NOVEL MICROWAVE VIBRATION MONITORING SYSTEM FOR INDUSTRIAL POWER GENERATING TURBINES

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ABSTRACT

A novel microwave sensor system for real-time monitoring of turbine blade vibrations is reported. The self-calibration of the sensor modules, a key feature of the implemented concept, is based on adaptive frequency tuning of the microwave source. By using this calibration, degradation of the measurement performance caused by temperature drift and dirt deposit is compensated. During pilot runs with a 65 MW gas turbine the microwave system proved to give excellent measurement results.

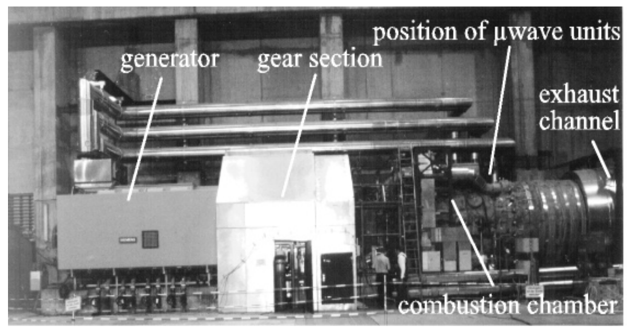

Fig. 1 - Photo of the 65 MW gas turbine installed in a power plant near Stuttgart.

INTRODUCTION

The most essential part of turbomachinery is the blading. Although modern design and calculation methods for efficient and reliable blading meet the physical realities with a high degree of accuracy, additional measurements of dynamic strain due to blade vibrations are essential. The monitoring of the vibrations of all blades in a row can be done with a well proven two sensor non contact blade vibration measurement technique [1].

With the use of simple magnetic sensors a continuous blade vibration monitoring is possible for steam turbines [2]. Since modern gas turbines incorporate largely non magnetic turbine blades, other reliable sensors have to be used. Optical sensors are quite sensitive to dirt deposit and thus not optimal for long-term testing or continuous monitoring.

In this paper a novel microwave system for measurements with the two sensor system is presented. Pilot runs were done with a gas turbine in a power plant near Stuttgart (Germany). The facilities are shown in Fig. 1.

SYSTEM CONCEPT

The turbine diagnosis system is based on two sensor modules (so-called „start“ and „stop“ sensor), a rotation detector and a signal processing unit. A schematic of the overall system is depicted in Fig. 2.

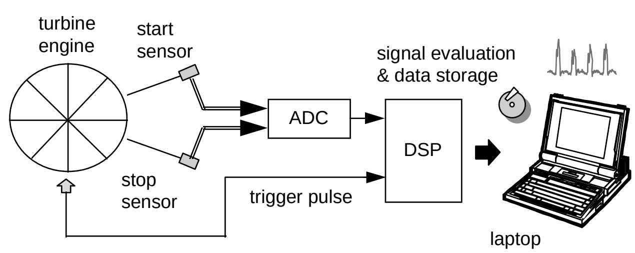

Fig. 2 - Schematic of the turbine diagnosis system.

For blade vibration analysis the start/stop time-of-flight (TF) of each blade tip between the start and stop position is measured. For a non-vibrating blade this time difference is constant, whereas a vibrating blade causes variations of the TF. The accuracy of the vibration monitoring is directly related to the precision of this time measurement.

The microwave sensors, which are described below, provide pulse sequences when the turbine engine rotates. Every impulse represents a passing blade (e.g. like in Fig. 6). The rotation detector provides a trigger pulse indicating each revolution of the engine and is used to unambiguously relate the pulses of the start and stop sensor to the corresponding blades.
The sensor signals are fed into the signal processing unit consisting of a DSP as well as some analogue electronic preprocessing circuits (amplifier, A/D-converter). The vibration analysis is done on a PC where the results are displayed and the data can be stored on harddisk for further off-line processing.
During normal operation the turbine revolves with 5400 rpm. Thus, in a blade row with 53 blades every 210µs a blade tip passes the sensor probe. The signal processing unit must be able to cope with this high speed demand.
Since the vibration frequencies are much greater than the systems sampling rate (one sample per turbine rotation), the vibration frequencies are only detectable as spectral lines of the aliasing frequencies in the baseband. The vibration frequency can be derived from the signal spectrum, if the relative position of the mechanical vibration frequency is known with regard to the closest integer multiple of the rotational frequency.
In order to measure the vibration amplitude of an integer multiple of the rotational frequency the second sensor is applied.

SENSOR SIMULATION

Fig. 3 shows a schematic of the 24 GHz sensor module. It consists of an oscillator (VCO) operating in CW mode, a mixer (schottky diode), a waveguide, an amplifier, a signal processing unit and a control unit.
The oscillator continuously emits microwaves at a fixed frequency. This signal is guided to the engine by the waveguide and is reflected by the turbine blades, when passing the sensor head. The transmitted and reflected microwaves are down-converted by the mixer diode mounted inside the waveguide between the oscillator and the waveguide probe.

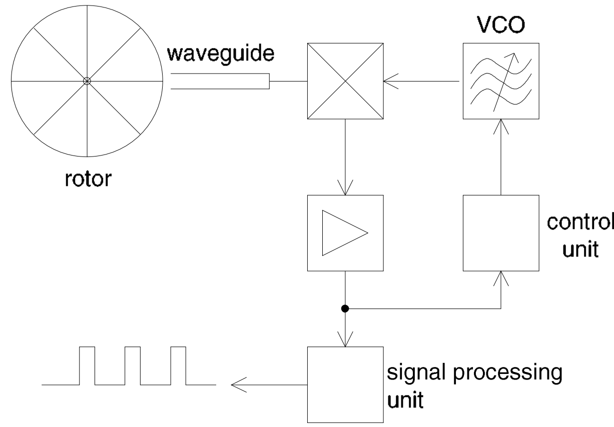

Fig. 3 - Schematic of the 24 GHz sensor module

In an ideal situation the blade tip passes the sensor head at a constant distance which leads to a constant offset according to:

$$s(t) = A \cdot \cos(2 \cdot \pi \cdot f_0 \cdot \tau), \quad (1)$$

where A is the maximum amplitude of the mixed signal $s(t)$ and f_0 is the oscillator frequency. The transmitted microwaves come back to the mixer with a time delay of τ according to the distance of the reflecting blade tip from the sensor head, which causes a τ-depending offset of the mixed signal.
In practice, the microwaves are not only reflected by the blade tip but also by the blade body and the waveguide probe, which causes a variation of the amplitude of the mixed signal $s(t)$. For precise computation of the mixed signal the complex geometry of the blade would have to be taken into account.
In a simplified model, a blade can be simulated by a rotating pointer whose tip is projected onto the sensor axis. The projected point moving towards and away from the sensor head is considered to be the reflecting part of the turbine blade. The corresponding distance $d(t)$ from the sensor can be well approximated by:

$$d(t) = l + d_0 - l \cdot \cos(\alpha(t)) \quad (2)$$

where d_0 is the minimum distance of the blade tip from the sensor and l is the length of the turbine blade. The angle $\alpha(t)$ between the blade and the sensor axis can be described as:

$$\alpha(t) = 2 \cdot \pi \cdot U \cdot t \,, \qquad (3)$$

where U is the rotation frequency of the turbine.
Assuming that the reflecting area is an infinitely expanded conducting area the amplitude $a(t)$ of the mixed signal can be approximated by:

$$a(t) = a_0 \cdot d_0^2 / d^2(t) \,, \qquad (4)$$

where a_0 is the amplitude when the blade tip is nearest to the sensor head.
An additional sinusoidal part of the mixed signal originates from the relative movement of the turbine blades' reflecting parts during rotation with regard to the sensor. That causes a continuously varying phase difference between the transmitted and the reflected microwaves (Doppler effect). Therefore τ is varying with time t according to:

$$\tau = 2 \cdot d(t) / c_0 \,, \qquad (5)$$

where c_0 is the speed of light.
Combining equations (1) to (5) the IF signal $s(t)$ obtained from the mixer can be approximated by equation (6).

$$s(t) = \frac{a_0 \cdot d_0^2}{d^2(t)} \cdot \cos\left(2 \cdot \pi \cdot f_0 \cdot \frac{2 \cdot d(t)}{c_0}\right) \qquad (6)$$

Figs. 4 and 5 show the signal of a single blade calculated with equation (6) for two different distances d_0 between the blade tip and the sensor. The figures illustrate that the signals are very sensitive to changes of the distance d_0. Changes within the range of half a wavelength lead to completely different shape and amplitude of the IF signal $s(t)$. The reason is, that the distance variation d_0 causes a phase shift between the transmitted and the reflected microwaves. Without a compensation of this critical phase sensitivity, the DSP unit cannot produce a correct digital pulse for every passing blade tip.

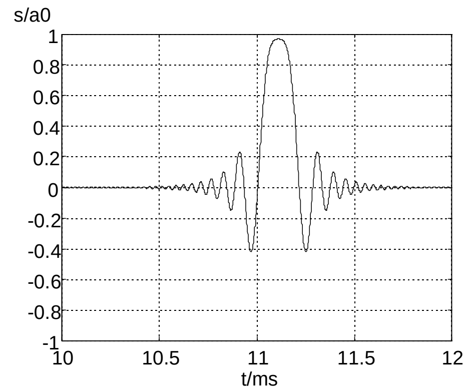

Fig. 4 - Simulated signal of a single blade with a tip distance d_0 of 6 mm.

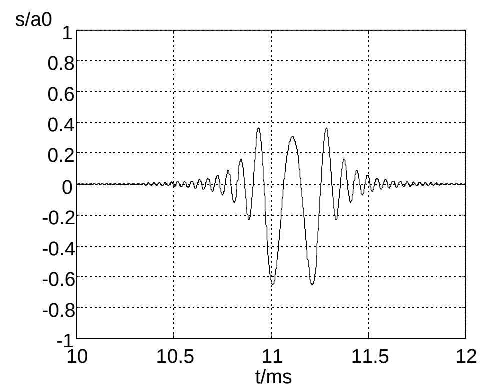

Fig. 5 - Simulated signal of a single blade with a tip distance d_0 of 7.5 mm.

It is obvious from equation (6), that the IF phase can be manipulated by tuning the oscillator frequency f_0. This fact is used for adaptively compensating the phase shifting effects such that the blade response signal is adjusted to an ideal shape (see Fig. 4). This self-calibration is done with the control unit, which continuously checks the ratio between the maximum and the mean value of the pulse sequence and adjusts the VCO's frequency if necessary. As a result, any degradation of the signal performance due to changing blade tip distances or temperature drifts of the VCO's operating frequency is suppressed.

MEASUREMENT RESULTS

The discussed turbine diagnosis system has been tested during measurement campaigns in a power plant.

The 24 GHz sensor probes (start and stop sensor) were installed at the lateral border of the turbine at the fourth blade row after the combustion chamber, where the probes are exposed to a temperature of about 600°C. The sensor probe is an air-cooled rectangular waveguide (material invar) that separates the sensitive electronic parts of the sensor from the high temperature section of the turbine.

A typical pulse sequence measured during the pilot runs is shown in Fig. 6a. It can be seen that each turbine blade produces a characteristic signal. From this signal qualitative information on completeness, shape and condition of each engine blade could be derived. In the present application the signals are only used to measure the exact time difference which the tip of a vibrating blade needs to pass the distance between the start and the stop sensor. In order to achieve this, in the signal processing unit first the raw signals are filtered and smoothed and finally digital pulses are created by threshold triggering (Fig. 6b).

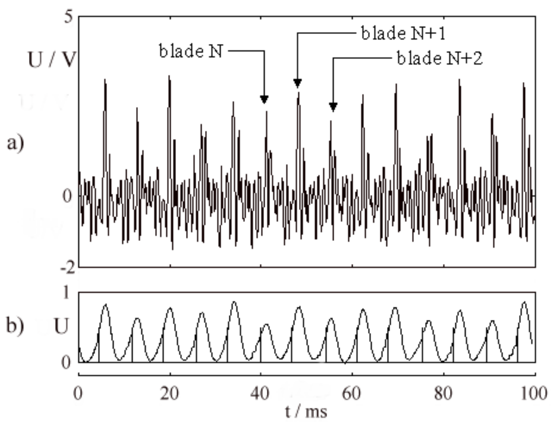

Fig. 6 - Measured pulse sequence during turbine rotation.
a) raw signal, b) filtered and smoothed signal.

An evaluation of the triggered blade signals with adequate algorithms leads to a plot of the individual blades' amplitudes versus time as shown in figure 7 for 40 selected blades. The time signals can be frequency analyzed to show the characteristic mechanical blade vibration frequencies.

It has to be mentioned, that the diagnosis system could also be used to monitor blade tip clearances, which is an important parameter concerning turbine efficiency.

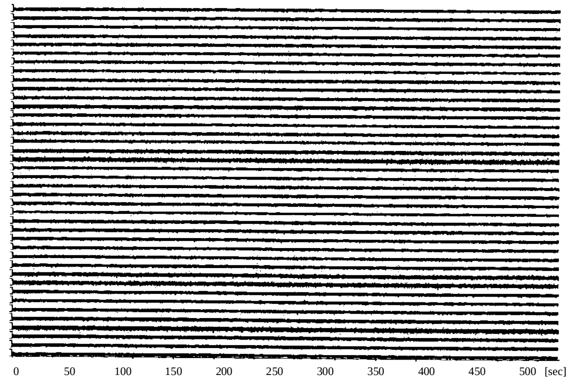

Fig. 7 - Measured vibration plot of several turbine blades.

CONCLUSION

A novel microwave sensor system for real-time monitoring of turbine blade vibrations has been presented. Pilot runs on a 65 MW gas turbine demonstrated that the system operates reliably and provides high measurement sensitivity even in rough industrial environments, where other sensor principles currently cannot guarantee stable operation.

The new self-calibrating approach has proven to give suitable sensor signals for every operating condition.

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