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BLADE TIP MEASUREMENT ADVANCED VISUALIZATION USING A THREE DIMENSIONAL REPRESENTATION

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ABSTRACT

A microwave tip clearance sensor capable of measuring the hottest stages of industrial and aero gas turbines has been developed. This new microwave sensor has been integrated into a commercial package for online real-time monitoring of machine data. However, data analysis of large numbers of tip clearance probes makes standard industry graphic techniques cluttered. A method has been developed to reduce this data and visualize it in order to provide intuitive representations of the data from which a user can quickly draw the right conclusions about machine behavior.

The main motivation for the development of a 3D graphical user interface is the density of information that can be shown to the user at one time. Tip clearance measurement is very data-rich, as every individual blade for each sensor mounted around the engine case is available. The result is that it may be difficult to find slight changes within hundreds of clearance trends. Only specialists with long experience in tip clearance measurement can synthesize all the data quickly enough using standard 2D plots.

The 3D graphical user interface brings all of this data together to calculate the aggregated blade pattern, rotor positioning, and estimated case shape. All of these measurements are available to the user in a single visualization. Colors indicating alarm or clearance scale quickly draw attention to the most important data such as the minimum clearance point around the engine case where a rub may be likely to occur. This method is based about a case shape fitting algorithm that combines data from multiple sensors to make a case shape estimate based on fitting of a non-uniform rational B-spline (NURB). The scaling is also distorted in order to accentuate the graphics in a way that provides an intuitive understanding of the machine state. The method of applying this data accentuation is important so as to not be misleading.

This innovative navigation interface presented in this paper capitalizes on modern advances in computer graphics to aid engineers and operators in understanding, access, monitoring, and analysis of tip clearance and air-gap measurements.

INTRODUCTION

Blade tip clearance measurement is gaining interest from the engine manufacturer community as it is an essential parameter to monitor. The tip clearance measurement is already used and known by engine manufacturer but has been mainly utilized on test engines on which the goal is to validate the design and to affine the models and mechanical simulations. Commonly, capacitance gages or optical sensors are used for this purpose, both having well-known limitations preventing their use for long term monitoring and active clearance control.

It has been identified that tip clearance is a key part in engine efficiency improvement as reducing this clearance between the blades tip and the surrounding casing leads to a lower tip leak [1] [2] but on the other hand, a too small tip clearance may generate an undesired rub event which would have the effect to remove material off the blade tip and increasing even more the blade tip clearance. Over time the blade tip deterioration will inevitably reduce the engine efficiency if no action is taken to keep the clearance at its design value. The first stages of the turbines are the most critical for efficiency gain. However they also are the hottest stages and harshest environment for blade tip clearance probes.

Different clearance control systems exist already which are passive and based on an engine clearance model with no real time on-line measurement feedback. The industry is moving toward active clearance control systems using real time tip clearance measurement of sensors [3]. To achieve this ultimate goal, the industry puts high requests on tip clearance measurement: high precision, the tip clearance measurement from low revolution speed to highest speed must be measured accurately; the tip clearance of all blades should be measured; the measurement result should not be affected by temperature and blade tip geometry; the dimension of the probe should be as small as possible; the measurement should be real-time and on-line to monitor and control the engine system promptly.

Meggitt is working on a microwave tip clearance system in order to monitor long term and provide valuable measurement to a control system and operators. The system measures individual blades tip clearances and supply numerous measurements to an operator as it provides every blade of every sensor mounted on the engine. Data reduction techniques shall be used in order to easily identify important parameters such as the minimum or average blade tip clearance, the blade pattern, the rotor motion or the case deformation. In order to efficiently represent and navigate through those measurements, a 3D interface was designed. The entire engine with all its compressor and turbine stage is represented with the possibility to use the actual blades and engine part models. Each stage instrumented is clearly identifiable with colors and animation and can be selected in a single stage view. The different objects are selectable and all the information and measurements are available by a computer mouse click on them.

MEGGITT MICROWAVE MEASUREMENT SYSTEM

The microwave displacement measurement system mentioned in this paper was originally developed and patented at Georgia Tech in 2001 [4]. The system uses a technique for determination of the sub-wavelength phase of a reflected continuous-wave (CW) microwave signal. The phase of the reflected signal is directly related to the distance to the point of reflection. The reflected signal is compared to an internal reference signal in order to determine the relative phase of the reflected signal as shown on Fig. 1. However, this distance is only the incremental distance within the last wavelength unless the number of wavelengths to the target is otherwise known. The output of the system is composed of two channels with 90 degrees phase offset.

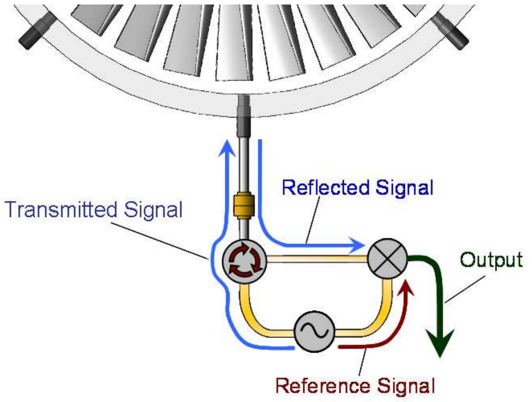

Figure 1: Sketch of the microwave subsystem of the tip clearance measurement system.

The two channels output of the system can be represented as a complex signal which after demodulation at of the microwave signal to DC frequency band is a sum of vectors. Those vectors are the mathematical representation of the multiple reflections of the microwave signal along the cable line. In the eq. (1), each reflection contributes to the measured signal and has an amplitude and a phase depending on its reflected energy and distance.

$$I + jQ = \sum_{n} A_n e^{j \cdot \phi_n} \quad (1)$$

For tip clearance measurements, a narrow-band microwave antenna is imbedded in the microwave probe installed in the engine. Transmitting out of the antenna pass-band causes the microwave signal to reflect off of the microwave antenna. This property of the microwaves can be exploited to provide information on each reflection along the cable line. As each reflection occurs at a different distance, decomposition is possible as illustrated in the figure 2. and provide valuable indication on cable break for example.

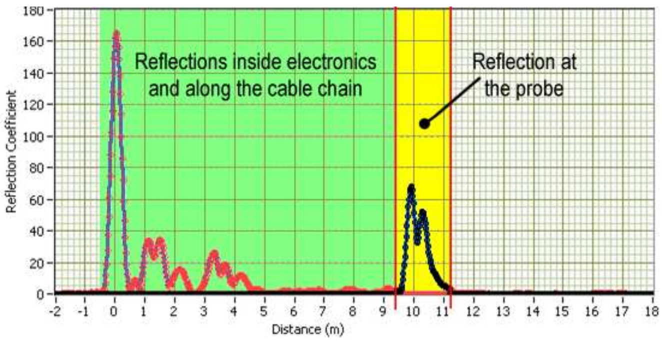

Figure 2: Decomposition of individual reflections occurring along the cable line used for diagnostics of the microwave system.

Transmitting in the pass-band of the antenna allows microwaves to pass through the antenna and reflect off of the passing blade tips.

In a microwave system, the phase signal over time depends on two parameters being the wavelength and the distance of the reflection as indicated in the eq. (2). Considering the blade measurement, the wavelength is constant as the measurement is performed at one frequency and only the distance of the reflection to the blade is changing with blades passing by the probe. The other reflections from eq. (1) are not changing over the course of the measurement can be easily removed.

$$\phi(x(t),\lambda(t)) = \phi_0 + \frac{4\pi}{\lambda(t)}x(t) \qquad (2)$$

Finally, by determining the phase measurement to the blade tip and the phase to the microwave antenna, an absolute phase difference in between these two points may be calculated by subtraction. This compensated phase difference relates to the absolute distance in between the two objects by the eq. (1).

$$\delta = \frac{\varphi'}{4\pi}\cdot\frac{c}{T} \quad \text{and} \quad \delta' = f_{cor}(\delta) \qquad (1)$$

Eq.1: Relation between the raw clearance δ, the compensated phase φ', the chosen frequency T and the light celerity c. The corrected clearance value δ' is obtained by using a calibration correction function f_{cor}.

The microwave system is made up of three main components in addition to a data recording and visualization server. First, the microwave probe is basically a microwave antenna in a body which mates and references it to the engine above the passing blade tips. Second, the microwave acquisition and processing electronics generate the microwave signal, compare the returned signal to the internal reference signal and acquire and process the data for measurement to send digitalized individual blade tip clearances to a server. Finally, a microwave extension cable connects the probe to the electronics.

The microwave system outputs the individual blade tip clearance of each probe at a rate of once per second. The measurement between the different sensors can be configured as synchronous to ensure a simultaneous acquisition starting at the same time on all the sensors looking at the same stage of the engine. This is particularly important to measure the rotor dynamic component.

TIP CLEARANCE MEASUREMENT

Advanced blade tip clearance systems provide individual blade tip values. The amount of data is consequent and therefore its analysis is crucial. Usually, the minimum clearance is of great interest so that undesired events of blade rubbing are avoided. With multiple sensors around the same bladed rotor installed, the case shape and the minimum clearance location around the casing can be estimated using interpolation techniques such as spline fitting or based on more complex modeling of the casing deformation. Knowing the minimum clearance and case shape estimation allow to identify the likely rub events and to give right information to a control system to properly squeeze or open the clearance to always keep the clearance at its optimum.

The tip clearance is influenced by different parameters. It can be decomposed into two main sources, the blade elongation and the casing deformation. Mainly the clearance is driven by the thermals in the engine especially in the turbine side which has an effect on both the blade length and the case shape. Regarding the blades, the centrifugal force pulling them out has an effect on the clearance not to mention the rotor axial displacement which drives the clearance in the conical sections of the engine mainly located in the compressor side.

3D ADVANCED VISUALIZATION CONCEPTS

The difficulty to deal with the large amount of data provided by the microwave tip clearance sensors triggered the development of a new way to visualize and access the measurements. Standard industry graphic displays mainly represent the data in two dimensions with defined functionality which can be used to represent blade tip clearance measurement but does not give a quick overview of the engine state. Only trained expert in tip clearance measurement are able to synthesize the information from the standard industry graphics. The three dimensional representation brings a synthesized view and allow the technician or engineer to navigate through the data and the different standard graphics easily and quickly.

The visualization of the high density tip clearance measurement concept involves modern computer graphics to create the 3D representation. The figure 3. shows the different inputs of the visualization module. The 3D processing unit creates the visualization based on the probe location, on their functionality and on the engine model – with the possibility to use the real engine parts geometry imported from various CAD software. A clearance model customizable with specific information about the engine – like the vibration modes, the model of the case deformation and clearance change with engine parameters like speed or output power – is required in order to give a physical signification to the interpretation of the measurements. Along with the clearance model, configured alarm levels for the monitored parameters are provided. Finally the measurements associated with the defined probes are the data inputs.

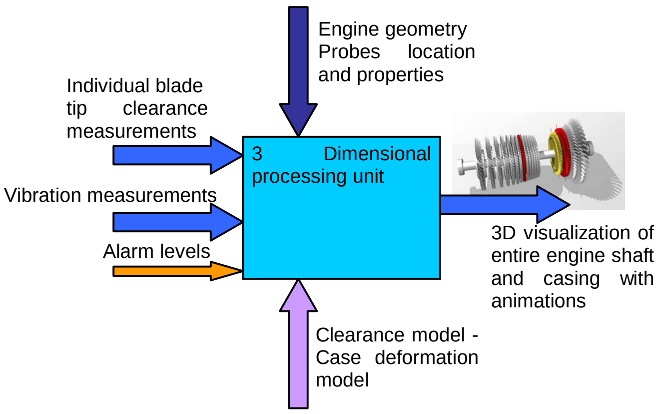

Figure 3: black box representation of the advanced 3D visualization of the tip clearance measurements

Current development state of the advanced visualization software does only consider the tip clearance measurement. However, it is foreseen in the near future to combine the measurements from other sensors as proximity probes with the tip clearance data into a more advanced model to create dynamic animation like shaft dynamics showing the shaft shape and its dynamic behavior – shaft bow and vibration mode of the entire shaft. The figure 4. illustrates the different measurement that are foreseen to be accessible and displayed using the 3D representation. The industry standard plots commonly used in shaft vibration monitoring as polar and orbit plot for example will be reachable.

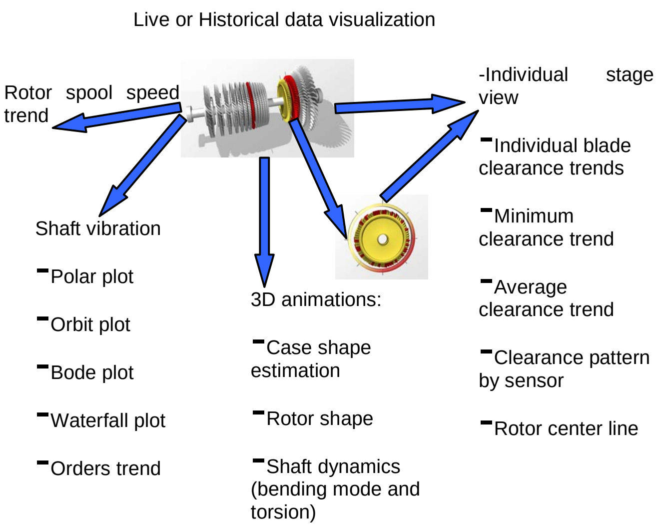

Figure 4: the 3D visualization as a common platform to access the engine measurement and for high level animations

BLADE ALIGNMENT AND ROTOR SHAPE

For each sensor around the same stage – measuring the same bladed rotor – a repeatable blade pattern is observable. It can simply be interpreted as the rotor signature which is similar between all sensors as the rotor shape does not change significantly within a revolution while the machine is running. Mechanically, there are a couple effects driving the rotor shape. Usually the blades are held onto a rotor disk using dovetail features which has mechanical tolerance such that the blades are moving into their sluts at low engine speed but the blades will settle when the rotor speed is above a certain value. In addition, each blade has tight mechanical tolerances but might have slightly different length once mounted onto the rotor due to the tolerance stack up which is usually minimized by a grinding operation of the entire bladed rotor. This leads to a mechanical stack up that introduce small variability into the blade to blade tip clearance caught by the microwave sensing system and seen as a signature pattern. In addition, rotor dynamics will be superposed to this pattern as well as the case shape translating to an offset of the entire measurement. The blade pattern is an identical component seen by all sensors but the rotor dynamics and case deformation is an addition to this common pattern and depends on the sensor location around the case.

A direct comparison can be made with two proximity probes mounted orthogonally and used to monitor the shaft vibration at the bearing location by measuring the distance and its variation between the probe and the shaft. The measured distance trace is repeatable from one revolution to the other and similar between the two sensors and is composed of a static part plus a dynamic part; the dynamic part being a typical mechanical vibration behavior as the response show single or multiple resonances phenomenon depending on shaft speed. The shaft run-out which is the static part would be closer to the blade pattern described for the tip clearance as it is a constant depending on the rotor machining imperfections which translates as the blade position into their dovetail slots and mechanical tolerances stack up leading to different blade length. The rotor dynamic part would be depending on the rotor speed as the vibration amplitude and phase are directly correlated to the engine speed.

From the raw measurement of the sensors around the same engine stage, a blade alignment can be done in order to extract an aggregated pattern. The measurements of the different sensors contain an identifiable pattern which can be extracted among all sensors. The location of each sensor around the stage is known and directly based on their angles; the measurement of each sensor can be shifted by the right amount of blades to have the same phase or blade reference in all the sensor measurements.

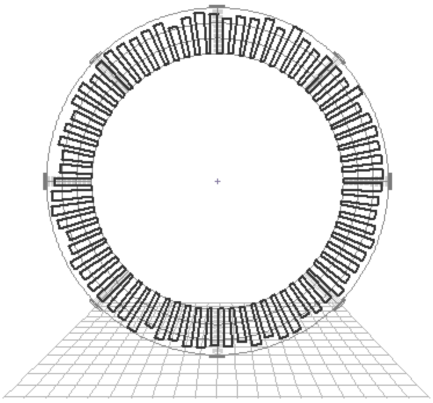

Figure 5: representation of a stage with an example random blade pattern measured from 8 tip clearance sensors mounted each 45 degrees around the casing.

The figure 5. shows the bladed-rotor representation as a polar plot which is a standard representation in the industry for the rotor shape, especially for air-gap measurement; and is suitable also for the blade tip clearance data. This plot was created conceptually using the tool LabView and show simulated blade pattern with exaggeration for an eighty blades rotor from eight sensors mounted 45 degrees apart around the casing. Although it is close to a standard polar plot in 2D, it is a 3D view with perspective added and a mesh representing the z-plane. The blade pattern is the aggregated pattern from all eight sensors after the blade alignment is performed. A scale is incrusted into the 3D view of the bladed rotor at the location of each sensors port. The indication of the longest blade – i.e. the smallest clearance – can be shown.

CASING SHAPE ESTIMATION

Usually the casing of a gas turbine is never perfectly round. Different effects are driving the case shape which can be rather complex. The temperature gradients being three dimensional and quite large magnitudes especially in the turbine sections induce load and stress on the casing due to the casing material thermal expansion differences. Steam turbine also have another factor which is the high pressure unevenly distributed coupled with thermal gradients. A good example is the presence of flanges on each side of most of the power generation turbines design in order to join together the two half circular parts of their casing. The thicknesses of the casing at the flanges is much more than the thickness of the rest creating uneven thermal gradients and are less likely to deform than the rest of the casing.

Casing might have different shape from a simple ellipse to a more complex eight shape – possible with flange on both sides – or even with higher modes. The case shape estimation is an interpolation problem where in most of the cases the number of measurement points is very limited. Those measurements come from each tip clearance sensor around the rotor. For practical stage instrumentation with tip clearance sensors, a maximum of eight is a good compromise between system costs and benefits in terms of measurements. Even with eight sensors, the number of points for the interpolation of the case shape is still limited and without a model to predict the actual casing deformation, it is difficult to estimate the correct shape if it is more complex than circular or elliptical. An intelligent disposition of the sensors around the casing might give better estimation but a minimum of knowledge on the engine casing behavior is required.

The first implementation of the case shape estimation was achieved using non rational B-spline using control points at the sensors locations as represented by crosses on figure 6. A nominal casing diameter is chosen to be the reference for the measurement and the tip clearance measurement is the deviation from this ideal circle. Typically the average or minimum tip clearance measurement at each sensor location is used as a control point to calculate the casing interpolated B-spline. Continuity of the spline at the measurement control points is ensured by an order 1 or 2 of parametric continuity – first and/or second derivatives are equal.

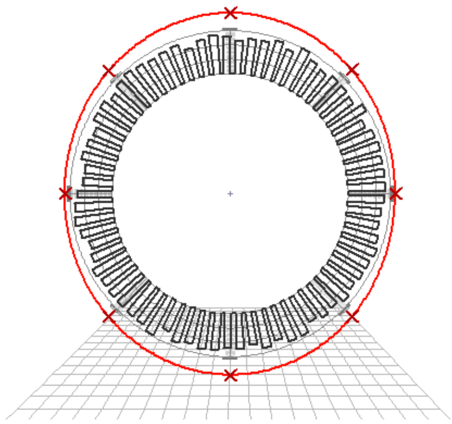

Figure 6: overlay of an example elliptic case shape estimation on the rotor blade signature. Casing shape interpolated based on the measurement of eight sensors.

The figure 6. shows the same bladed-rotor polar plot as in figure 5. with addition of the case shape estimation based on the average clearance of each eight sensors around the casing. In this example the case shape has been greatly exaggerated to clearly show the rotor which is not centered and to highlight the likely minimum clearance area around the case. A simple elliptical shape is represented in this figure.

In reality, the deformation of the surrounding casing is usually predominant compared to the blade elongation and rotor centerline motion. The case shape estimation is of great importance in those conditions in order to estimate the minimum clearance and its location as well as possible rub event occurrences.

DATA EXAGERATION AND COLORING

The tip clearance and its variation are usually an order of magnitude below the rotor diameter. On the largest power generation turbines with bladed-rotor diameter of about 2 meters, the blade tip clearance is changing within millimeters. For this reason, the deformations will not be visible unless an exaggeration is applied to the data. The bladed-rotor diameter and the blade tip clearance range are known such that the scale for the tip clearance measurement display can easily be adapted.

The use of colors proportional to the tip clearance also greatly helps the visualization. Both exaggeration and color coding which can be also configured to reflect alarm levels bring an immediate overview of the complex and rich tip clearance measurement.

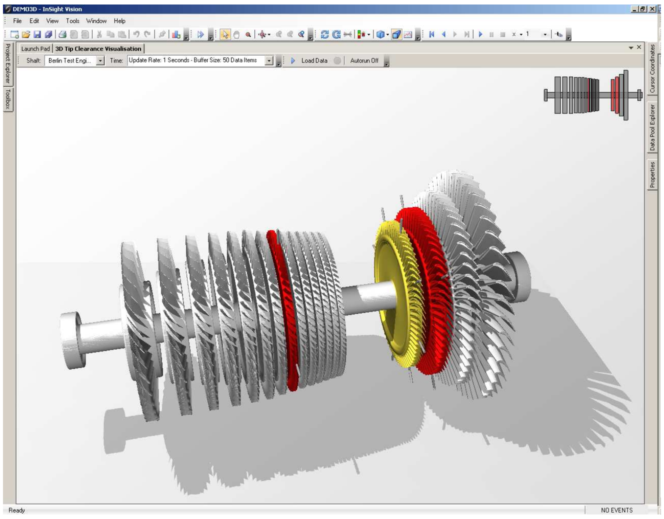

Figure 7: example machine shaft view of the advanced tip clearance 3D visualization. The stages instrumented with tip clearance sensors are in colors.

The figure 7. illustrates the color coding where stages with no tip clearance instrumentation are colored in light grey whereas the instrumented stages are colored with color associated to configurable alarm levels. The eighth compressor stage on the left side of the picture and the second turbine stage on the right side of the picture are in red which means that they are in critical alarm level – the clearance being close to zero and the probability of rub event high. The second turbine stage on the right side of the picture is in yellow which is the intermediate alarm level. Multiple alarm levels can be configured with associated color and in this example only two are shown.

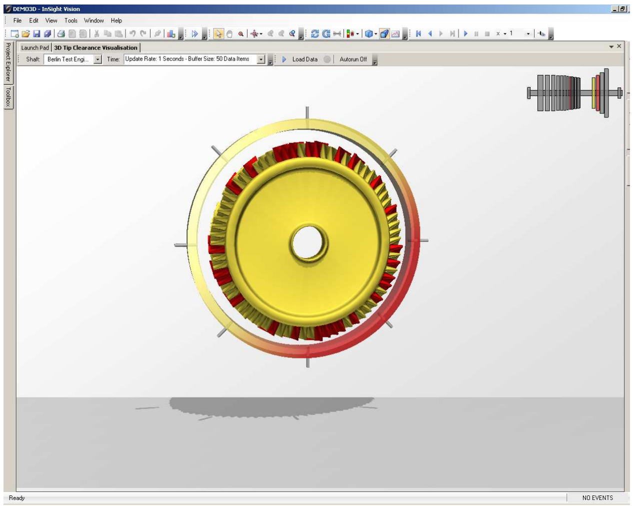

Figure 8: example single stage view of the advanced tip clearance 3D visualization. Coloring and exaggeration can be observed.

The figure 8. shows an example of the single stage view where the same color scheme based on alarm level is used. The eight tip clearance sensors mounted around the casing are displayed and the aggregated blade pattern is shown. The color scheme is used on each blade which make it easy to look for the longest ones, and then to select one or several and access historical trend measurement for those particular blades. Same concept for the case shape estimation, a color gradient is used such that the smallest clearance location around the casing is quickly identifiable and the selection of the probe close to this location allows visualization of blade pattern and average of minimum clearance trends.

The benefits of this high level visualization is being a user friendly interface to quickly identify and access measurement trends and data in order to diagnose more in detail the source of the problem with the machinery.

OTHER ADVANCED VISUALIZATION

Advanced concepts are also in study such as rotor dynamics visualization using 3D representation. Part of this is the estimation of the shaft bending and vibration modes using the measurement of the rotor dynamic of the different sensors along the shaft. The measurements from the proximity probes at the bearings and from the tip clearance probes can be combined to provide multiple measurement plans. Interpolation can be done between those measurement plans based on a model to provide estimated shaft shape. Industry standard uses proximity probes at the bearings to monitor turbomachinery shaft fault. The proximity probe maximum temperature limitations do not allow monitoring inside the hot sections. The microwave blade tip clearance sensors can provide the extra measurement of the rotor dynamic behavior inside the engine based on the blade tip clearance measurement.

The figure 9. shows a conceptual 3D representation of the shaft vibration envelope from the simulated shaft vibration at four locations. The cold compressor and hot turbine bearings measurement plans are on each side and the thick blue curve with the red dot represents the orbit plot for the 1X vibration order. Similarly, the two middle shaft vibration plans are from tip clearance sensors with one in the compressor and one in the turbine sections. The small blue lines show the interpolated points of same vibration phase with the phase reference interpolated line in orange thus getting through all red dots which are the key-phaser phase reference. A click on one measurement plan would display the orbit plot in industry standard manner.

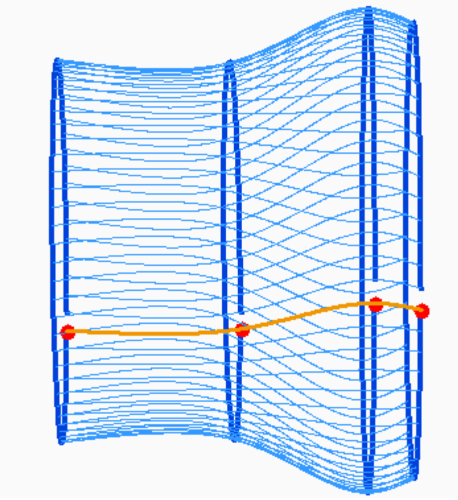

Figure 9: Concept of 3D representation of shaft vibration orbit plots with interpolation in-between measurement plans.

The shaft torsion measurement using the blade tip timing measurement between different stages on the compressor or turbine side is on study. This estimation of the shaft torsion could give a valuable input as the torsion is a metric of the power generated in the turbine section and transmitted to drive the compressor and the generator. Those concepts are still in early development but are area of interest to extend the capability of the 3D advanced visualization platform. The figure 10. shows early concept of full shaft dynamics visualization with both shaft torsion and shaft bending modes animated. The lines help for the visualization and represent the identical phase points.

Figure 10: Concept of shaft bending with torsion and dynamics 3D visualization. The lines help to see the actual shaft shape.

ACKNOWLEDGMENTS

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