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MEASUREMENT OF TURBULENCE IN LP PART OF THE 1090 MW STEAM TURBINE

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ABSTRACT

The aim of the paper is to demonstrate a use of the hot-wire anemometry for measurement of turbulent fluctuation in a steam turbine. Measurement technique and used methods are presented in the paper. An experimental research was performed in the last stage of LP (low-pressure) part of the 1090 MW steam turbine in nuclear power-plant turbine. The last moving steel blade has a length of 1220 mm. The experiment was carried out by Institute of Thermomechanics of Czech Academy of Science (IT CAS) in cooperation with Doosan Škoda Power s.r.o. (DSPW), the manufacturer of the turbine.

NOMENCLATURE

E	[V]	Output anemometer voltage
e	[V]	Standard deviation of E
U	[m/s]	Effective velocity
u	[m/s]	Standard deviation of U
W	[m/s]	Modulus of mean velocity vector
w_i	[m/s]	Standard deviation of velocity component
T	[K]	Flow temperature
t	[K]	Standard deviation of T
F, G, F_i	[1]	Probe sensitivities
r	[m]	Radial coordinate
x'		Axis of turbine

INTRODUCTION

The hot-wire anemometry was used for the turbulence measurement. Two constant-temperature anemometers: DISA M10 and Dantec StreamLine were utilized. Several hot-wire probes with a single 45-degree slanted wire of the diameter of 0.005 mm and the length of 1.25 mm were used. A probe support consists of 4 segments. The probe support segments were joined and inserted into a guide tube with the outer diameter of 30 mm and the length of about 4.5 m. The guide tube was positioned in the turbine port and rotated during measurement. The measurement points were located in two planes: in the front and behind the last stage of the LP section of the steam turbine. There was performed a number of points with varying radial coordinate in each plane. Each point of measurement consists of 36 rotational steps (of 10 degree). In all angles, the temperature of sensor is the reference one. Above that the wire temperature was set to 6 different values in 5 selected angles. A method of rotating probe with slanted wire was applied to determine three components of velocity fluctuation.

HOT-WIRE TECHNIQUE

Anemometers operate in CTA (constant-temperature) mode. Measurement was performed with slanted-wire probes rotating about its axis. The sensor of probes was inclined at a 45 ° angle to the axis.

Three types of Dantec probes were used: miniature wire, gold-plated wire and film sensor probe. All types have a sensor with an active part of 1.25 mm length. The wire probes are fitted with a tungsten wire of a 5-micron diameter; the film probe has a nickel filmed sensor of a 70-micron diameter.

All three types of probes were used for measurement in turbine. It is clear from the data in the tables that all probes meet the maximum speed and frequency requirements. However, the probes differ significantly in directional sensitivity. Probes with gold-plated end of wire show perfect directional characteristics, high directional sensitivity and regular, symmetrical shape. The film sensor probe has a rather unsymmetrical and irregular directional sensitivity, a side-dependent shape. This is probably caused by the uneven film thickness on the quartz body or the irregular shape of the body itself. Miniature wire probes show the worst directional characteristics. There, the signal is affected by the presence of electrodes in the immediate vicinity of the sensitive part of the sensor.

However, probes with gold-plated ends are very fragile, so their use in turbine is tricky. The most durable are miniature-wire probes.

Hot-wire probe were calibrated for measurement in turbine. Since the actual measurement was performed in a fluid of unknown physical properties, only directional calibration of the probes was performed. This characteristic is independent of the properties of the flowing medium (Jonáš 2005, Jonáš 2013). The purpose of the calibration was to determine the directional sensitivity of the sensors in the air flow. The calibration procedure was as follows:

First, the directional dependence of the probe output voltage on the angle of rotation of the probe holder was determined. Knowing the geometry of the probe, for each probe rotation value, the sensor probe angle was determined relative to the direction of the air flow. An example of the directional calibration is shown in Figure 1.

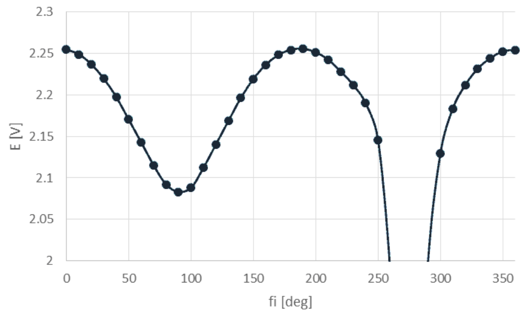

Figure 1: Directional calibration

Then the temperature and velocity calibration of the probe sensor in the air stream was performed at the probe sensor position perpendicular to the air flow.

After application of the velocity and temperature calibration of the sensor, the effective velocities were calculated at different angles of the sensor and the air flow. From this dependence, the Hinze´ coefficient of directional sensitivity of the probe was evaluated.

Figure 2 illustrates the angles determining the direction of the wire and the flow velocity vector relative to the turbine axis x'.

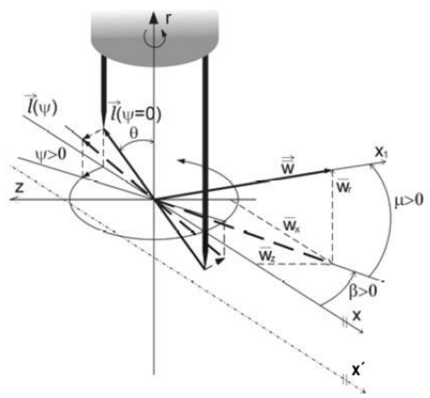

Figure 2: Coordinate system

Evaluation of measurement goes in following way. First, we determine the direction of the mean flow velocity vector, then we solve the fluctuations in the coordinate system defined by the flow velocity vector.

Fluctuations of velocity u and fluctuations of temperature t can be evaluated from voltage fluctuations e and sensitivity coefficients F, G, F_1, F_2, F_3 by solving equations:

$$\frac{e}{E} = F\frac{u}{U} + G\frac{t}{T}; \quad \frac{u}{U} = F_1\frac{w_1}{W} + F_2\frac{w_2}{W} + F_3\frac{w_3}{W}.$$

Definitions of sensitivity coefficients and detailed description of the method can be found in Jonáš (2013). The system of equations for different probe angle positions is then solved.

EXPERIMENTAL SET-UP IN TURBINE

A probe carrier has been specially designed for measurement in turbine purpose and is compatible with the insertion system of pressure probes.

Parts of the probe carrier of the combined rotating probe are schematically illustrated in Figure 3. It consists of a commercially manufactured hot-wire probe Dantec "1". The probe is plugged into the socket "2" mounted to the holder "3" (diameter of 23.4 mm). Electrical resistors "4" create a resistance platinum-film thermometer (3 x 1000 Ohm) for monitoring the reference temperature Tref of the stream. A reference pressure Pref is sampled at the end of the combined probe "5". The probe carrier "6" has a diameter of 51.5 mm.

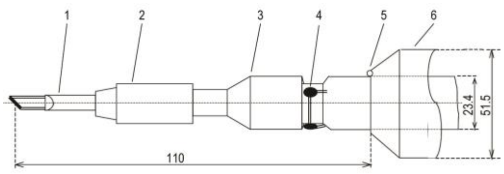

Figure 3: Scheme of the rotating probe carrier

The Dantec StreamLine Anemometer, which was successfully used in steam turbines in superheated steam, was tested for the measurement. However, the apparatus proved to be inappropriate for wet steam measurements. The problem is a protection circuit of Streamline, that turns it off when the voltage peak occurs. Voltage peaks occur abundantly in the presence of steam droplets. Therefore, the older type of anemometer, DISA 55M, was also used for the actual measurement.

The anemometer signal was sampled with a 250 kHz A / D converter. The National Instruments NI PCI-6122 Multifunction Card was used. The card has 4 analog inputs, 500 kS/s for each channel, 16-bit resolution, maximum range ±10 V.

For pressure measurement near the probe, a DRUCK 145 manometer with a range of 100 kPa and an accuracy of 0.05% from the range was used, the temperature was evaluated by measuring the resistance of the Pt1000 sensors by the Agilent 34970A.

To measure the probe position in the radial direction was used telescope Leica. Angle and position of the probe were set manually, read by the devices connected to the measuring PC. The process was controlled by LabVIEW software.

Certain problems during measurement occurred and were mainly related to the life of the probes, which gradually "passed away". During the measurement in front of the stage 1 pc of film sensor probe, 3 pcs of gold-plated probe and 2 miniature wire probes were destroyed. In the area behind the stage, the current conditions were significantly more dynamic, including the intermittent occurrence of large drops of water and 3 probes were destroyed.

Figure 4: Rotating probe carrier with the anemometer

The measurement in turbine was arranged so that a DISA anemometer was placed directly at the end of the probe carrier tube (see Figure 4 and Figure 5). The anemometer was operated manually. The actual measurements were made using a measuring PC located next to the turbine and checked by anemometer operator on the synchronized laptop.

Figure 5: Laptop with LabVIEW controlling software and the anemometer

One measurement point consists typically of 33 recordings at the nominal sensor temperature and various angles (about 10 deg steps), at 7 angles the sensor temperature varied, 5-6 values. Each record has a length of 20 s. One measurement point is about 70 records at a sampling rate of 250 kHz for 20 s, 2 channels are recorded, an anemometer voltage output, and a synchronization mark on the turbine shaft (one pulse per revolution). All measured signals were stored on the HDD and are available for later evaluation.

RESULTS AND DISCUSSION

An example of anemometer signal is shown in Figure 6. A coarse water droplet hitting the hot-wire sensor makes a visible peak, that should be filtered out. First step of processing the signal is that filtering.

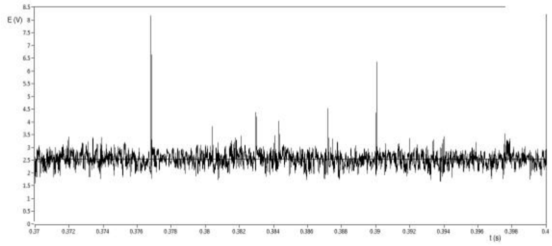

Figure 6: Anemometer signal of steam flow with water droplets

The average values of the anemometer output voltage were around 5 V - see the resulting mean voltage for the nominal wire heating temperature of 110 ° C in Figure 7 (black). Red points represent the mean values for higher and lower wire heating temperatures, in this case the range of heating temperatures: 102, 106, 110, 120, 130 and 140 ° C.

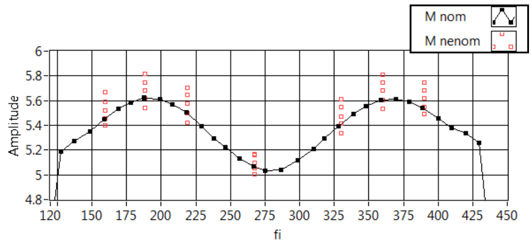

Figure 7: Example of the rotating probe record. The output voltage at the nominal wire temperature (black) and at additional temperatures (red)

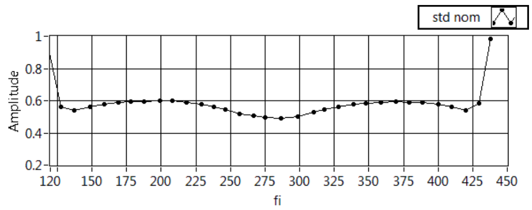

Figure 8: Example of standard deviation of the output voltage at nominal wire temperature

The corresponding standard deviation of the signal for the nominal heating temperature is plotted in Figure 8, the values are about 0.6 volts, but the output signal has isolated peaks exceeding 10 volts.

Simultaneously with the output voltage of the anemometer, the trigger signal was recorded. A once-per-rotor-revolution trigger was used. Figure 9 is an example of record (time of about 0.5 s).

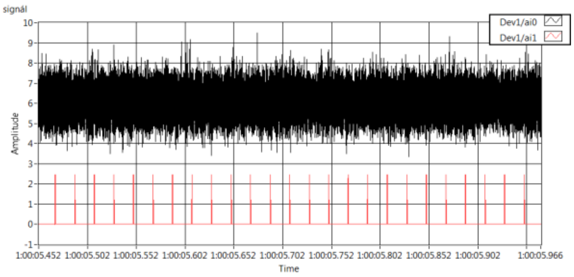

Figure 9: Example of part of the signal sequence (black) with the trigger (red)

During the measurement campaign, 19 measurement points were recorded, with more than 100 GB of data recorded on the HDD.

An anemometer signal was used for a phase-locked analysis. Wire orientation was perpendicular to the flow velocity direction.

A phase averaging was done using a trigger located on the rotor shaft. First, the average anemometer signal was evaluated at one rotor speed. One revolution was divided by 1000 phase angles.

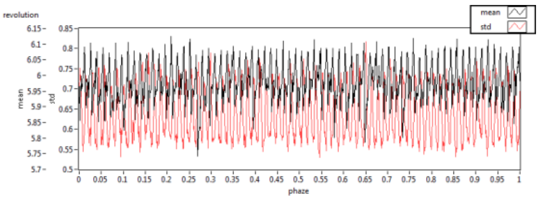

Figure 10: Phase-averaged signal, one revolution, in front of the last stage (r = 310 mm)

In graph, the black line shows the measured values of the output voltage from the anemometer and the red line the standard deviation of this value.

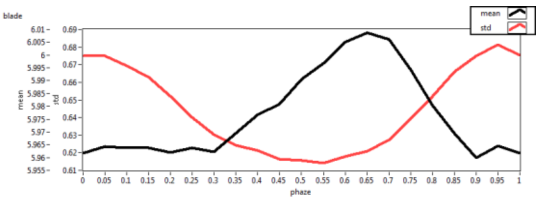

Figure 11: Phase-averaged signal, one blade, in front of the last stage (r = 310 mm)

For the calculation, a complete 20 s signal, i.e. 1000 periods, was used. The mutual phase shift of the mean values and the standard deviations can be observed.

Also spectra were calculated from signals. Wire was perpendicular to the flow velocity, thus represents fluctuations in the velocity direction. The spectrum was calculated by dividing the 20 s length signal into a second sections, spectral power density calculated from each section. The obtained 20 spectra were centered, resulting in the performance spectrum presented. Kolmogorov's law is represented in charts with log-log coordinates by a straight line with a slope of -5/3 (red line).

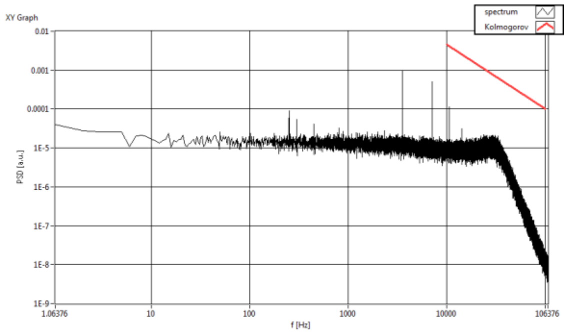

Figure 12: Example of spectra in front of the last stage (r = 310 mm)

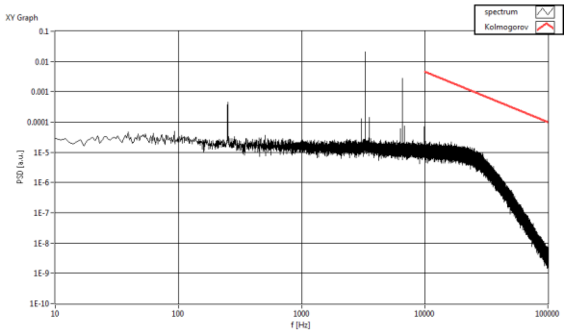

Figure 13: Example of spectra behind the last stage (r = 310 mm)

Presented spectra indicate that the turbulence is not fully developed and contains non-isotropic structures.

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