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SAW-Based Wireless Measurements of the Fast-Varying Deformations in Rotating Vibrating Objects

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***Abstract*—Measurement of vibration characteristics with SAW-sensors is attractive in applications for power generation, transport and aviation. The possibility of wireless data acquisition is especially useful for interrogation of sensors fixed on rotating vibrating objects, such as turbine blades for example. This paper reports on details of experimental wireless acquisition of vibration related information from rotating tuning forks which simulate the behavior of the vibrating objects at room temperature. SAW-resonators are used as sensors for fast-varying deformations measurements. Tuning forks with known frequencies of mechanical resonances equal to 512 Hz were fixed on a rotating shaft of an electrical motor. Commercial 224 MHz quartz SAW resonators were glue-bonded to tuning forks shoulders in the area of maximal strain. The resonators were wire-bonded to intermediate PC-boards. They could be connected either as feedback circuits to a miniature oscillator circuit with the output connected to rotating electromagnetic couplers (near-field antennas), or directly to the couplers for interrogation by external signals without the battery and the oscillator electronics. The oscillator had a miniature battery fixed on the same shaft and its output signal was frequency modulated by the tuning fork vibration, inducing fast varying deformations in the SAW resonator. The 512 Hz vibration of rotating at 900-2700 rpm tuning forks was excited by compressed air flow or by hammer shocks. After demodulation of the oscillator signal about 15 s long exponentially decaying bursts were digitized by a computer sound card and recorded. This approach to data acquisition, although applicable only to low temperature experiments, has shown a better frequency resolution (0.005% in initial experiments) than the interrogation with external signals, and a much larger working distance: above 10 m with vibrator-type antennas and oscillator power of only 10 µW. The spectrum of the output signal contained the rotation related contribution.**

Keywords—vibration measurements, surface acoustic wave, SAW deformation sensor, wireless interrogation

I. Introduction

The long period of workability is one of the important parameters for the expensive construction or its parts. Vibration is one of the important parameters for monitoring in equipment with moving parts. Meanwhile controlled objects can be in motion described by different and complicated pathways. This complicates the measurements and sometimes excludes the use of the wired connections for the sensors monitored objects conditions. This paper reports on investigation of the sensor based on the surface acoustic waves (SAW) for vibrations monitoring of moving objects. The sensor based on the SAW resonator has a number of advantages for example the capability to work in harsh environments like high temperature, radiation and other. Measurement of vibration characteristics with SAW-sensors is attractive in applications for power generation, transport and aviation. High temperature vibration measurements by SAW-sensors were reported in [1]. This suggests the possibility of using the sensor in a hot area above 100°C. The possibility of wireless data acquisition is especially useful for interrogation of sensors fixed on rotating vibrating objects, such as turbine blades for example.

This paper reports on details of experimental wireless acquisition of vibration related information from rotating tuning forks which simulate the behavior of the vibrating objects at room temperature. SAW-resonators are used as sensors for fast-varying deformations measurements. Section II presents the sensor design. Section III contains the description of the test setup and the experiment part details. The results and their discussion are described in Section IV.

II. Sensor Configuration

The SAW device used in this work as a sensor for fast-varying deformations measurements is a single-port SAW-resonator. Commercial 224 MHz quartz SAW resonators were used as well as specially designed resonators on ST-quartz. It contains aluminum interdigital transducer and short-circuited reflectors. The connection of the sensor interdigital transducer to a PC-board is made with gold wires by ultrasonic welding (Fig. 1).

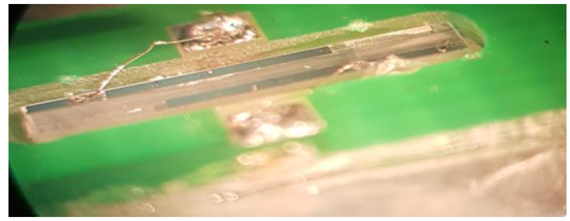

Fig. 1. Wire bonding connection of the sensor PC-board and SAW-resonator sensor interdigital transducer with a gold conductor.

III. Experimental

The sensor described in section II is glue-bonded to a tuning fork shoulder close to the area of maximal strain. The test setup uses commercially available medical tuning forks with known frequencies of mechanical resonances equal to 512 Hz. Two tuning forks were fixed on a rotating shaft of an electrical motor in order to statically balance the rotating structure. Rotating shaft speed can be changed and the contribution of rotation to sensor response spectrum can be studied. The 512 Hz vibration can be excited by compressed air flow or by hammer shocks. The influence of the vibration amplitude on the frequency deviation was described in [2].

The deformation sensing SAW resonator could be connected either into the feedback circuit of a miniature oscillator circuit with the output connected to a rotating electromagnetic coupler (that consists of a pair of near-field antennas), or directly to the coupler for interrogation by external signals without battery and oscillator electronics. The oscillator was supplied with a miniature battery fixed on the same shaft (Fig. 2) and its output signal was frequency modulated by the tuning fork vibration, inducing fast varying deformations in the SAW resonator (Fig. 3).

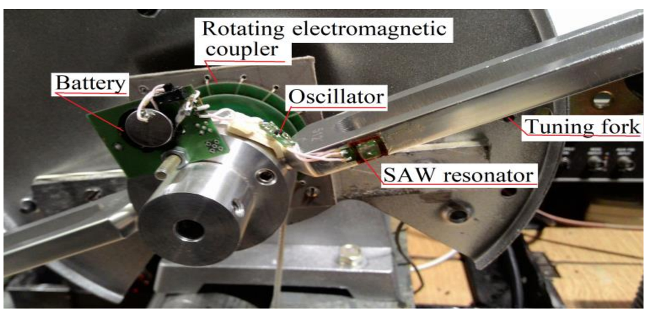

Fig. 2. Vibration sensor test setup including: rotating electromagnetic coupler, tuning fork, SAW resonator, oscillator and battery.

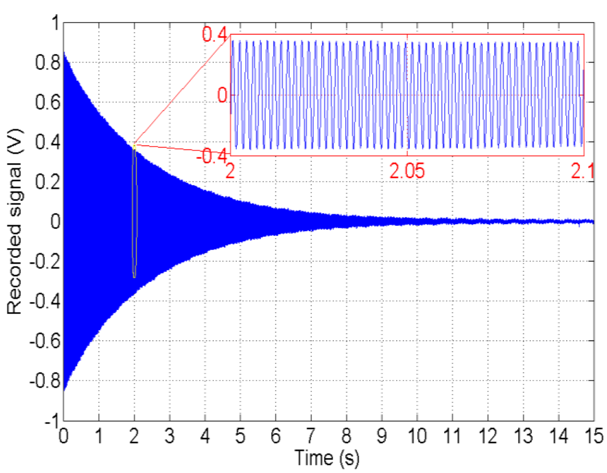

Fig. 3. Recorded FM-demodulated signal of the oscillator with a SAW resonator under fast varying deformation.

A. *Experiments with a resonator connected into oscillator circuit feedback*

The electrical motor is rotating the shaft with fixed tuning forks at a chosen constant speed. The oscillator signal frequency has a fixed value close to 224 MHz, it is modulated when the vibration occurs. The electromagnetic wave at 244 MHz propagates between the rotating and fixed near-field antennas of the coupler, thus excluding any wired or sliding contacts connection between the rotating parts. The signal from the fixed antenna output is frequency converted in a mixer finally allowing to use a commercial FM receiver for FM demodulation. The demodulated audio-frequency signal is acquired by a PC audio card. This experiment allows utilizing a regular PC audio card as an analog to digital converter. However, it usually imposes a frequency restriction to a half of 44.1 kHz sampling frequency. The card also influences the frequency resolution. Besides the upper frequency of the response the particular audio card used in present experiments restricts the minimum frequency value to 8 Hz. The benefit of the using a PC audio card is found in a long time of recording on an HDD. The experiment consists of two steps: the tuning fork vibration excitation without rotation and with rotation at different speeds. This can help to study the impact of rotation on the spectrum of the vibrations related signals.

B. *Experiments without oscillator circuit*

Experiments without oscillator circuit were performed in pulse interrogation mode. In this case the resonator was directly connected to the rotating electromagnetic coupler. In order to make these experiments with an increased wireless interrogation distance the output port of the fixed part of the coupler was connected to a separate antenna of the sensor. The CW interrogating signal was time-gated by a switch controllable by a commercial pulse oscillator, in the same way as described in [1, 3] and amplified by the HP8447 amplifier. Radiated from a transmitter antenna this impulse radio-signal was received by the sensor antenna connected to the fixed near-filed antenna of the coupler. After transmission into the rotating near-field antenna of the coupler this signal pumped the energy into the SAW-resonator sensor. After the end of the interrogation pulse the resonator enters the free oscillation mode with the frequency equal to its current resonance frequency. The resonance frequency varies with the SAW resonator deformation induced by vibration that changes the interdigital transducer dimensions and the propagating acoustic wave velocity as described in [4, 5]. The resulting signal was transmitted by the sensor antenna to the third separate antenna of the receiver. Another controllable switch was included between the antenna and the receiver in order to block the strong direct interrogating signal from amplifier. A commercial AM/FM receiver was used as a demodulator in both modes: amplitude demodulation and frequency demodulation. Because the informative signal has simultaneously the amplitude and the frequency modulation, as was studied in [2]. The demodulated signal was processed by a PC audio card and recorded into an HDD for further processing and Fourier transform analysis.

IV. Results and Discussion

Using of the first approach (oscillator signal modulated by vibration) gives a long exponentially decaying burst realization, over 12 s long (Fig. 3) that is recorded after frequency demodulation. The ratio between the signal amplitude strictly after the start of the tuning fork vibration and the signal amplitude after 12 s exceeds 77. The signal cannot be resolved from noise and interferences by used measuring instruments after 12 s. The signal spectrum is shown in Fig. 4 with scaled noise and interferences spectrum contributions in the range up to 75 Hz. The signal spectrum in the experiment with rotation is shown in the Fig. 5. Increased level of noise and interference spectrum contributions has emerged with the switching-on the electrical motor. This can be a reason for worse frequency resolution. The benefit of this approach is the absence of amplitude modulation, the oscillator FM signal level is defined by the battery voltage. All vibration information is found in FM of the signal. The spectral frequency resolution is 0.025Hz in initial experiments (0.005% of the vibration frequency). Depending on the strength of the vibration excitation shock, the bandwidth of the FM-signal spectrum could approach 100 kHz and it could even exceed the bandwidth of a commercial receiver FM demodulator. In such cases the beginning of the demodulated signal was distorted. Sometimes the resonator substrate or bonding wires were destroyed by excessively strong shocks. Such situations should be considered as they can occur in real-life conditions.

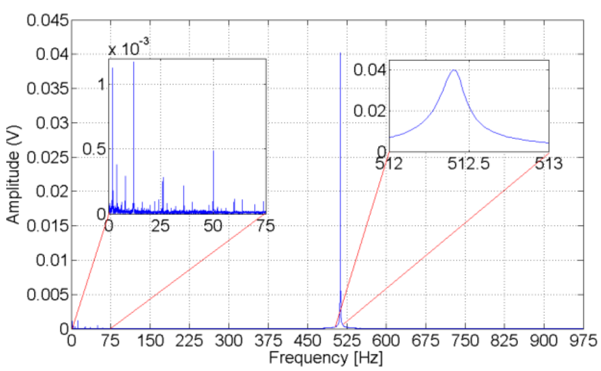

Fig. 4. The spectrum of FM-demodulated recorded signal of the oscillator without rotation.

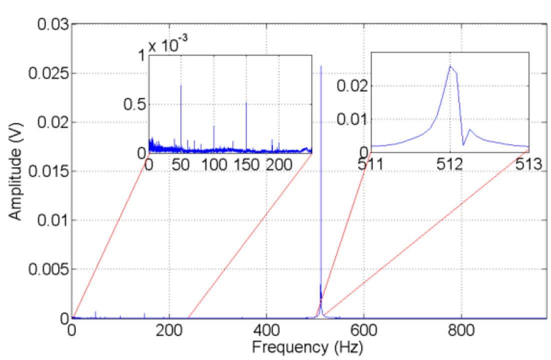

Fig. 5 The spectrum of FM-demodulated recorded signal of the oscillator with rotation.

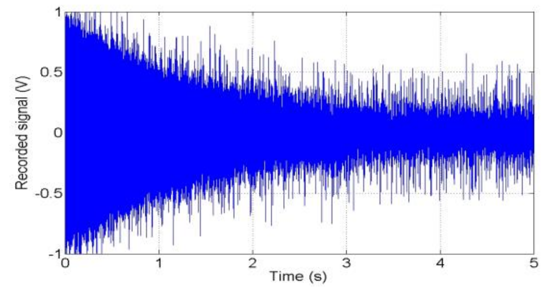

Fig. 6. Recorded vibration related signal after AM-demodulation without rotation.

Using of the second approach (without oscillator) results in amplitude and frequency modulation of the external interrogation signal as described in [3]. When the vibration exciting shock is weak the received re-radiated signals after AM demodulator look as exponentially decaying bursts. The length of the recorded signal that can be attributed to vibration is 3-6 s (Fig. 6). The remaining part of the recording is related mainly to noise and interferences. The signal spectrum in the experiments with rotation and without rotation are shown in Fig. 7 and 8 with scaled noise and interferences spectrum contributions in the range up to 250 Hz shown in insets. When the shock is strong, the re-radiated demodulated signal becomes distorted at a much lower vibration amplitude, than the demodulated oscillator signal.

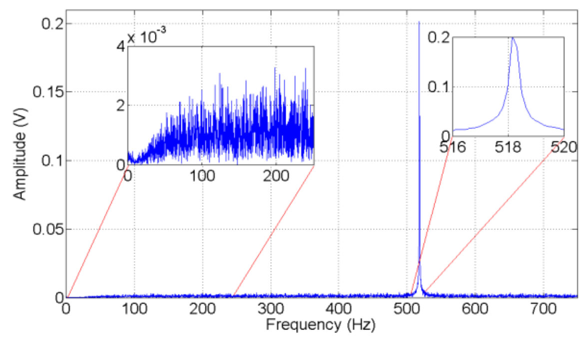

Fig. 7. The spectrum of AM-demodulated recorded signal in impulse interrogation approach.

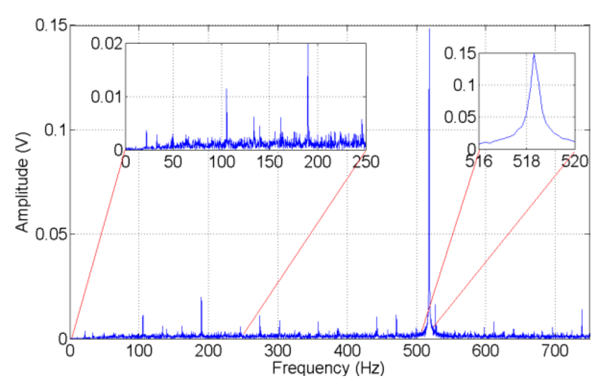

Fig. 8. The spectrum of AM-demodulated recorded signal in impulse interrogation approach with rotation.

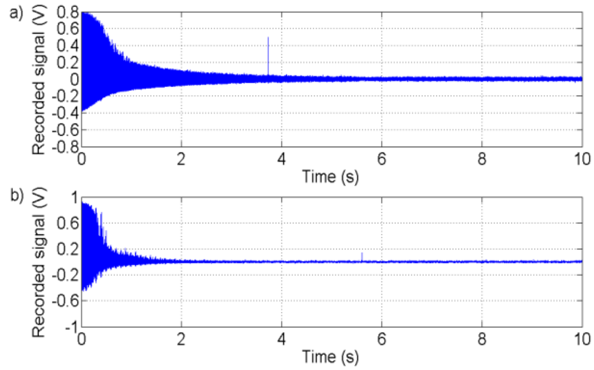

Fig. 9. Recorded signal after FM-demodulation of: a) the signal related to vibration without rotation, b) the signal related to vibration with rotation of the vibrating object.

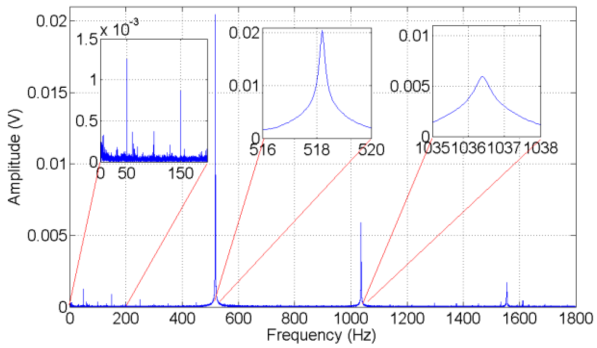

Fig. 10. The spectrum of FM-demodulated recorded signal.

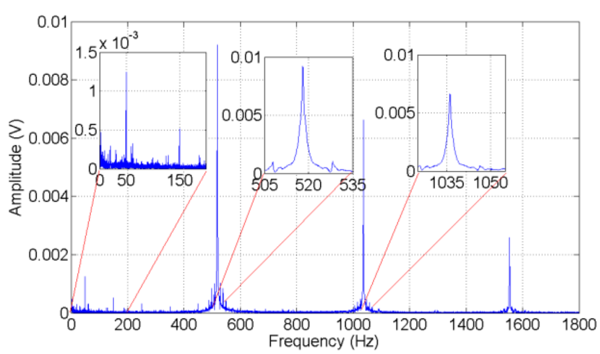

Fig. 11. The spectrum of FM-demodulated recorded signal with rotation.

This happens because the deviation of the resonator resonance frequency can exceed the spectrum of the interrogation pulse and the width of the resonator frequency response. With a strong shock the received interrogation signal after FM demodulator has a disturbed shape (Fig. 9) at the start, while the vibration amplitude is large. The spectrums of demodulated FM recorded signal for the cases with and without rotation are shown in the Fig. 10 and 11.

Note, that the spectrum has a larger ratio of the second harmonic to the main harmonic in the case of the experiment with rotation. This feature corresponds to faster decay of the time domain signal in Fig. 9(b) if compared to Fig. 9(a) close to the start of the vibration. Such signal shape can be attributed to vibration exciting hammers difference (a soft and heavy hammer for experiments without rotation against a rigid and light hammer for experiments with rotation). The spectrum of the output signal also contains the rotation related contribution.

The first approach to data acquisition, although applicable only to room temperature experiments, has shown a better frequency resolution (0.005% in initial experiments) and a larger dynamic range of measured vibration amplitudes than the interrogation with external signals.

Conclusion

Using the sensor in the feedback circuit of the oscillator allows to receive an FM signal with a stable level of amplitude and a high signal-noise ratio. This ensures a good frequency resolution of the demodulated signal, and a large dynamic range of vibrations due to the described signal registration technique. The signal from the oscillator with a power of 10 μW could be detected at a distance exceeding 10 meters. Nevertheless, when detecting vibration signals there is a need to consider means of protection from external sources of interferences. Also, the presence of active elements and of the battery limits the applications to normal conditions. If the environment does not allow using an oscillator, the same SAW-resonator sensor should be used in an alternative circuit with external signal interrogation, accepting that the signal-to-noise ratio will be substantially lower, the interrogation distance will decrease to several meters, the frequency resolution will drop as well as the measured vibration dynamic range. However, for many applications where the vibration signal level is higher than the existing noise and interferences, the external signal interrogation approach will be useful, especially for high temperature environments.

Acknowledgment

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