Wireless System for Structural Health Monitoring Based on Lamb Waves

U. LIESKE, A. DIETRICH, L. SCHUBERT
and B. FRANKENSTEIN

ABSTRACT

For comprehensive fatigue tests and surveillance of large scale structures, a structural health monitoring system based on Lamb waves in kHz range was realized and tested. The system is based on a wireless sensor network and focuses especially on low power measurement, signal processing and communication. Thereby we met the challenge of synchronizing the wireless connected sensor nodes with sufficient accuracy.

The sensor nodes were realized by compact, sensor near signal processing structures containing components for analog preprocessing of acoustic signals, their digitization, algorithms for data reduction and network communication. The core component is a digital microprocessor ARM Cortex-M3 von STMicroelectronics, which performs the basic algorithms necessary for data acquisition synchronization and filtering. Each node in the sensor network can be used for Lamb wave excitation by an arbitrary waveform generator of about 40V peak-to-peak voltage.

Four Sensor nodes where used to detect an artificial damage inside a CFRP plate.

INTRODUCTION

Structural damage on engineered structures like bridges, pipelines in chemical or power plants of any kind or transportation vehicles like aircrafts can significantly influence their operation safety and result in immense monetary loss or even loss of life. Therefore, structural health monitoring systems emerging into infrastructure, industrial and transportation environments where continuous monitoring of the overall integrity of a structure or at least on hot spots is highly desired.

Uwe Lieske, uwe.lieske@izfp-d.fraunhofer.de, phone +49 351 88815-558; fax +49 351 88815-509, Fraunhofer Institute for Nondestructive Testing, Maria-Reiche-Str. 2, D-01109 Dresden, Germany

Wireless systems for electro-mechanical impedance and strain monitoring mainly used in civil infrastructure have been developed and tested so far by Zimmerman et al [1] and Taylor et al [2] and others. A detailed review of wireless SHM sensor systems developed until 2005 was provided by Lynch and Kenneth [3] illustrating academic and commercially available wireless solution for structural health monitoring applications.

Beside electro-mechanical impedance and strain based diagnostic approaches, Lamb-wave based systems and methods for active and passive structural damage detection have been developed in recent years [4]. Lamb-waves are ultrasonic waves occur when one dimension of a structure is small compared to the wavelength of the propagating waves. Therefore, Lamb-waves are commonly used in plate and shell structures.

A passive SHM system uses only sensors and the ultrasonic waves are generated by the rapid release of energy from sources within a material. Acoustic emission (AE) can be used for monitoring structures regarding active damage even when ambient noise levels are extremely high. Sources of acoustic emission include fracture and plastic deformation.

An active SHM system based on Lamb-waves uses actuator transducers to excite ultrasonic waves that can travel long distances inside the structure. Ultrasonic waves are reflected by surfaces and interfaces, attenuated by dispersion and absorption, and undergo mode changes during reflection and transmission. These effects depend strongly on the frequency of the wave, its direction of propagation, its initial mode, and the location and orientation of surfaces and damage. When damage has occurred to a structure, changes in the signal and therefore the acoustic signature can indicate the type of damage like cracks and delaminations [5]. By pre-calculating the expected changes in the signal from given types and degrees of damage, the damage can be evaluated from active Lamb-wave measurements also known as acousto ultrasonic measurements (AU) and even located by employment of total focusing techniques on the measured data [6]. This kind of measurements is repeated according to the expected increase of the damage extend under the actual environmental and structural loads.

A high spatial resolution is achieved by using high frequencies with the disadvantage of shorter possible travel paths. The propagation velocities of the ultrasonic waves are temperature and load dependent and the damage might also be load dependent. Therefore, calibration in the undamaged state (baseline) must be measured to describe the undamaged situation at different load levels and temperatures.

The active SHM approach based on Lamb-waves is most suitable for wireless sensor systems, because measurements can be carried out on demand, whereas the sensor nodes need to be on-line all time for an acoustic emission approach, which causes a battery based power supply to be drained rapidly.

So far, only a minority of the developed wireless systems make use of guided waves for damage detection. Dondi et al [7] and Dürager et al [8] have developed sensor systems for active Lamb-wave actuation and sensing recently.

HARDWARE

The sensor network is built around the commercially available ZWIR4511 transceiver modules provided by ZMDI. The modules integrate an IEEE802.15.4 compliant transceiver (TRX) with a powerful ARM Cortex M3 microcontroller (MCU). The complete radio front-end is integrated. The transceiver performs analog and digital radio processing and implements parts of the medium access control (MAC) layer. The microcontroller implements the remaining part of the MAC and the higher protocol layers.

Actuation Circuit

The analog front-end provides the functionality that is needed for excitation and sensing of guided waves based on piezoelectric Lead-Zirconate-Titanate (PZT) transducers. Piezoelectric transducers are usually excited by windowed tone-burst signals with peak to peak voltage (Vpp) of several decades of volt for Lamb-wave generation. Therefore, an arbitrary waveform is created by the built-in 12bit digital-to-analog converter (DAC) of the ARM Cortex M3 microcontroller with a sampling frequency of up to 1MSample/sec. The waveform is passed through a 1 kHz high-pass (HP) filter and amplified by two differential amplifiers. Both amplifiers (LT1795 from Linear Technology) are connected in a bridge circuit where one amplifier is inverted and the other one is non-inverted to generate a maximal excitation voltage of 24Vpp. The supply voltage for the differential amplifiers is created by a step-up switching regulator (LT1961 from Linear Technology). The amplified signal is passed through a 1 MHz low-pass (LP) filter for smoothing.

Sensing Circuit

For sensing, the sensor node measures the voltage signal from the piezoelectric transducer. The voltage generated by the piezoelectric transducer is passed to a pre-amplifier (LT6234 from Linear Technology) which acts as impedance converter and band-pass (BP) filter (10 kHz – 1 MHz). A variable gain amplifier (LT6910-1 from Linear Technology) is connected to the ARM Cortex M3 microcontroller and can be programmed to allow signal amplification from 0dB up to 40dB. Another low-pass filter at 1MHz is used to remove unwanted signal information above the sampling rate. The sampling frequency of the built-in 12bit ADC of the ARM Cortex M3 microcontroller is MSample/sec. All analog components can be powered for low power consumption when neither sensing nor excitation is needed.

Transceiver Module

The ZWIR4501 is a fully integrated system-on-chip CMOS transceiver providing license-free multi-channel operation in the 868.3 MHz (EU) and 902 MHz to 928 MHz (North America) ISM bands. This low-power RF transceiver is optimized for data rates up to 40 kbit/s and incorporates direct sequence spread spectrum technology (DSSS) to ensure reliable data transfer in hostile RF environments. Key-features of the wireless sensor nodes for active SHM application are summarized in Table 1.

Table 1. Technical specification of wireless sensor system.

Monitoring Method	Guided Waves (active)
ADC Resolution	12bit
ADC Sampling Rate	up to 1 MS/s
DAC Resolution	12bit
DAC Sampling Rate	up to 1 MS/s
Microcontroller	ARM Cortex-M3
Actuator Voltage	24Vpp
Dimensions	Prototype 100 mm x 100 mm
Power requirements	50 mW (standby), 300 mW (sensing, data transmission), 735 mW (actuating)
Range	100+ m
Trigger Jitter	~1µs

Figure 1 shows one prototype sensor node that consists of one analog and one digital circuit board mounted onto a motherboard and powered by a Lithium-Polymer battery (4.2V, 1500mAh).

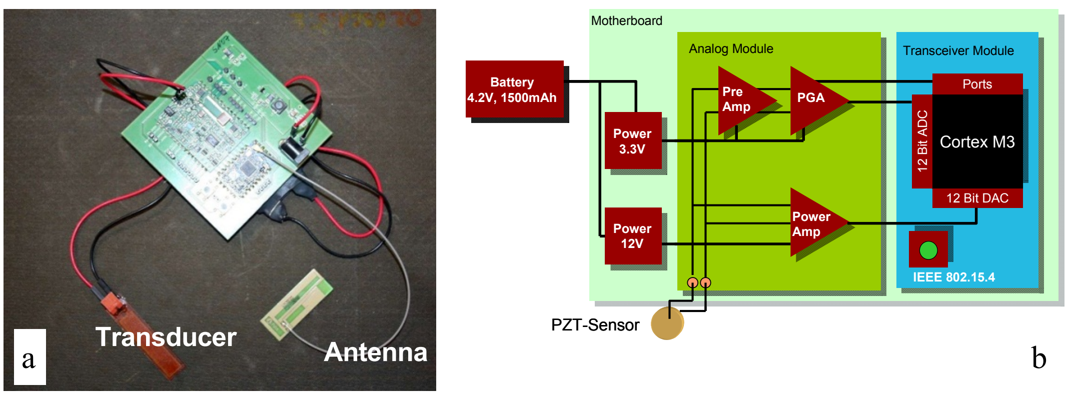

Figure 1. Sensor node prototype (a) and hardware schematic (b).

Sensor Network Layout

The sensor network is meant to have distributed sensor nodes along the structure und surveillance. One of the sensor nodes acts as gateway for an on-site system base station, where the user can remotely setup the sensor nodes using the Ethernet in WAN and LAN, make measurement schedules or collect the data from the system base station. This system base station can be a commercially available personal computer or an embedded device connected to the gateway node

EXPERIMENTAL TEST

For demonstration purposes, four piezoelectric transducers (DuraAct, 51mm x 11mm x 0.5 mm from PI Ceramic) where attached to a CFRP plate and connected to the sensor nodes. The thickness of the plate was 4 mm. An “artificial damage” was introduced by attaching a small steel test piece (Ø 10 mm) to the specimen to create two different structural states in the travel paths of the Lamb waves. The prepared specimen is shown in **Figure 2**.

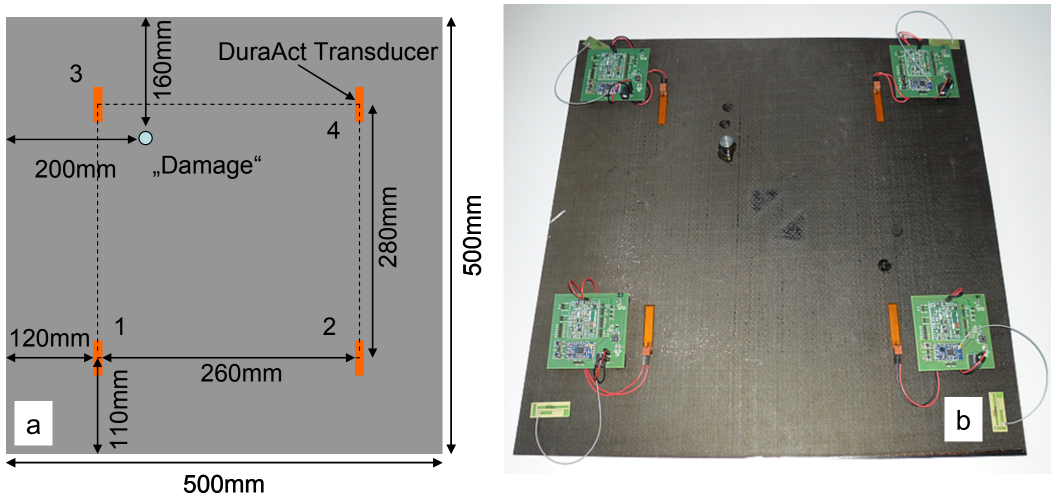

Figure 2. Prepared specimen.

The excitation waveform was a windowed (Hanning) tone burst signal (raised cosine) with 4 cycles. The center frequency was 20kHz and the excitation amplitude was 24 Vpp. The sensor gain was set to 20 dB. The results of two pitch-catch paths are shown in **Figure 3**. The signals show a good signal to noise ratio and the damaged and undamaged state could be clearly distinguished.

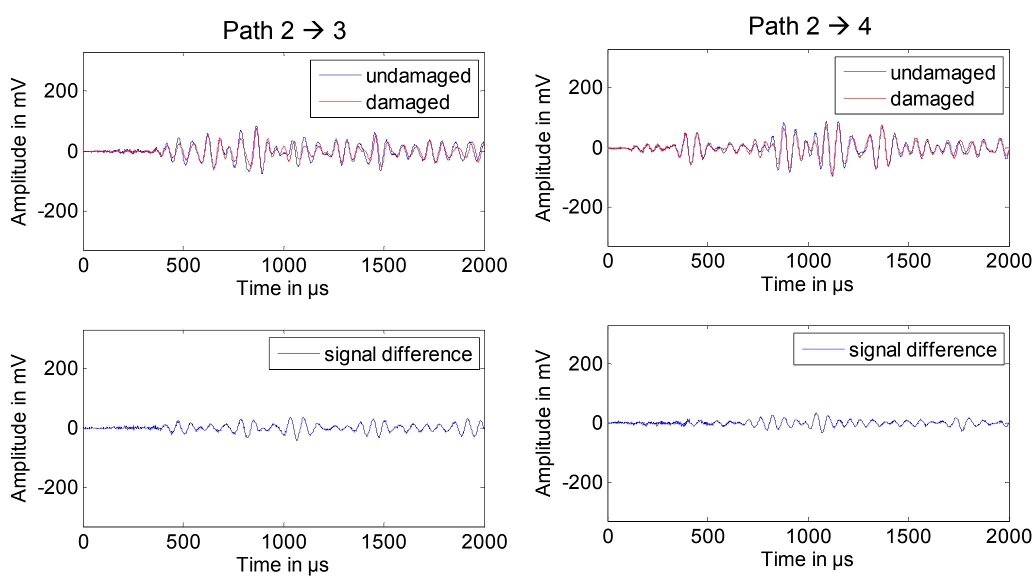

Figure 3. Sample measurements with RC4, 20kHz, 1MS/s for undamaged and "damaged" condition.

One important aspect of SHM application using Lamb waves is the synchronization of the different sensor nodes to measure or transmit at exactly the same time. Therefore the sensor nodes are triggered by a transceiver signal from the gateway node the causes an interrupt on each sensor node. This interrupt is used for triggering and the jitter was thereby minimized to typical values around 1 µs.

Beside the functional validation of the wireless sensor network, another important aspect is the power consumption of the wireless sensor nodes. **Figure 4** illustrates the power consumption for typical measurement scenarios.

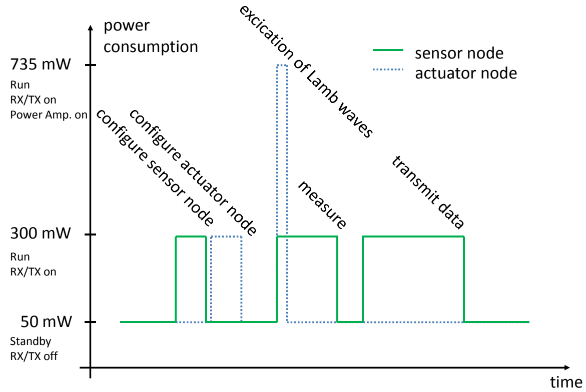

Figure 4. Power consumption for different activities during a common measuring usage.

The sensor requests periodically setup information from the gateway node. If a measurement is planned until the next request, the gateway node provides the setup information and waveform to the requesting node. Power consumption during the standby is 50 mW mainly caused by analog board components. During the request, the sensor node is set in run mode and the transceiver is powered on, which will cause the largest part of the consumed power. For excitation of a Lamb wave, the power consumption raises up to 735 mW due to the power amplification of the DAC generated waveform. However, this duration equals several microseconds depending on the chosen waveform.

SUMMARY AND OUTLOOK

The developed wireless sensor system for an active Lamb wave based SHM system has proofed its ability to excite and receive ultrasonic waves with a remarkable signal to noise ratio even on structures with high damping values. The sensor network is highly scalable. The number of sensor nodes is only limited by the transceiver range.

Future work will address the reduction of the standby power consumption and the improvement of the transceiver based wireless synchronization issues.

ACKNOWLEDGEMENT

This research was funded by the VDI Technologiezentrum GmbH in the project “CoolSensorNet” with grant no. 13N10261 within the CoolSilicon leading-edge cluster framework.

REFERENCES

1. Zimmerman, A., Lynch, J.P., Zussman, G., Rubenstein, D., "An Intelligent Wireless Structural Health Monitoring Solution" Proceedings of the 8th International Workshop on Structural Health Monitoring, Stanford University, Stanford, CA September 13 – 15, pp. 2004 – 2011 (2011).
2. Taylor, S.G., Farinholt, K. M., Flynn, E. B., Figueiredo, E., Mascarenas, D. L., Moro, E. A., Park G., Todd, M. D. and Farrar, C. R, "A mobile-agent-based wireless sensing network for structural monitoring applications", Meas. Sci. Technol. 20, 045201 (2009).
3. Lynch, J.P., Kenneth, J.L., "A summary Review of Wireless Sensors and Sensor Networks for Structural Healt Monitoring", The Shock and Vibration Digest, 38, 91 (2006).
4. Su, Z., Ye, L., Lu, Y. "Guided Lamb waves for identification of damage in composite structures : A review", Journal of Sound and Vibration, 295, pp. 753-780 (2006).
5. Köhler, B., Schubert, F. and Frankenstein, B., "Numerical and experimental investigation of Lamb wave excitation, propagation, and detection for structural health monitoring", Proceedings of the 2nd European Workshop on Structural Health Monitoring, Munich, Germany, July 7-9, Eds.: C. Boller, W. J. Staszewski, pp. 993-1000 (2004).
6. Schubert, L., Schwerz, R., Leibowitz, M., Lieske, U., Frankenstein, B., "Guided wave based SHM approach using SAFT-algorithm for impact detection in composite materials", Proceedings of the 8th International Workshop on Structural Health Monitoring, Stanford University, Stanford, CA September 13 – 15, 2011, pp. 1948 – 1955 (2011).
7. Dondi, D., Di Pompeo, A., Tenti, C., Rosing, T.S., "Shimmer: A wireless harvesting embedded system for active ultrasonic Structural Health Monitoring", IEEE SENSORS 2010 Conference, November 1-4, pp. 2325 – 2328 (2010).
8. Dürager, C., Heinzelmann, A., Riederer, D., "Wireless Sensor Network for Guided Wave Propagation with Piezoelectric Transducers", Proceedings of the 8th International Workshop on Structural Health Monitoring, Stanford University, Stanford, CA September 13 – 15, pp. 2028 – 2034 (2011).