allows prompt detection of potential cracks. One of the well-known methods is the so-called Blade Tip-Timing method (BTT), named also as the Non-Contact Stress Measurement System (NSMS). The BTT method is based on analyzing the time histories of single blades with respect to the position of stationary sensors, called the blade time of arrival (ToA). This is compared to the speed of revolution which leads to the measurement of vibrations since the blade ToA is influenced directly by the vibration amplitude and frequency. During the early 1970s, the first non-contact measurement was introduced by Zablotsky and Korostelev [2] based on their own device to measure vibration called ELURA. Heath and Imregun [3] extended the Zablotsky-Korostelev technique by providing a rigorous and enhanced formulation to derive the blade arrival times using optical laser probes. Several sensing technologies have been
proposed to monitor blade positions in turbomachinery relying on capacitance, optics and eddy-currents. Flotow et al. [4] summarized a variety of vibration blade monitoring technologies and they pointed out the need to distinguish between the effect of cracks and any other source of damage (e.g. thermal expansion or centrifugal force) on the blade lengthening measurements. In the last decade, Zielinski and Ziller [5-6] described several developments in non-contact blade vibration measurement based on crack detection techniques by illustrating various experimental applications using optical and capacitive probes. Woike et al. [7] outlined key results and contributions from three different structural health monitoring approaches. They introduced promising technology using a microwave blade tip clearance sensor and demonstrated its capability to provide both timing and clearance measurements.

Many researchers have explored the potential of eddy current sensors (ECS) to assess the health of an engine without any need for direct access to the blade (e.g. the possibility to monitor through the casing). ECS are also insensitive to the presence of any type of contaminant (e.g. fluid or high temperature). Also, both tip timing and tip clearance of each blade could be measured by these sensors in real time and at high resolution. However, some limitations such as case thickness or material could be a major obstacle in monitoring the system. Garcia-Martin et al. [8] provided an overview of the fundamentals and main variables of eddy current testing. In terms of experimental studies investigating the eddy current assessment of rotating systems, Lackner [9] assembled a test rig of three spinning test blades to test the ability of ECS in a simulated gas turbine environment. Compared to strain gauge data extracted from the test rig, he showed that ECS could mitigate the drawbacks of other type of sensors, such as optical or capacitive sensors. The arrival times of a rotor blade based on ECS were measured by Chana and Cardwell [10] in various engine trials to evaluate the ability of these sensors to detect pre-existing damage and to capture dynamic foreign object damage events. Similarly, Cardwell et al. [11] pursued the prospect of using ECS for the measurement of rotor blade tip timing. They developed an improved ECS system through laboratory tests to measure rotor blade arrival times. In addition, Chana et al. [12] evaluated the ability of an ECS and Reasoner software system to isolate a crack propagated in a cyclic engine and to predict its remaining useful life. More recently, Mandache et al. [13] developed pulsed eddy current technology to monitor the health of the engine through its casing based on blade tip displacement. Using a combination of ECS and optical sensors, Guru et al. [14] instrumented a low pressure turbine stage of a developmental aero engine to monitor blade vibrations during engine tests.

It is observed that these past investigations using eddy current testing in blade tip timing of rotating blades ignored the blade and sensor geometry effects and have just concentrated on extracting response frequencies. Therefore a detailed quasi-static finite element model of the electromagnetic field is needed to understand the integrated measured output and investigate methods to separate the blade response from the blade tip geometry effect. In this paper, a simple rotating blades passing an eddy current sensor will be modelled to investigate the accuracy of the timing measurement when the blades pass by the sensor. The effect on the sensor output of many variables, such as the gap between the sensor and the blade tip and the blade speed, will be considered. These effects can then be compared to experimental data to give a better understanding of the errors introduced in the sensor’s output during the process of monitoring a rotating bladed disk using the blade tip timing method.
2. MECHANICS OF EDDY CURRENT SENSORS (ECS) IN MONITORING A MOVING TARGET

In this section the concept of eddy current monitoring is described. A model is presented to reveal the main principle of eddy current distribution along a moving conductive target and the variation of impedance that occurs in the coil sensors. The operating principles are understood as follows [8]. An alternating current placed in a coil of ECS generates a time-varying magnetic field formed around the coil. If an electrically conducting target is moving past it, the primary magnetic field penetrates the moving object causing a variation of the magnetic flux through it. Following Faraday’s law of induction, this induces a flow of electric current, named the eddy current. The induced currents in the target generate a secondary magnetic field that acts against the primary magnetic field as shown in Figure 1. Therefore a change in the impedance of the coil is captured by the sensor. Measuring this discrepancy of coil impedance will reveal particular information, such as the gap between the sensor and the target, or the vibration of the target tip.

The model of an eddy current sensor for a moving target can be described under certain assumptions by the following differential equation [15-16]:

\[
\nabla \times (\nabla \times A) - \mu \sigma \left(-\nabla \phi - \frac{\partial A}{\partial t} + \nu \times (\nabla \times A)\right) = \mu f_s. \quad (1)
\]

Where \( A \) is the magnetic vector potential, \( \phi \) the scalar potential, \( f_s \) is the external electric current density induced in the sensor, \( \mu \) is the magnetic permeability of the medium, \( \nu \) is the velocity of the target and \( \sigma \) is the conductivity of the target’s medium.

3. NUMERICAL METHOD FOR BLADE TIP TIMING USING ECS

In this section, a simulation of the distribution of an eddy current by ECS in a simple rotating bladed disk is described. To achieve this task, a commercial FEA software package, COMSOL Multiphysics® was used. The 2-D geometry of the model is shown in Figure 2 and was generated based on the design parameters given in Table 1. The bladed disk is composed of a disk and 4 simple blades, and a rectangular eddy current sensor fixed to a casing is modelled.

<table>
<thead>
<tr>
<th>Name</th>
<th>Expression</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>rpm</td>
<td>2000[1/min]</td>
<td>33.333 1/s</td>
<td>Rotational speed of the rotor</td>
</tr>
<tr>
<td>( R )</td>
<td>0.1[m]</td>
<td>0.1 m</td>
<td>Radius of the rotor hub</td>
</tr>
<tr>
<td>( l )</td>
<td>0.1[m]</td>
<td>0.1 m</td>
<td>Blade length</td>
</tr>
<tr>
<td>( b )</td>
<td>0.005[m]</td>
<td>0.005 m</td>
<td>Blade width</td>
</tr>
<tr>
<td>( a )</td>
<td>0.003[m]</td>
<td>0.003 m</td>
<td>Overlap of blade into the disk</td>
</tr>
<tr>
<td>( \omega )</td>
<td>0.2[cm]</td>
<td>0.002 m</td>
<td>Sensor width</td>
</tr>
<tr>
<td>( l_s )</td>
<td>0.5[cm]</td>
<td>0.005 m</td>
<td>Sensor Length</td>
</tr>
<tr>
<td>( \delta )</td>
<td>5[mm]</td>
<td>0.005 m</td>
<td>Gap between Sensor and Blade tip</td>
</tr>
<tr>
<td>( R_a )</td>
<td>( R + l - a + \delta/2 )</td>
<td>0.1995 m</td>
<td>Radius of Moving surrounding air circle</td>
</tr>
<tr>
<td>( R_s )</td>
<td>( R_a + 10^4 l_s )</td>
<td>0.2495 m</td>
<td>Radius of Static surrounding air circle</td>
</tr>
<tr>
<td>( R_i )</td>
<td>( R_s + \delta/2 + l_s/3 )</td>
<td>0.20367 m</td>
<td>Inner radius of the casing</td>
</tr>
<tr>
<td>( R_o )</td>
<td>( R_s + \delta/2 + 2^* l_s )</td>
<td>0.212 m</td>
<td>Outer radius of the casing</td>
</tr>
</tbody>
</table>

The blades, disk sensor and casing are assumed to be solid aluminum. To discretize the 2-D domain of the model, the geometry was cut along the air gap into two parts: one containing the static part of the model (the sensor, the casing and surrounding air), and the other containing the moving part (i.e. the disk, the blades and the
surrounding air) as shown in Figure 3. The two parts are then meshed separately. Triangular elements were used in the discretization (Figure 4). The static part remains stationary while the moving part rotates. These two parts with the corresponding meshes always stay in contact at the cut boundary. As shown in Figure 4, the COMSOL software enables the moving mesh with the rotating part and guarantees suitable transformations of the electromagnetic field. After creating the mesh, the boundary conditions were obtained by the software, considering continuity of the magnetic potential along the blades and applying the quasi-static approximation where the displacement current density is ignored. Finally, a stationary and time-dependent analyses for an interval of time of 0.014 seconds and at a rotational speed of the rotor equal to 2000 rev/min were performed.

4. SIMULATION RESULTS FOR THE MOVING BLADED DISK AND ECS

All simulation results were generated by the COMSOL software. A mesh refinement study has been performed to optimize the computation time and obtain converged results. The mesh was refined by decreasing the mesh element size and therefore increasing the number of elements. Figures 5 shows the measured sensor signal corresponding to the meshing after refinement. The total number of elements used was 20620 elements.

Figure 6 shows the surface plot of the norm of the magnetic flux density at the initial time, t=0s. The magnetic vector potential is also shown by magnetic flux lines induced thorough the plane of the bladed disk. We can see that there is no variation or effect on the magnetic flux lines since the blades are still static and the electromagnetic field is continuous across the surrounding air, since a homogenous material is assumed.

At t=0.0025s, one of the blades passes by the ECS, and Figure 7 shows a variation in the induced magnetic flux lines. This variation is due to the interference between the primary magnetic field generated by the ECS and the secondary magnetic field generated by the moving blades past the sensor. This agrees with the concept of eddy current sensors described in Section 2.

Figure 5 shows the corresponding coil voltage captured by the sensor when a blade passes by it. As observed, a signal peak is obtained every time a conducting blade enters the field of the sensor which alters the magnetic field through the induced eddy currents in the blades. This describes clearly the behavior of an eddy current sensor; based on a reference voltage which will correspond to a known position on the blade, the time of blade passing can be determined. This gives information about the time of arrival of the blade at the sensor probe.

Figure 8 shows the effect of the variation of the width of the moving blades. By increasing the width of the blade, the amplitude of the sensor signal increases. Also, as expected, we notice a translation of the time corresponding to the peak of the signal since the width is increasing. This is due to the large disturbance caused by the larger blade width in the magnetic field.

Figure 9 shows the effect of the variation of the gap (i.e. the distance separating the blade tip and the surface of the sensor during the rotation of the bladed disk) on the sensor output. There is a clear decrease in the signal amplitude with increasing gap between the sensor and blade tip. This shows the sensitivity of the ECS to small distance variations.

Finally, Figure 10 shows the effect of the rotational velocity of the bladed disk on the sensor voltage. For further clarity of this effect, MATLAB was used to shift the different curves in such a way that the blade passes the sensor at the same time. The
amplitude of the signal tends to increase with the rotational speed. This sensitivity shows that the speed of the target moving past the sensor could be a source of error.

5. CONCLUSION

This paper has considered a simple bladed disk that is rotating and surrounded by a casing to which an eddy current sensor has been attached. The aim was to investigate the accuracy of the blade tip timing method for condition monitoring of blades in rotating machines. Eddy current sensors have been considered in this paper due to their robustness in harsh environments. The governing equations modelling the magneto electric field of a moving target have been described for a quasi-static problem. A numerical simulation using the COMSOL software has been considered. A detailed description of the geometry of the model as well as the meshing and physics applied where described. The results showed a sensitivity of the eddy current sensor measurement to the air gap and sensor location as well as to the geometry of the blades and the rotational speed of the system. This sensitivity is a great help to understand the errors that could be introduced due to the inhomogeneities in the blades or the disk and the time of blade passing can be estimated more accurately by taking in consideration these effects. Moreover, this investigation into the sensitivity of the eddy current signals to different model parameters allows these parameters to be fixed strategically in order to increase damage sensitivity. Thus in terms of experimental work, the voltage picked can be chosen with minimal influence of the blade.

ACKNOWLEDGEMENTS

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Fig. 3 The geometry of the moving and static parts.

Fig. 4 The mesh of the model.

Fig. 5 Effect of mesh refinement on the signal sensor corresponding to mesh with 20620 elements.
Fig. 6 Magnetic flux density norm (surface) and magnetic vector potential Z-components (contour) at \( t=0 \)s.

Fig. 7 Magnetic flux density norm (surface) and magnetic vector potential Z-components (contour) at \( t=0.0025 \)s.

Fig. 8 The induced voltage in the sensor with time for different blade widths.
Fig. 9 The induced voltage in the sensor for different blade gaps.

Fig. 10 The induced voltage in the sensor for different rotational speeds.
References


