ABSTRACT

In gas turbines, the blade vibration caused by aerodynamic excitation or by self-excited vibration and flutter leads to high cycle fatigue that represents the main cause of damage in turbomachinery. Turbine operators have resorted to assess the blade vibrations using non-contact systems. One of the well-known non-contact methods is Blade Tip Timing (BTT). BTT is based on monitoring the time history of the passing of each blade tip by stationary sensors mounted in a casing around the blades. The BTT method evaluates the blade time of arrival (ToA) in order to estimate the vibration. To perform the BTT technique, optical sensors were widely used by industry due to their high accuracy and performance under high temperatures, but the main drawback of these systems is their low tolerance to the presence of contaminants. To mitigate this downside, Eddy Current Sensors (ECS) are a good alternative for health monitoring application in gas turbines due to their immunity to contaminants and debris. This type of sensor was used by many researchers, predominantly on the experimental side. The focus was to extract response frequencies and therefore the accuracy of the timing measurement was ignored due to the lack of modeling. This paper fills the gap between experiments and modeling by simulating a BTT application where detailed finite element modeling of active and passive ECS outputs was performed. A test rig composed of a bladed disk with 12 blades clamped to a rotating shaft was designed and manufactured in order to validate the proposed models with experimental measurements. Finally, a comparison between these different types of sensor output is presented to show the effect of the blade tip clearance and rotational speed on the accuracy of the BTT measurement.

INTRODUCTION

In turbomachinery, severe vibratory loads may lead to blade failures and therefore the total failure of the engine. Maintenance of the rotating machine is very important and has a tremendous impact on the life cycle cost of the engine. To obtain the best efficiency, an intelligent assessment is necessary for early damage diagnosis and condition based maintenance activities. Different monitoring techniques have been developed using sensors in the casing around the rotating part to measure and estimate the time of the arrival (ToA) of the blade tips passing by the sensors. In the 1960s, Fragman et al. [1] developed a contact method where the measurement of rotating blade responses was performed by means of blade mounted strain gauges. This method has several shortcomings such as time and cost, and the low resistance to the harsh environment found inside the machine. An alternative to this method, many investigators have considered contactless methods to monitor blade vibrations in the rotating machinery due to the
non-intrusive and easy installation of sensors which allows prompt detection of potential cracks. One of the well-known contactless method is the Blade Tip Timing (BTT) approach, which estimates the blade vibration that is crucial in the assessment of machine operation and the prediction of blade failure due to fatigue as shown by Georgiev et al. [2]. The concept of this method relies on using a number of probes fixed to the casing of the machine to detect the blade tip as it passes by the probes. Then, Dimitriadis et al. [3] showed that the difference between the time of arrival (ToA) of non-vibrating and vibrating blades leads to the estimation of the vibration displacement that is utilized to identify vibration parameters.

During the early 1970s, Zablotsky and Korostelev [4,5] introduced the first non-contact measurement based on their own device to measure vibration called ELURA. This technique was extended by Heath and Imregun [6] based on an improved formulation to extract the blade arrival times using optical laser probes. Dimitriadis et al. [3] simulated data from traditional BTT tests of rotating blades. They performed a qualitative analysis of different phenomena that can affect the identification of blade vibration parameters such as mistuning or coupling. A modal parameter identification of rotating machine blades was presented by Salhi et al. [7] using BTT data. Liu and Jiang [8] monitored the blade vibration of a rotating machinery test rig using the BTT method. They proposed a method to improve the accuracy of the measurements in the presence of torsional vibration. Similarly, Madhavan et al. [9] conducted an experiment to monitor the vibration measurement using the BTT technique. Therefore, the focus in the previous researches has been mainly on experimental work to describe the BTT method.

Several sensing technologies have been proposed to monitor blade positions in turbomachinery relying on capacitance, inductance, optics, microwaves and eddy-currents. The focus in this paper will be mainly on the ECS due to its potential to assess the health of a machine without any need for direct access to the blade (e.g. the possibility to monitor through the casing) and therefore they are insensitive to the presence of any type of contaminant. Also, both tip timing and tip clearance of each blade could be measured by these sensors in real time and at high resolution. Dowell and Sylvester [10] described the physical principles of ECSs and the approach used to develop a health management program for turbomachinery. In addition, Lackner [11] assembled a test rig of three spinning test blades to test the ability of ECSs in a simulated gas turbine environment, he showed that ECSs could mitigate the drawbacks of other types of sensors, such as capacitive sensors. The arrival times of a rotor blade based on ECSs have been measured by Chana and Cardwell [12] in various machine trials to evaluate the ability of these sensors to detect pre-existing damage and to capture dynamic foreign object damage events. More recently, Mandache et al. [13] developed a pulsed eddy current technology to detect the blade and disk damage through the machine casing based on monitoring the blade tip displacement.

The emphasis in the existing literature was on the experimental side more than the modeling side. Therefore, a detailed model of the use of ECS in blade tip timing is required for further development of BTT systems and in order to increase the accuracy of the timing measurement.

In this paper, 3-D models of a rotating bladed disk passing active and passive ECSs are implemented using the COMSOL Multiphysics software. These models were validated thorough a comparison with a test rig measurements using commercial Passive Eddy Current Sensor (P-ECS) and Active Eddy Current Sensor (A-ECS). Finally, the effect of the rotation speed and the tip clearance between the blade tip and the sensor on the sensor output is investigated.

**FUNDAMENTAL PRINCIPLES OF EDDY CURRENT SENSOR MONITORING OF A MOVING TARGET**

In this section, the principle of an eddy current sensor monitoring a moving target is described in addition to the basics physical background of this principle.

**Principle of Eddy Current Sensors**

If a conductive material moves through an alternating or permanent magnet field is acting on a moving target, induced eddy currents are generated and detected by the coil system of an ECS. There are two cases that correspond to a P-ECS and A-ECS that have both been used for BTT applications. Starting with the case of the A-ECS, the operating system is understood as follows [13]. A primary time-varying magnetic field formed around the coil is generated by an alternating current running through the coil of the ECS. If an electrically conducting target is moving past it, eddy currents are generated and induced in the target due to Faraday’s law of induction. These induced currents generate a secondary magnetic field that acts against the primary magnetic field as shown in Fig. 1.

![FIGURE 1. PRINCIPLE OF EDDY CURRENT SENSOR](image-url)
This results in a variation of the coil’s impedance which is captured by the sensor. Measuring this discrepancy of coil impedance will reveal particular information, such as the vibration of the target tip, or the gap between the sensor and the target.

A P-ECS follows similar approach to an A-ECS, except that the primary magnetic field is permanent and the induced eddy currents are generated by the motion of the target. Therefore, the sensor picks up the secondary magnetic field generated by these eddy currents. This type of sensor is not considered as a displacement sensor since it measures velocity, but it does work well for BTT where the blade is always moving past the sensor.

**Electro-Magnetic Governing Equations**

In this section, the effect of the eddy current in a moving target is modeled using the vector and scalar potential terms. To describe the electro-magnetic field in terms of sources, Maxwell’s equations (Eqs. (1)-(4)) along with constitutive equations (Eqs. (5) and (6)) and the magnetic and electric material properties of the moving target are used as (Karakoc et al. [14] and Rosell and Persson [15]):

\[
\nabla \times H = J + \frac{\partial D}{\partial t} \tag{1}
\]

\[
\nabla \times E = -\frac{\partial B}{\partial t} \tag{2}
\]

\[
\nabla \cdot D = \rho \tag{3}
\]

\[
\nabla \cdot B = 0 \tag{4}
\]

\[
\rho = \varepsilon E \tag{5}
\]

\[
B = \mu H \tag{6}
\]

where \( H \) is the magnetic field strength, \( B \) is the magnetic flux density, \( E \) is the electric field, \( D \) is the displacement flux density, \( J \) is the current density, \( \rho \) is the charge density, \( \mu \) is the magnetic permeability and \( \varepsilon \) is the electric permittivity of the medium.

Considering an eddy current sensor monitoring a conductive target, the total electric current generated is given by

\[
J = J_e + J_s \tag{7}
\]

where \( J_e \) is the electric current density in the conductive target and \( J_s \) is the external electric current density induced in the sensor. Following Ohm’s law for a moving conductor, along with the presence of the magnetic field, the eddy current generated in the target is defined as

\[
J_e = \sigma (E + \nu \times B) \tag{8}
\]

where \( \nu \) is the velocity of the target and \( \sigma \) is the conductivity of the target’s medium.

Satisfying two of Maxwell’s equations, Eqs. (2) and (4), the magnetic vector potential \( A \) and the scalar potential \( \phi \) are defined as

\[
E = -\nabla \phi - \frac{\partial A}{\partial t} \tag{9}
\]

\[
B = \nabla \times A \tag{10}
\]

Since the eddy current problem is a magneto-quasi-static problem (Pohl et al. [16]), the displacement current can be ignored, i.e. \( \frac{\partial D}{\partial t} \approx 0 \). Therefore, substituting Eqs. (6-10) into Eq. (1) yields

\[
\nabla \times B = \mu J_s + \mu \sigma (E + \nu \times B) \tag{11}
\]

By rearranging the terms in Eq. (11) and replacing the electric field and magnetic flux density by their expressions in Eqs. (9) and (10), we obtain, in terms of \( A \) and \( \phi \), the following magnetic governing equation

\[
\nabla \times (\nabla \times A) - \mu \sigma \left( -\nabla \phi - \frac{\partial A}{\partial t} + \nu \times (\nabla \times A) \right) = \mu J_s \tag{12}
\]

**NUMERICAL MODELS**

In this section, a simulation of the distribution of an eddy current by a passive and active ECS in a designed rotating bladed disk is described. In a previous work (Jamia et al. [17]), the authors implemented 2-D and 3-D models of a simple rotating bladed disk passing a P-ECS using a commercial FEA software package, COMSOL Multiphysics® (Weststrate et al. [18]), to investigate the accuracy of the timing measurement when the blades pass by the sensor. The effect of the rotation speed and the tip clearance between the blade tip and the sensor on the sensor output was investigated. This presented a first step towards realistic geometries where it is complicated to change parameters easily.

**Bladed disk design**

An integral bladed disk composed of 12 blades is designed using the SolidWorks design software. The design of the blade is a rectangular blade with a blade twist angle equal to 20 degrees. Regarding the disk, the outer and inner diameters of the disk were fixed to 200mm and 60mm, respectively. The outer thickness of the disk is set at 30mm and the inner thickness is set at 20mm. The blade disk design is shown in Fig. 2.
Modeling of Passive Eddy Current Sensors

The 3-D geometry of the model described in the previous section was uploaded to the COMSOL Multiphysics® software. In order to reduce the computational time, a bladed disk with only two blades was used. A hollow cylindrical ECS is fixed at a distance $\delta$ which equals the gap between the blade tip and the sensor. The blades, disk and sensor are assumed to be structural steel. The geometry of the model is shown in Fig. 3.

The 3-D domain is discretized by cutting the geometry along the air gap into two parts: one containing the static part of the model composed of the sensor and surrounding air (purple colour), and the other containing the moving part composed of the disk, the blades and the surrounding air (orange colour) as shown in Fig. 4.

The two parts are then meshed separately. Tetrahedral elements were used in the discretization of the 3-D model. 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. The COMSOL software enables the moving mesh for the rotating part and guarantees suitable transformations of the electromagnetic field. The total number of elements used was 957562 elements, as shown in Fig. 5.

The COMSOL interface applies Ampere’s law to the conductive domains (e.g. bladed disk and sensor). For the free-current domain, such as the surrounding air, a magnetic flux conservation feature is applied based on the assumption that the magnetic field is curl free in the no-current region and this gives an important decrease of computational time. A coil feature from the Magnetic Fields interface in the COMSOL software was assigned to the hollow cylinder in the model geometry in Fig. 3 to model the sensor as a conductor subject to an externally applied current or voltage. This feature transforms the applied excitation into local quantities (e.g. electric field and electric current density), and calculates the lumped parameter of interest such as impedance in this case. In addition, due to convergence issues of the model, the current value in the coil was ramped from a low value using a smoothed step function. Finally, the boundary conditions were fixed by the COMSOL interface, considering continuity of the magnetic potential along the blades, and applying the quasi-static approximation where the displacement current density is ignored.

A time-dependent analysis for an interval of time of 1.7 seconds and at a rotational speed of the rotor equal to 100 rev/min was
performed for the P-ECS model. Figure 6 shows the volume plot of the magnetic flux density’s norm at the instant when one of the blades passes by the sensor. The magnetic vector potential is also shown by magnetic flux lines induced through the bladed disk. We can notice 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 ECSs described above.

**FIGURE 6.** VOLUME PLOT OF THE MAGNETIC FLUX DENSITY’S NORM AT THE INSTANT WHEN ONE OF THE BLADES Passes BY THE SENSOR

This model is based on measuring the change in the coil impedance which is related to the gap between the sensor and the target, and hence the sensor output gives the relative displacement. Therefore, compared to the P-ECS model, the continuous rotation approach is ignored and replaced with a series of blade positions using a sweep of geometry parameter defined as

$$\text{rot angle} = t_{\text{para}} \cdot \Omega \cdot 2\pi \text{ (rad)}$$  (13)

where $t_{\text{para}}$ is the parametric time and the blade will rotate with respect to this time at a rotational speed $\Omega$. Then, the model is solved as a series of frequency domain studies whilst rotating the blades in the geometry via a Parametric Sweep. A frequency domain study defines that an alternative current is used for the coil excitation oscillating at a parameter $f_0$. This excitation has been set to be 1000 times the spinning speed of the blade, to ensure that the quasi-static approximation is valid. A very fine mesh is used for the fan and the coil. The mesh in the blades has been heavily refined to resolve the currents well. Finally, 468634 tetrahedral elements have been used for the model as shown in Figure 9.

**FIGURE 9. MESH DETAILS OF THE AECS MODEL**

Ampere’s law was applied to the different domains of the model, and similarly to the P-ECS model, a coil feature is assigned to the cylinder in the model geometry to simulate the sensor. The A-ECS model is solved for a full period of rotation of the bladed disk, $T_b = 1/\Omega$, for 1000 time steps within that time interval.

**FIGURE 10. SURFACE: MAGNETIC FLUX DENSITY NORM (T) ARROW VOLUME: INDUCED CURRENT DENSITY OF THE PECS MODEL**

Figure 10 shows the volume plot of the magnetic flux density’s norm at the instant when one of the blades passes by the sensor.
The magnetic vector potential is also shown by magnetic flux lines induced through the bladed disk. Figure 11 shows the variation of the impedance in the coil due to the passing of the blades.

Figure 1 shows the variation of the impedance in the coil due to the passing of the blades.

FIGURE 1: THE IMPEDANCE VARIATION OF THE AECS MODEL.

EXPERIMENTAL TEST RIG

In this section, an experimental test rig setup is described and a validation of the models performed with the experimental measurements is presented.

Test Rig Setup

A test rig was designed and manufactured in order to generate BTT measurements using A-ECS and P-ECS. The test rig is composed of a bladed disk with 12 blades surrounded by a cylindrical casing at distance \( \delta \) (the gap between the blade tip and the sensor). The bladed disk is clamped to the end of a rotating shaft supported by two ball bearings fitted in two split Plummer block housings. The shaft is driven by a servo motor at 100 rpm. The manufactured test rig details are shown in Fig. 12.

A commercial P-ECS from the Jacquet company and an A-ECS from Micro-Epsilon company were used to collect the Blade Tip Timing (BTT) measurements, and were mounted on the casing through different holes that were drilled in the casing, as shown in Figure 13.

FIGURE 13. ECSs MOUNTED ON THE CASING

These sensors were connected to a National Instrument Data Acquisition system in order to collect the different measurements.

Model Validation

In order to improve the reliability of the models discussed above, we need to validate these models with experimental measurements obtained from the test rig. At a rotational speed equal to 100 rpm and a gap of 3mm between the sensors and the blade tip, the BTT measurements were collected from the A-ECS and P-ECS and compared to the simulated data from the described models.
FIGURE 14. (a) COMPARISON OF NUMERICAL RESULTS WITH EXPERIMENTAL MEASUREMENTS FOR THE P-ECS (b) A LOCALLY ENLARGED GRAPH OF FIG. 14a

Figures 14 and 15 show a good agreement between the simulated and measured data of BTT for a P-ECS and A-ECS.

PARAMETERIC STUDY

Figures 16 and 17 show 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 corresponding to a P-ECS and an A-ECS, respectively. There is a clear decrease in the signal amplitude with increasing gap between the sensor and the blade tip. This shows the sensitivity of the ECS to small distance variations.

FIGURE 16. (a) THE COIL CURRENT OUTPUT OF THE P-ECS MODEL WITH TIME FOR DIFFERENT GAPS (b) A LOCALLY ENLARGED GRAPH OF FIG. 16a

FIGURE 15. (a) COMPARISON OF NUMERICAL RESULTS WITH EXPERIMENTAL MEASUREMENTS FOR THE A-ECS (b) A LOCALLY ENLARGED GRAPH OF FIG. 15a
Finally, Figure 18 shows the effect of the rotational velocity of the bladed disk on the sensor output. The output curves have been shifted so that the blade passes the sensor at the same time. The variation of signal amplitude is more important for the P-ECS than the A-ECS which agrees with the fact that the P-ECS is not a displacement sensor and is affected by the target speed while the velocity doesn’t affect the A-ECS output. This sensitivity shows that the P-ECS could be more efficient for the BTT measurement.

CONCLUSION

This paper has simulated a rotating bladed disk monitored by passive and active eddy current sensors. The aim was to simulate the measurement process used for blade tip timing using eddy current sensors. Eddy current sensors have been considered in this paper due to their robustness in harsh environments. The governing equations modeling the magneto electric field of a moving target have been described for a quasi-static problem. A detailed description of the geometry of the 3-D models were described, together with the meshing details and the physics of the coupled problem of mechanical and electro-magnetic fields. The simulations gave sensor outputs that correspond to those measured and reported in the literature for P-ECS and A-ECS. These models were validating using a test rig designed and manufactured to generate BTT measurements for P-ECS and A-ECS. The parameter studies showed that the eddy current sensor output is sensitive to the air gap and the sensor location, as well as to the rotational speed of the system. This sensitivity can help to understand the errors that could be introduced and the time of blade passing can be estimated more accurately by taking in consideration these effects. Moreover, this modeling approach can be utilized to design and optimize blade tip timing systems with multiple sensors and complex geometries; such studies will be the subject of future research.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support of the Qatar National Research Fund through grant number NPRP 7-1153-2-432.

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