Optical Measurements
Paper 17

EXPERIENCES WITH THE MINIATURISATION OF A COMBINED PNEUMATIC-OPTICAL PROBE

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Abstract

Normally wetness measurements in steam flows at LP turbines are divided into flow field measurement with pneumatic probes and wetness measurement with thermodynamical or optical probes. This procedure has several disadvantages. In this paper we describe the combination of a pneumatic and an optical probe for measurements in two phase steam flow in a model turbine. The idea is to measure thermodynamical and fluiddynamical properties of the flow simultaneously.

The pneumatic part consists of a four-hole wedge probe and the optical part is a multi-wavelength light extinction probe. Due to the use of these measurement principles we are able to design a combined probe with a stem diameter of $d = 10\,mm$.

To prove the function of the measurement system we carried out investigations about the behaviour of the single components and the combined probe. Several experiments were performed in a water tunnel and different kind of wind tunnels. The results show that the measurement system is well suitable for wetness measurements in two phase steam flow.

Nomenclature

D	μm	droplet diameter
D_{32}	μm	Sauter Mean Diameter (SMD)
$\overline{D}, k$	–	parameters of distribution function
E	–	light extinction coefficient
I	mV	intensity of transmitted light
I_o	mV	intensity of incident light
L	mm	length of the light path
Ma	–	Mach number
Re	–	Reynolds number
T	K	temperature
d	mm	probe stem diameter

m	–	refractive index
p	Pa, kPa	pressure
α	°	yaw angle
γ	°	pitch angle
λ	μm	light wavelength

subscripts

dyn	dynamic pressure
stat	static state
tot	total state
1, 2, 3, 4	No. of probe tappings

1 Introduction

In order to understand the behaviour of two phase steam flow in the last stage of low pressure (LP) turbines the wetness and the wetness distribution along the blade should be measured. These measurements are performed by using thermodynamical or optical probes. Due to the problems in using thermodynamical probes and there is no information about droplet size, more and more optical probes are developed. With optical probes the volume concentration and droplet size of fine droplets can be measured.

However, to determine the wetness and other thermodynamic properties of wet steam flow knowing the results of the optical probe like volume concentration of fine droplets or droplet size is not enough. The density of water droplet and saturated steam should be known, too. Therefore flow field measurements to determine static pressure are also necessary for wetness measurements with optical probes. For these measurements pneumatic probes are used.

The idea of the combined pneumatic–optical probe is to do these measurements with one measurement system (Fig. 1).

The aim of the development of a miniaturised combined pneumatic–optical probe is essentially to design a system for wetness measurements at our low–pressure model steam turbine. Fig. 2 shows a longitudinal-section of the test facility.

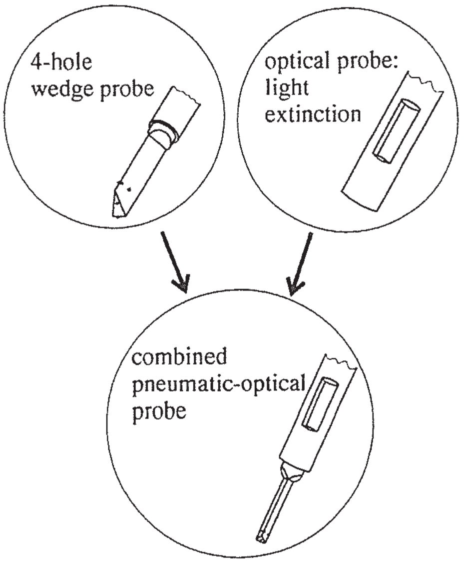

Fig. 1: Idea of combined probe

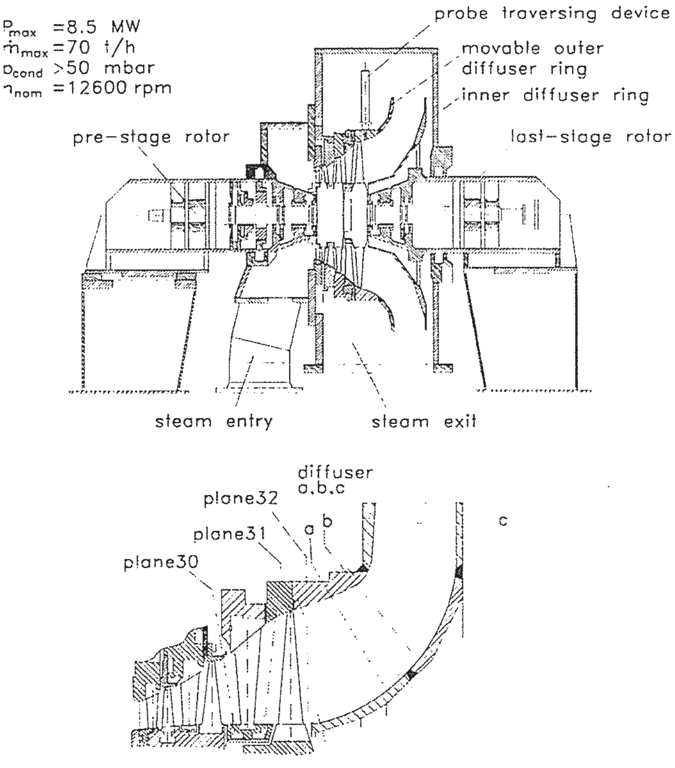

Fig. 2: Model steam turbine

With the moveable diffusor ring and the probe traversing device it is possible to measure the thermodynamic conditions at any location of plane 31 and 32. That is before and behind the rotor blades of the last stage. Furthermore there are several others probe traversing planes in front of the last stage and in the diffusor.

One important demand for the combined probe is – besides the measurement range of the droplet size of the optical probe – the dimension of the probe head. The reasons to design the probe head as small as posssible are first because there is not a large space and second in order to avoid changes in the flow field due to blockage effects.

2 Measurement Principles

The new probe measurement system combines two different measurement principles. The pneumatic part of the combined probe consists of a four–hole wedge probe. The measurement principle of the optical part is multiwavelength light extinction. By using this principle the size, size distribution and the concentration of droplets can be obtained. It is not possible to determine the velocity of the droplets. However the slip velocity for fog droplets is negligible and the steam velocity measured by the pneumatic probe can be considered as droplet velocity.

Pneumatic System

Due to the demands in minimizing the probe size a four hole wedge probe and not a five hole probe is used. The pneumatic four–hole wedge probe has an asymmetric shape in the radial direction and matches special characteristics of the flow in the last stages (Fig. 3) of the turbine. The sharp wedge makes it very sensitive to the flow direction and suitable for high Mach numbers. In the pneumatic probe head a thermocouple is integrated. Beside the measurement of the flowfield temperature the thermocouple is to protect the optical components from high temperature. The maximum temperature of the probe head is about T = 375 K.

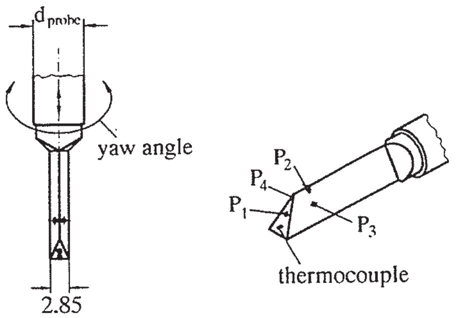

Fig. 3: Wedge probe

Optical System

Due to the effects of scattering, when a beam of plane wave monochromatic light passes through the measured droplets, the intensity of incident light I_o will be attenuated as shown in Fig. 4. Because there is no change of optical axe this principle is suitable to be used in a miniaturised combined probe. The probe head can be designed very small.

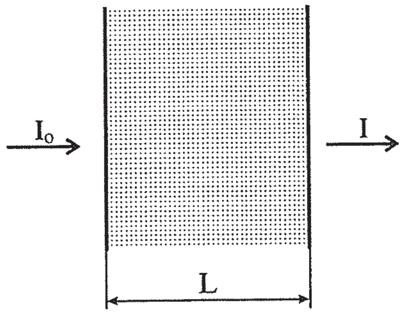

Fig. 4: Principle of light extinction

The ratio of intensities of incident light I_o and transmitted light I can be described by Beer-Lambert law:

$$ln(I/I_o) = -\frac{\pi}{4} L \int_0^{\infty} N(D) D^2 E(\lambda, m, D)\, dD. \qquad (1)$$

Where L is the path length of light in measured droplets, $N(D)$ is the size distribution of droplets and E the light extinction coefficient, which is a function of wavelength of incident light λ, of the size of measured droplets D and of the relative refractive index of droplets m, and can be calculated with Mie's theory [1], [2].

Equation (1) is a Fredholm equation of the first kind and has no theoretical solution. To solve this equation an algorithm, *'Dependent Model'*, is developed [3]. We assume the size distribution of droplets can be described by a two parameter function $N(D, \bar{D}, k)$, for example the Rosin-Rammler function.

Substituting $N(D, \bar{D}, k)$ into equation (1) and measuring the droplets with several different wavelengths of monochromatic light, we can get the following equations

$$ln(I/I_0)_i = -\frac{\pi}{4} L \int_0^{\infty} D^2 N(D, \bar{D}, k) E(\lambda_i, m, D)\, dD, \qquad i = 1, 2, ..., n. \qquad (2)$$

Above equations can be rewritten as following

$$\frac{ln(I/I_0)_i}{ln(I/I_0)_j} = \frac{\int_0^{\infty} D^2 N(D, \bar{D}, k) E(\lambda_i, m, D) dD}{\int_0^{\infty} D^2 N(D, \bar{D}, k) E(\lambda_j, m, D)\, dD}, \qquad i \neq j. \qquad (3)$$

By solving equation (4) with the optimizing algorithm the size distribution $N(D, \bar{D}, k)$ may be determined [4].
The wetness of steam Y is defined as

$$Y = \frac{V_w \rho_w}{V_w \rho_w + (1 - V_w)\rho_v} * 100\%, \tag{4}$$

where V_w, ρ_w and ρ_v are volumetric fraction of droplets in wet steam, specific volume of saturated water and specific volume of saturated steam respectively. The volumetric fraction of droplets may be calculated by integrating $N(D, \bar{D}, k)$ as follows

$$V_w = \frac{\pi}{6} \int N(D, \bar{D}, k) D^3 \, dD. \tag{5}$$

3 Components of pneumatic–optical probe

The optical probe system is composed of five parts: measurement volume at probe body, light source, light disperse and detecting system, data acquisition and processing system, and purge air system. Light source, light disperse and detecting system as well as purge air system are integrated in an instrumental box. The pneumatic part of the combined probe consists of the following components: probe head, valves, pressure transducers, reference temperature and data acquisition system (Fig. 5).

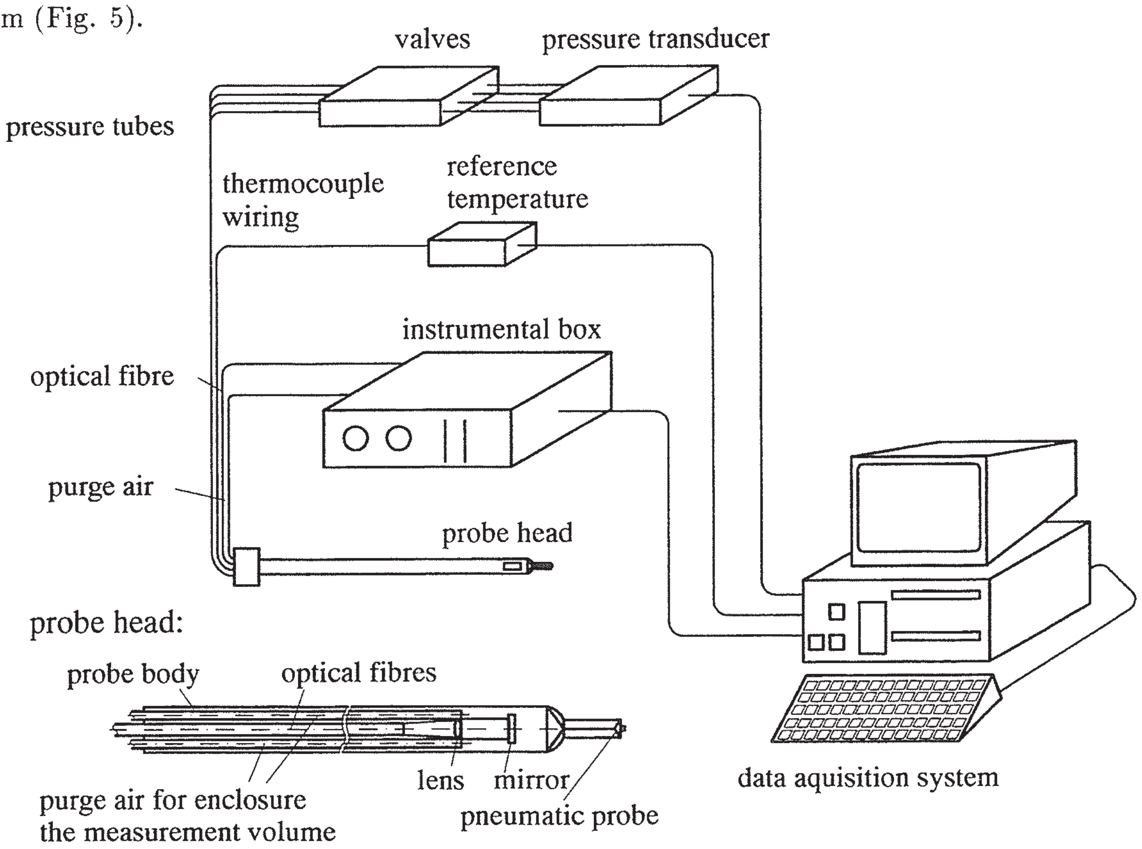

Fig. 5: Pneumatic–optical measurement system

The measurement region of the optical probe and the four–hole wedge probe are at the tip of the probe body. White light from light source guided by an optical fibre passes through the measurement region, then it is reflected by a mirror installed at the end of the probe, and passes through the measurement region again. The attenuated light reaches the light disperser and detecting system where the light signals are transformed into electrical signals and acquired by the data acquisition system. Because the outputs of the light detectors are parallel, the measurement values of all detectors are taken at the same time.

For minimizing the size of probe head, we modify the design normally used for light extinction probes [5], [6]. For example we are using a special designed optical fibre and cancel the injection of purge air.

To prevent intrusion of steam into the tappings of the pneumatic probe head, continuous purging by atmospheric air is used [7].

Fig. 6 shows a photo of the combined probe head. The diameter of the probe stem is d = 10 mm. The slot of the optical region is 15 mm long and 6 mm wide. The distance between the center of the optical part and the center of the pneumatic part is x = 40 mm.

The measurement range for the optical system is from d = 0.02 μm up to d = 10.0 μm. The probe is calibrated over a range of Mach numbers from 0.3 to 1.1, for pitch angles between $\gamma = -10^o$ and $\gamma = 35^o$, and yaw angles between $\alpha = -10^o$ and $\alpha = 10^o$ yielding pressure and temperature coefficients for every adjustment.

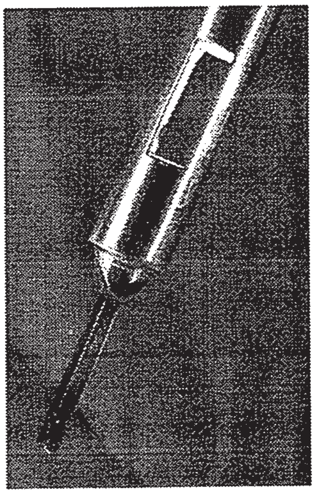

Fig. 6: Combined probe

4 Experimental results

There are some problems for the design of the combined probe head because of the different requirements for the pneumatic part and the optical part of the probe. For the optical part a large stem diameter is needed for having enough space for the optical components and for guarantying low influence of the probe stem to the flow through the measurement volume. For the pneumatic part the probe stem should be as small as possible to reduce blockage effects and increase measurement accuracy. For the combined probe one requirement is, that the distance between the optical measurement region and the pneumatic probe head is not too large. An other question is the influence of the slot in the probe stem for the optical part on the flow around the pneumatic part.

To answer these questions and to prove the function of the system we have tested the single components and the combined probe at different investigations.

Tests for Pneumatic Part

In a first step the influence of the probe stem to the pneumatic probe head was tested by the differences in calibration coefficients for different designs of probes. The geometry of all wedge probe heads is the same. Only the length of the probe head or the diamter of the probe stem is different. The diagramm (Fig. 7) shows results of probe coefficient $CP_{dynamic}$. These results are based on measurements in a free jet wind tunnel. The diameter of the nozzle is about 60 mm. Therefore the stems of the probe no. 2 and no. 3 are inside the jet and in contrary to this for probe no. 1 only the wedge part is inside the flow. The influence of the probe head design and the diameter of the probe stem is obviously. The curves for $CP_{dynamic}$ of probe no. 2 and no. 3 are similar at different level. The curve of probe no. 1 shows an higher gradient.

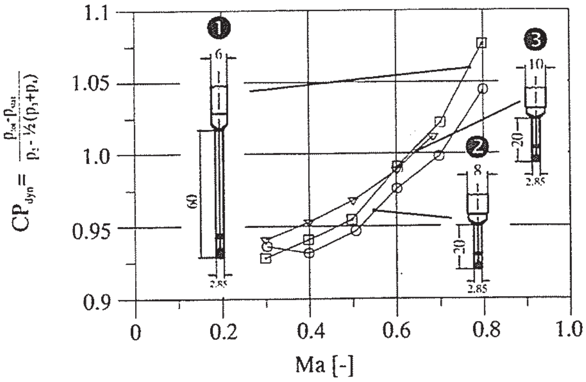

Fig. 7: Results of probe calibration

In other investigations we try to measure the influence of the slot in the probe stem on the pneumatic part of the combined probe.

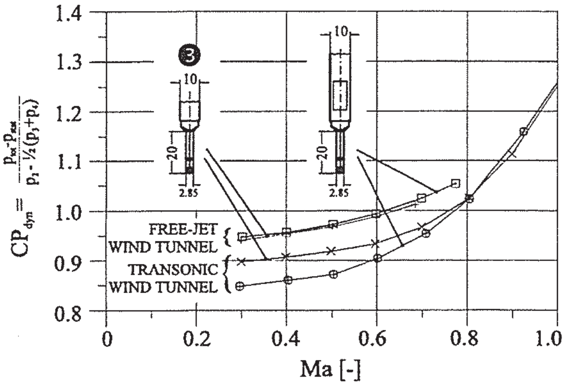

Fig. 8: Results of probe calibration

For this test we calibrate probe no. 3 and the combined probe in two wind tunnels. The first one is a free jet wind tunnel with a nozzle diameter of 60 mm, the second one is a transonic wind tunnel (half–open typ) with a nozzle diameter of 125 mm. Fig. 8 shows the result of calibration measurements in both wind tunnels for both probe types. The results of probe calibration in the free jet wind tunnel are almost identical for both probe designs. However the results in the larger transonic wind tunnel are quite different.

In further tests at a model steam turbine we investigate the consequences of these differences from probe calibration to the result of flow field measurement, that is tantamount to the influence of the blockage effects to flow field measurements [8]. Further results of these tests are presented in this symposium [11].

The conclusion of these tests is that if the Mach number is less then Ma = 0.7 the influence of a probe stem diameter d = 10 mm including the slot for the optical part on the pneumatic part is neglectible. Due to this result it is possible to use this probe behind and in front of the last stage, because only nearby the tip of the blades in the jet stream the Mach number is increasing to transonic and supersonic range. However it is difficult to make a proper measurement with pneumatic probes and optical probes respectively between stator blades and rotor blades [8].

Tests for Optical Part

Before testing it in a wind tunnel, we tested the optical system at measurements of standard particles. The correspondence of the results and the nominal size of particles is very good.

The transonic wind tunnel can be operated by air and by steam. Therefore it was possible to measure spontaneous condensation of steam [9] and of wet air [10]. For these tests the used optical probe has a stem diameter d = 10 mm. Both tests show, that also a small optical probe is well suited for measurements in two phase flow.

The difference between the measurements in a wind tunnel and in a steam turbine is a variable flow angle. The interaction between the probe head and the flow through the optical measurement region must not be accompanied with a change in wet steam prameters. A water tunnel was used to visualize the flow field around the probe head and through the optical measurement region. Fig. 9 and 10 show results of this test for different flow angles. The Reynolds number for all tests is calculated with the stem diameter of the models.

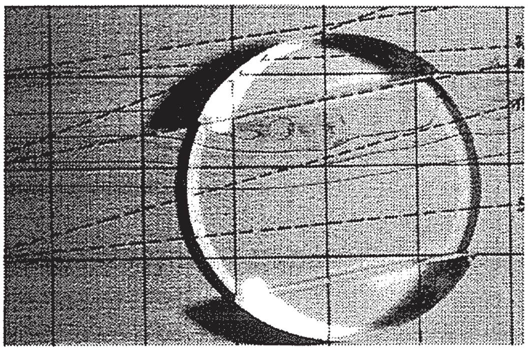

Fig. 9: Model of the combined probe in water tunnel ($\alpha = 10^o$, Re = 8800)

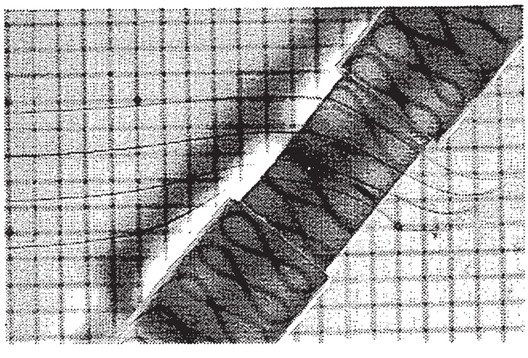

Fig. 10: Model of the combined probe in water tunnel ($\gamma = 40^o$, Re = 2500)

Obviously are the changes in the streamlines in the area of the optical measurement region. In Fig. 9 ($\alpha = 10^o$) seperation of the flow at the suction side of the model is visible. For measurements of the intensity I it should be guaranteed, that this part of the flow is not taken into account. Tests were done for several models with different diameter (Re = 4000 up to Re = 10000) and it can be concluded, that smaller probes should be adjusted to flowfield exactly. The difference in yaw angle is less then $\Delta\alpha = 5^o$. In figure 10 it is visible, that the length of the slot is not equal to the length of the light path in the two phase flow L. However due to the measurment principle the length L has large influence on the result of the optical probe.

On the base of these results we have measured the distribution of flow velocity around the probe head by a Laser–2–Focus system. Fig. 11 shows the result of these measurements made in a free–jet wind tunnel. The velocity field shows a large wake behind the bottom part of the measurement region. In this area it is impossible to detect any flow direction. The velocity of the flow through the measurement region is increasing to about 120 % related to the velocity of the undisturbed jet. The ratio of the widths of the jet behind the probe and in front of the probe is less then 0.5. This result confirms the results of investigations in water tunnel and for this reason the relation between the data for intensity I and pitch angle γ of the flow has to be investigated.

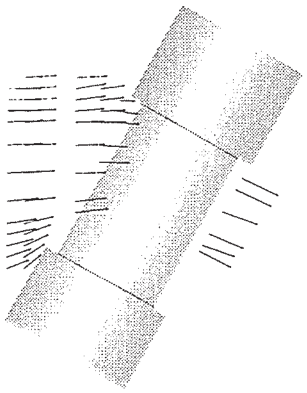

Fig. 11: L2F measurement results ($\gamma = 30^o$, Re = 130000)

This test was done in a transonic wind tunnel using wet air as flow media. Fig. 12 shows the ratio of intensities I/I_0 as a function of the pitch angle γ. Up to pitch angle $\gamma = 20^o$ there is nearly no difference, however for larger angles the signal reduces considerable. If the pitch angle is larger than $\gamma = 20^o$ the probe has to be calibrated to get the relation between the flow angle and the light intensity I. This effect of reducing the length of the light path in the two phase flow should be taken into account for measurements especially in steam turbines.

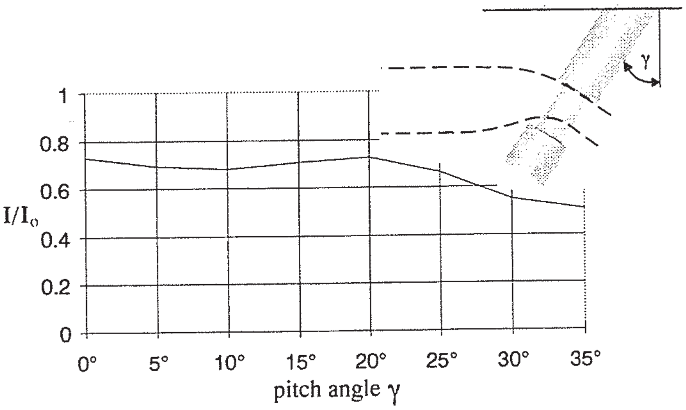

Fig. 12: Signal of the optical probe for different pitch angle

5 Conclusion

In several investigations the function of the new measurement system has been proved. There are several advantages in using this system for wetness measurements in LP steam turbines:

- Measurements were done at the same time. There are no problems caused by thermodynamical and flowdynamical changes of the system.
- There is no time lag between the measurements of thermodynamical and fluiddynamical properties. Higher accuracy of the results can be expected.

- Adjusting the optical probe to the flow field direction is very easy.
- The length of the optical measurement region is small. Therefore it is possible to detect details in wetness distribution along the blades.
- Due to the information of the flow field direction it is possible to determine the influence of pitch angle of steam flow to the results of the optical probe.
- Probe is traversing only once a time. Measurement time is reduced drastically.
- The design of the total system and especially of the probe head is as simple as possible to get a reliable system.

In the future – besides measurement at model steam turbine – we plan to calibrate the pneumatic part as a function of the wetness and the droplet size. Further we plan to carry out the development of the system to a on–line measurement system.

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