An Opto-Electronic Data Transmission System for Measurements on Rotating Turbomachinery Components

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Abstract

The paper presents the development of an opto-electronic data transmission system for high frequency measurements in rotating turbomachines. A model test rig was built to verify the response capabilities of the system for high speed rotating pressure probes traversing strong pressure gradient fields. Finally, the paper describes the construction of a rotating probe mechanism for measurements in a high speed annular turbine test rig.

INTRODUCTION

Ever since the beginning of the research on rotating turbomachinery, the transmission of signals recorded by sensors mounted on rotating blades has been a challenging problem for many researchers. Beside problems related directly to the sensors, like their miniaturization, their fixation on blades and probes, and their sensitivity to centrifugal forces, there is the equally important problem of the transmission of the signals from the rotating to the stationary frame. There are two categories of transmission systems:

a) the transmission of electric signals from hot wires, thermocouples, heat transfer gauges, strain gauges and rotating pressure transducers,
b) the direct transfer of a pressure measured on a rotating component to a stationary transducer.

A short survey of rotor flow transmission systems is given by Lakshminarayana (1980).

The most widely used transmission systems for electrical signals are mechanical slip rings, mercury slip rings and telemetry. The transmission of the signals is never faultless. Either the systems generate their own electric noise or they pick it up from the environment. The quality of the transmitted data depends on the signal-to-noise ratio.

The development of sensor miniaturization and rotatability of pressure probes resulted in the necessity of electric signals to be transmitted in time. The authors became aware that a similar system had been developed by Heil et al. (1987) using the same technique. However, Heil and Kappler applied their optical transmission techniques to the slow cooling down process of respectively the rotor of an asynchronous motor (Heil) and the disc of a gas turbine rotor (Kappler). Neither of the authors addresses any of the issues relevant for high frequency aerodynamic measurements.

DESCRIPTION OF OPTO-ELECTRONIC TRANSMISSION SYSTEM

The use of optical diodes for the signal transmission calls for digitization of the signal before its transmission. The digitization has the advantage that all noise below a certain threshold is rejected, while the direct transmission of an analog signal via sliprings implies the integral transmission of the signal, noise included. There exist two principles for the digitization of an analog signal: the analog-digital conversion and the voltage-frequency conversion. The second solution was preferred because of its relative simplicity, lower cost and smaller size of the converter. The size of the components was important because of the confined space for the electronic in the shaft of the rotating probe traversing mechanism. The precision of a V/F converter is superior to that of an A/D converter but its conversion rate is much smaller.

The choice of the diodes, laser or infrared diodes, was made rapidly in favor of the latter because of the prohibitive cost of the laser diodes.
The transmission system is shown in form of a block diagram in figure 1a:

Components in rotating frame:
- measurement device (e.g., kulite pressure transducer) with a voltage output range from 0-50 mV;
- an amplifier with a gain of \( \approx 100 \);
- a V/F converter transforming the analog signal into a frequency between 500 KHz and 1 MHz;
- a circuit with a second amplifier driving the infrared diodes.

Components in fixed frame:
- a receiver diode with a very high impedance pre-amplifier and an operational amplifier;
- a F/V converter integrated in a PLL circuit;
- a low pass filter used to filter the residual frequencies of the PLL.

The transmission diode is the Hamamatsu LED 1939 with a peak wavelength of 890 nm and a frequency band of 1 MHz. It is characterized by a very large emission angle. At 90° from its principal emission direction it conserves a power output of 75% of the maximum power.

The receiver diode S1223 is also from Hamamatsu. It has a peak wavelength of 920 ± 50 nm and a bandwidth of 30 MHz.

The dynamic range of the entire system depends on the frequency to voltage phase locked loop, composed of a phase frequency comparator, a filter, an integrator amplifier and the F/V converter, Fig. 1b. The natural frequency and the damping of the PLL is controlled by the integrator amplifier. For the low pass filter following the F/V circuit, a 5th order Butterworth filter was chosen. Since the low pass filter influences the PLL, the optimization asks for a careful tuning of the natural frequency and the steepness of the attenuation of the low pass filter on the other side.

In a first step, a one channel prototype was designed, built and tested with both the emitter and receiver optics in fixed positions facing each other. The frequency response curve of the optimized transmission system to a square wave input signal is presented in Fig. 2a. The bandwidth is 100 kHz (defined by a gain of -3 dB). A maximum positive gain of 4.058 dB occurs at 52 KHz.

![Fig. 2a Frequency response curve](image)

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![Fig. 2b Delay and phase shift of transmission system](image)

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![Fig. 2c Error in signal transmission for DC input](image)

Fig. 2c Error in signal transmission for DC input

Fig. 2b presents both the phase angle shift and the corresponding time delay of the transmission system. The time delay is of the order of 8 µs in the frequency range up to 10 Hz and rises progressively to 10.5 µs at 100 KHz. To appreciate properly the significance of this delay on the probe measurements at a blade passing frequency of 3 KHz let us assume that the wake covers 25% of the blade pitch. Considering the wake as a half sine-wave, then the characteristic frequency for the wake is equal to twice the blade passing frequency, i.e., 6 KHz with the corresponding time period of 166 µs. A delay of 8 µs for a time period of 166 µs appears to be quite significant but one has to keep in mind that this delay corresponds to a square wave input signal, while the wake profile is close to a semi-sinusoid, which will considerably reduce the delay time.

Fig. 2c shows finally the response of the transmission system to a DC input. The deviation of the output voltage from the input voltage is of the order of ±0.7°/oo over the measured voltage range. Testing of several transmission systems showed a typical error bandwidth of ±1°/oo over the same range.
MODEL TEST RIG

A small test rig was built to test the transmission system in rotation. Fig. 3 shows the design of the model. A fast response total pressure probe (Kulite transducer) is rotated through air jets exiting from 5 equidistant closely spaced 10 mm Ø nozzles, arranged circumferentially on a circle of 300 mm Ø in the rear wall of an annular settling chamber. The probe is attached to a disk mounted on a shaft, which, in its central part houses the electronics for signal amplification and transmission.

![Fig. 3 Model for testing opto-electronic data transmission system](image)

A 5-PSI Kulite pressure transducer of 1.6 mm Ø, type XCS-062-5D with screen B, is mounted in the probe tip. The distance between nozzle exit and transducer is 5 mm. Because of the shear layer on the jet border and due to the finite size of the transducer, the probe does not sense a pressure discontinuity but yet a very strong pressure gradient.

The voltage supply for transducer and electronics is transmitted via ordinary sliprings (copper rings and carbon brushes) arranged on the right end of the shaft. A voltage supply of ±15 V is needed. Three carbon brushes, positioned at 3x120° around the shaft proved to be necessary to eliminate random strong voltage peaks observed in the signal output when using single brushes only.

To the right of the sliprings the shaft carries the emitting diodes. This leaves the shaft end for the electric drive. To establish a permanent contact between the emitter and receiver unit, several emitting diodes are to be distributed around the shaft.

![Fig. 4 Area coverage of IR-diode emission angles for 3, respectively 4, diodes on the rotorshaft](image)

Fig. 4 shows the emission angle curves of 3, respectively 4, emitting diodes, mounted on the shaft of 37 mm Ø. The curves present the distance of equal power with respect to the power at 0 degree emission angle. The distance of 90 mm corresponds approximately to the maximum distance between emitting and receiving diodes for a safe transmission at 0° emission angle. The table below shows that a system with only one receiver diode can operate in the following limits:

<table>
<thead>
<tr>
<th>Emitting Diodes</th>
<th>Receiving Diode S1223</th>
</tr>
</thead>
<tbody>
<tr>
<td>LED 1939</td>
<td>Min. Dist.</td>
</tr>
<tr>
<td>3</td>
<td>17 mm</td>
</tr>
<tr>
<td>4</td>
<td>7 mm</td>
</tr>
</tbody>
</table>

The wide angular sensitivity of the receiver diode S1223, Fig. 5, would enable a transmission with 3 emitter diodes, but at the end a system with 4 diodes was adopted.

MODEL TEST RESULTS

Tests were run with settling chamber gauge pressures of 150 to 200 m bar resulting in air jet velocities of 150 to 170 m/s. The rotational speed of the probe was varied from 1000 to 3000 RPM corresponding to peripheral speeds of 15.7 to 47.1 m/s. With a nozzle spacing of 9° the jet passing frequency at 3000 RPM amounts to 2 KHz.

The data are acquisitioned with a BE 490 plug-in board high speed data acquisition card with a maximum sampling frequency of 1 MHz. A maximum of 8 channels may be acquisitioned with this card which implies, of course, a corresponding decrease of the maximum sample frequency.

Fig. 6a shows a typical pressure signal trace taken at 1000 RPM, i.e., at a jet passing frequency of 666 Hz. The traces show very clearly the pressure pulses due to the jets. Typical pressure rise and pressure fall times are of the order of 0.06 ms. A rise time of 0.06 ms at 1000 RPM corresponds to a pressure rise over approximately 1 mm distance. The reason for this gradual change can entirely be attributed to the combined effect of a shear layer thickness of ≈1.1 mm and a probe head diameter of 1.6 mm.
To eliminate the high frequency noise, a numerical filter with a cut off frequency of 40 KHz was used. The result of the filtered signal is presented in Fig. 8. The pressure trace in between the air jets is remarkably flat, which indicates an overall very low noise level. The low noise level between the jets allows to conclude that the strong fluctuations in the jets are representative for the flow turbulence.

Superimposed on the jet pressure signal is a high frequency noise. Stretching the time scale of the signal makes appear a periodic signal with a frequency of 94 KHz. Fig. 6b shows this stretched signal for the probe displacement between jet 1 and 2. The trace is typical for a dynamic system of the second order with a slight damping. The power spectrum density of the signal containing all five air jets confirms the existence of a resonance frequency at 94 KHz, Fig. 7. The fast drop of the signal for higher frequencies is due to the fifth order Butterworth filter.

To conclude a test was run at 3000 RPM at zero flow with a cover on the Kulite pressure transducer, Fig. 10. The pressure transducer calibration was the same as for the test in Fig. 9. The
peak-to-peak pressure variation for the zero flow test is 4 mbar. This is representative for the overall noise of the transmission system for the considered test setup and running conditions including electronic, optical and mechanical (bearings) effects.

**DESIGN OF 4-CHANNEL TRANSMISSION SYSTEM FOR MEASUREMENTS IN THE VKI COMPRESSION TUBE ANNULAR CASCADE**

The very satisfactory performance of the opto-electronic data transmission system led to the design of a 4 channel system for a high speed rotating probe traversing system in the VKI Compression Tube Annular Cascade Facility CT3, Fig. 11. The overall construction is very similar to the model test rig. The parallel transmission of several channels requires the implantation of as many rows of emitting diodes as there are channels. Of course one has to ensure that each receiver diodes capture the light pulses from 1 row of emitting diodes only. Disks are used to separate the LED rows from each other. It is sufficient that the receiver diode enters slightly into the space between two disks to prohibit any interference from the neighbouring channels. The complete traversing unit with the transmission system is shown in Fig. 12.

The length of the transmission unit depends on the diameter of the receiver diodes which is 9.2 mm for the S1223 diodes. Recently Hamamatsu has developed a new diode S2858/01 with incorporated amplifier and a 5.6 mm base diameter. The study of a 16-channel transmission system using this new diode is underway. The costs of the electronic components for the present 4-channel system including emitter and receiver diodes are about 1150 ECU (≈ 1550 $).

**CONCLUSION**

The development of an opto-electronic data transmission system for high frequency measurements on rotating turbomachinery components was successfully completed. The selected system makes use of voltage to frequency converters and signal transmission by infrared diodes. The system has a bandwidth of 100 KHz. Tests on a model test rig with a rotating Kulite pressure probe traversing a series of air jets shows a high signal-to-noise ratio and confirms its high frequency response capabilities. The low costs of the electronic and optical components and the relative short time for building the in-shaft electronics make this system cheap and easy to apply in any research laboratory. A four-channel system for parallel transmission of data has been designed and built for use in the VKI Compression Tube Annular Cascade Facility.

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