A low-coherence interferometric tip-clearance probe

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Abstract

Proof-of-principle measurements are presented for a novel tip-clearance measurement technique. The self-calibrating, economical probe is capable of near-real-time single port simultaneous blade-to-blade tip-clearance measurements in the first stages of gas turbines with sub-millimeter accuracy (typ. < 70 µm, absolute). It relies on the interference between backreflected light from the blade tips during a 1 µs blade passage time and a frequency-shifted reference, making use of a special low-coherence light source. A single optical fiber of arbitrary length connects the self-contained optics and electronics to the turbine.

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1. Introduction

Leakage flows, i.e., fluid flowing through the gap between the blade tips and casing of a turbine or compressor, are responsible for a significant percentage of the overall rotor losses and can also locally increase the heat transfer[1]. Due to different expansion coefficients and heating rates, the tip-clearance is not constant, but changes during the turbine start-up and shut-down. A turbine has to be designed such that the blades do not touch the casing under normal operating conditions because it would lead to excessive wear or even damage. In this case, the tip-clearance is often not optimized for a certain operating state but such that a clearance safety factor guarantees no damages at the blade tips.

With given real-time data about the gap between the blade tips and the casing, future turbines might be able to control this tip-clearance actively. Also, monitoring the tip-clearance can provide valuable information about the condition of the stage for maintenance. The current tip-clearance probes, mostly of inductive or capacitive type with typical accuracies of about 5 %[2,3], are sufficient in situations where the probe can be mounted flush with the turbine casing, because the absolute errors can be kept small. This mounting scheme is only possible in parts of the turbine with relatively low temperatures, because the maximum operating temperature of these sensor types is near the Curie point of the rare earth magnets used. Due to the changes of the heat transfer coefficient with tip-clearance, measurements in the hot stages of a turbine, close to the combustion chamber, are of special interest. Here, the high temperatures make it impossible to provide either inductive, capacitive nor optical probes flush with the shroud[4,5] and probes must be mounted in a protective recess within the casing. In that case a system is advantageous where the measurement errors are independent of the measuring distance.

The setup of a novel optical probe configuration and proof-of-principle measurements are presented. The measurement errors of this probe are independent of the distance between the probe and the blade tip, so that this sensor can be used in the first turbine stages by mounting the otpical front-end in a cooled recess.

2. Working principle

Fig.1 shows the schematic setup of the optical components in the measuring circuit of the system. A superluminescent diode SLD (Superlum, SLD56-HP2) emits low-coherence light into a single-mode fiber. A fiber-optical isolator protects the sensitive light source from back-reflections. The circulator transfers the light into a single-mode fiber of arbitrary length, which ends inside the turbine with a special endoscopic front end EFE (custom designed by ALSTOM) with a collimator lens.

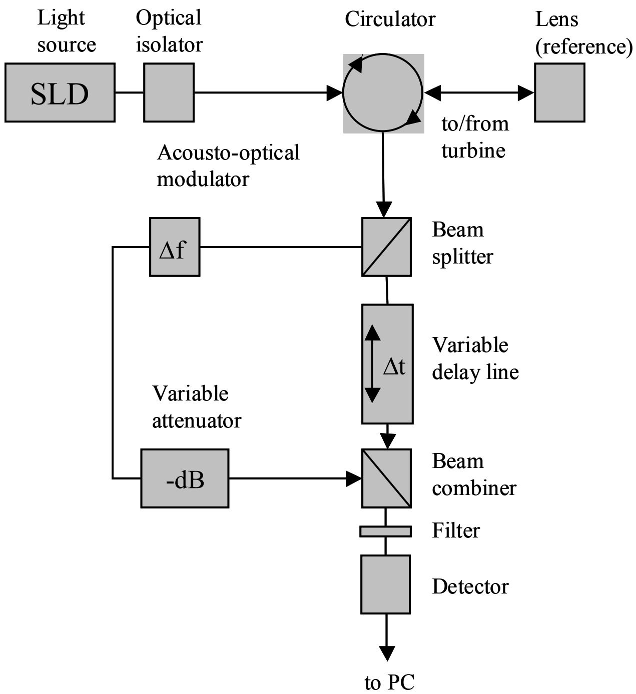

Fig. 1: Low coherence interferometer setup

A small fraction of the collimated light is reflected from the passing blade tips back onto the collimator and into the fiber towards the circulator, where it is deflected into the interferometer part of the measurement system. Similarly, a small amount (~1 %) of the light is also reflected from the two surfaces of the collimator lens, which defines the reference light. Following the nomenclature of Fig.2, the light reflected from the blade tips is denoted as ray 1 and the light reflected from the lens's front and back surfaces as rays 2 and 3, respectively.

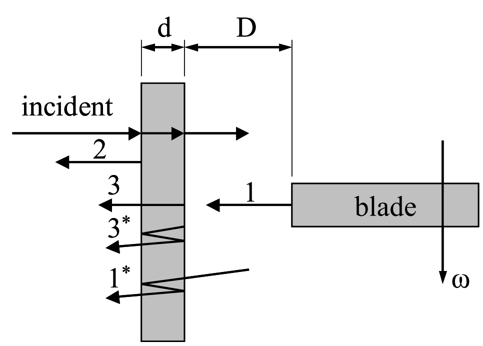

Fig.2: Setup ray denoting

The light back-reflected from the turbine blades and the collimator surfaces (rays 1, 2, 3) is fed into two interferometer arms by a fiber-optical beam splitter. In the reference arm, an acousto-optical modulator AOM (NEOS, model 26055) shifts the frequency of the light by a certain amount and a variable attenuator allows to adjust the intensity ratio between the reference and the delay arm. In the described setup the shift is of about 55 MHz, which is high enough for the short measuring times (~1 µs). The delay arm contains a motorized variable delay line VDL (General Photonics, MDL 001). The two interferometer arms are re-combined by another beam splitter. A broadband photoreceiver (NewFocus, model 1811) is used as detector. Provisions are made for an optical filter, which can be used in front of the detector to filter out background noise due to flow luminosity in the turbine.

In the proof-of-principle experimental setup, data is recorded and preprocessed on a digital storage oscilloscope DSO (LeCroy Waverunner-2). It calculates the power spectrum and only the spectral intensity at 55 MHz is transferred to a PC for final storage and processing.

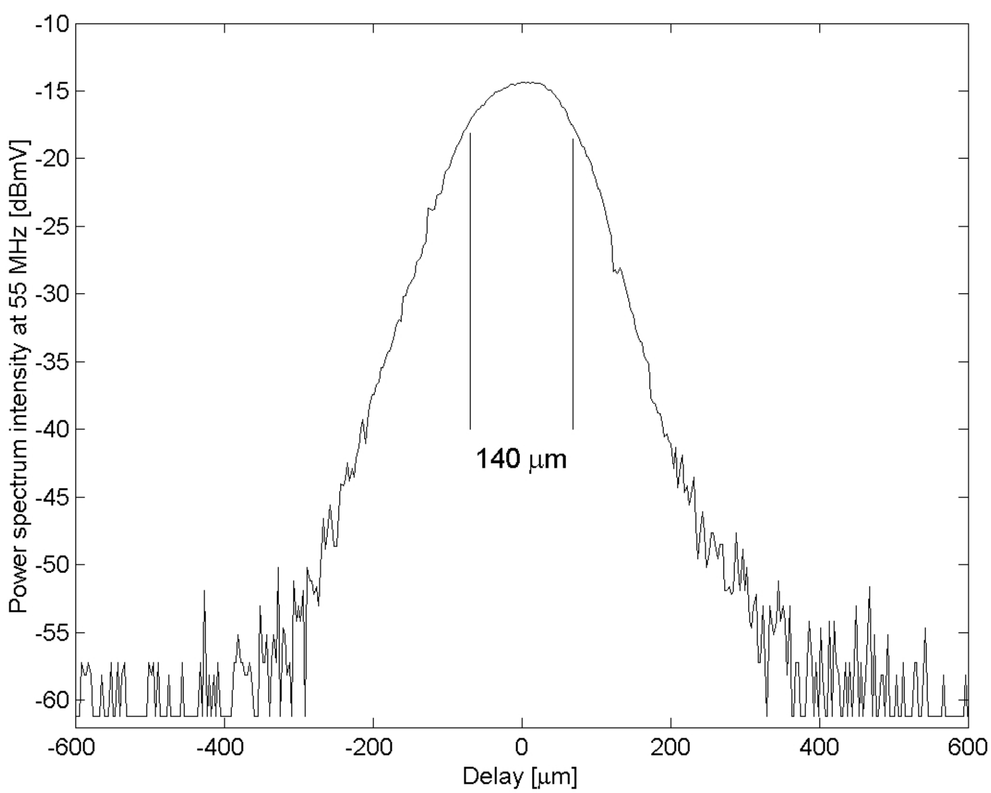

Fig. 3: Measured coherence function

Fig.3 shows the measured autocorrelation function of the SLD light source used. The –3 dB width is only 140 µm and thus two light rays can only interfere with each other if the absolute path length difference is less than 140µm around the zero point of the interferometer (both interferometer arms have equal lengths) and less than 70 µm at any other delay point (tip-clearance detecting case). This result agrees well with the theoretically calculated coherence length of the SLD of about 60 µm.

Referring to Fig.2, the path length between the turbine and interferometer of ray 1 is longer than that of ray 2 and 3. Denote the tip-clearance as *D,* the thickness of the collimator lens as d and the path lengths of both interferometer arms (between the two beam splitters) as l_{ref} and l_{delay}. If the VDL is set such that $l_{ref} + 2(D+d) = l_{delay}$, for example, the part of ray 1 going through the reference arm interferes with those parts of ray 2 which go through the delay arm. The frequency of the AOM is now seen as beat note at the detector together with the DC signal components of the other, non-interfering rays and flow luminosity. The presence of this beat note leads to a peak at 55 MHz in the calculated power spectrum. Similarly, interference between ray 1 and ray 3 is observed, if $l_{ref} + 2D = l_{delay}$. By checking the delay setting where ray 2 and ray 3 interfere together, i.e., if $l_{ref} + 2d = l_{delay}$, the system can be calibrated with the known thickness and thermal behavior of the sapphire lens used in the custom made EFE.

3. Proof-of-principle experimental setup

An aluminum disc with notches of various depths (0-4.8 mm) rotating at 60 Hz was used to simulate a turbine stage. During the initial tests the special EFE was not used, but a collimator optimized for the wavelength of the SLD. With this collimator the reflections at the lens surfaces are insufficient to provide the reference rays. Instead a clear plastic disc (CD-ROM stripped of its reflective layers) was glued onto the aluminum disc to simulate the two lens surfaces. The measurement time was artificially limited to 1 µs to reproduce typical blade passage times. The power spectrum intensity at 55 MHz was recorded while the VDL swept in steps of 30 µm through a given measurement range (100 mm as the maximum of the VDL used). The sweep rate had to be set such that the delay changes are less than the coherence length per revolution of the disc. In general lower sweep rates minimizes the measurement error, but increase the measurement time.

In the timing setup used, every single notch was measured separately, but measurements of all notches (blades) simultaneously can be achieved by merely modifying the data processing.

4. Initial test results

Fig.4 shows the power spectrum intensity at 55 MHz versus the setting of the VDL for the *D=4.8 mm* notch. The horizontal scale is converted into depth, which is half the path length difference.

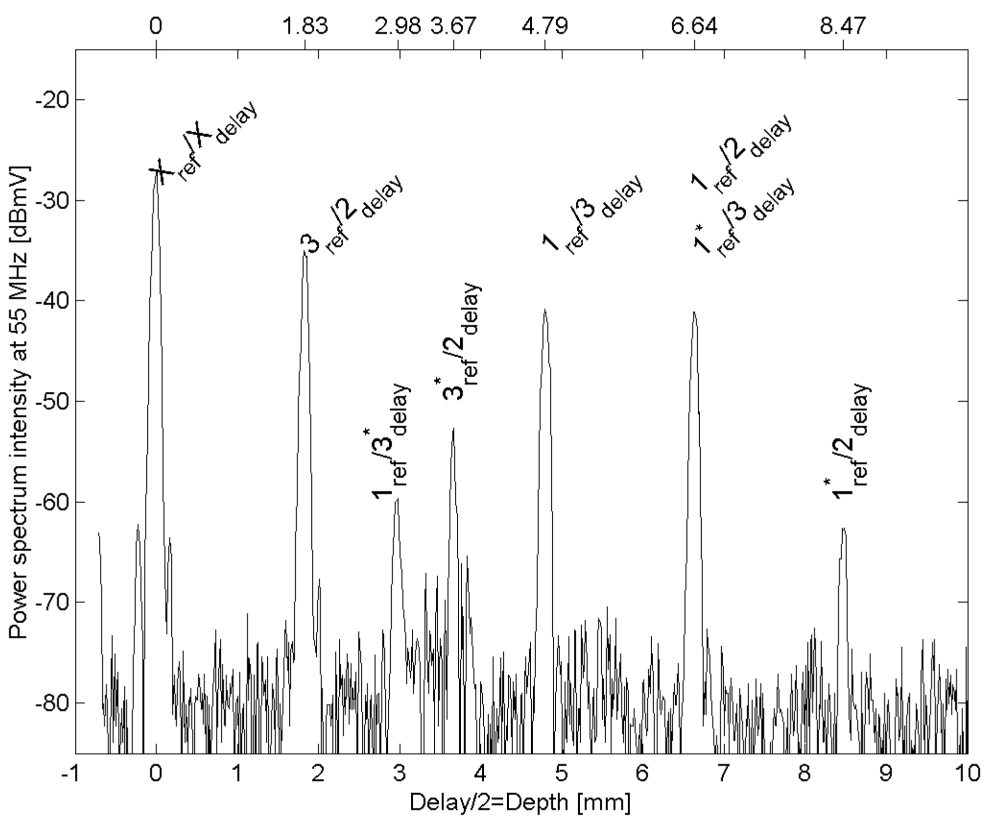

Fig. 4: Measured power spectrum intensity at 55MHz

Several peaks are visible, indicating various interfering ray combinations, because the interferometer is an autocorrelator. The first peak at the origin corresponds to self-interference of all rays, i.e., the case when both interferometer arms are of equal length, if $l_{ref} = l_{delay}$. Consequently, this peak is the strongest peak with a SNR of about 47 dB. The second peak at 1.83 mm represents the thickness of the CD-ROM, *d”*, used to simulate the special EFE collimator lens. The symbol *d”* emphasizes the different speeds of light between air and the lens material.

The peak labeled *“*$1_{ref} / 3_{delay}$*”* originates from interference between ray 1 (blade tip) going through the reference arm and ray 3 (back surface of lens) going through the delay arm. The spacing between this peak and the first peak represents the measured tip-clearance, *D*. The next peak at 6.64 mm *(≈ D + d”)* shows interference between ray 1 and ray 2 (front surface of lens). The same path length difference results from the combination $1_{ref} / 3_{delay}$. Three additional weaker peaks are labeled which are due to multiple reflections within the lens (see Table 1 for a summary).

peak location		beam paths	
Fig.4[mm]	general	ref. arm	delay arm
0	0	1,2,3	1,2,3
1.83	d"	3	2
2.98	D-d"	1	3*
3.67	2d"	3*	2
4.79	D	1	3
6.64	D+d"	1	2
6.64	D+d"	1*	3
8.47	D+2d"	1*	2

Table 1: Beam combinations

The signals from multiple reflections within the lens seem to be a problem for an automated data analysis, but with the custom EFE lens the spacing between these reflections is larger than the originally required measuring range. The optically measured values for the notch depth of 4.79 mm are very close to the nominal value of 4.8 mm. The measured thickness of the lens has to be corrected by its index of refraction (1.55 according to standard ECMA-130 for CD-ROM’s). Thus the thickness measured is 1.19 mm, which is again very close to the conventionally measured value of 1.20 mm.

The statistical error is estimated to be half the coherence length. Systematic errors may arise from slight variations in the speed of light due to changing densities and temperatures in the flow around the blade, as well as from the positioning errors of the VDL. The sum of these effects is less than 70 µm.

The accuracy is largely independent of the distance between probe and object. The amount of light reflected back into the measuring part decreases with the square of the distance, but that will decrease only the SNR and not the inherent accuracy.

5. Conclusions

Proof-of-principle measurements were presented for a novel tip-clearance measurement technique. The demonstrated accuracy is high (< 70 µm) and independent of the distance between output coupler and blade tip.

Due to the binary character of the signal (beat signal present/not present), the technique is expected to be very robust when employed in harsh environments, such as inside a hot turbine. Only a single fiber of arbitrary length has to enter the turbine and the sensitive parts of the system can be located in a remote environment.

Ongoing experiments in laboratory turbomachines and with the custom EFE confirm the good results of the initial tests. No major shortcomings for measurements with an industrial turbine were detected in these tests. Tests in gas-turbines will follow after a redesigned, minimized and user-friendlier version of the actual lab-prototype is finalized.

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