AN INTELLIGENT STAND-ALONE ULTRASONIC DEVICE FOR MONITORING LOCAL DAMAGE GROWTH IN CIVIL STRUCTURES

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ABSTRACT. For aged, in-service civil structures, continuous structural health monitoring is vital to avoid catastrophic failure. This includes monitoring local damage growth at points crucial to the structure's stability. While traditional ultrasonic devices are well-established for scheduled local human inspections, they are ineligible for continuous monitoring. The objective of this research is to develop a stand-alone, self-contained, compact ultrasonic device for continuous structural health monitoring of civil structures. The battery powered device integrates small ultrasonic transducers with a compact high speed data acquisition and processing unit and a wireless communication device. Rayleigh surface waves, generated by the device, will be used to detect and assess surface cracks. This study, documenting the ongoing development, presents a concept for the functional layout of the ultrasonic device. It also examines a method for the assessment of surface breaking damage using Rayleigh waves in a simulated environment. The examination is under the limitations on power levels that can be supplied by batteries. The ultrasonic device may later be combined with global approaches, like analysis of vibration signals, to increase the sensitivity of damage detection in order to avoid catastrophic failures.

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INTRODUCTION

The service life time of civil infrastructure is typically on the order of several decades. During this period, a structure's condition gradually deteriorates due to environmental influences and mechanical loading. Failures of civil infrastructure, often with fatal consequences, demonstrate the risks that are associated with such slow degradation. To avoid these consequences, continuous monitoring of damage growth can be used to react to critical situations in time. This study proposes a new concept for continuous ultrasonic monitoring of local damage growth in steel, which can be applied to a variety of civil structures.

As an example for the degradation of civil structures, consider bridges in the United States of America. The National Bridge Inventory (NBI) lists over 600,000 bridges, 71,469 (or 12 %) of which are classified as structurally deficient [1]. For bridges that are more than 40 years old, the percentage of structurally deficient bridges is even higher: close to 60,000 (or 20 %) of a total of about 300,000 bridges are structurally deficient (cf. data given in [2]). These example figures demonstrate the need for regular inspections of bridges, which are commonly performed every 48 months. These human inspections are mainly visual, and are very time- and labor-intensive; additionally, the results obtained from visual inspections are subjective, and the classification of damage varies significantly among different examiners, as a recent study [3] shows. Visual inspections also only have the potential to detect damage at the surface, so internal damage may remain undetected.

To obtain reliable and objective results, many structural health monitoring (SHM) techniques have been proposed (e.g. [4, 5, 6]). One possible approach for SHM calculates the modal response of a structure based on stress, strain, or acceleration data acquired by a network of sensors that are spread over the structure. Changes in the modal behavior can be used to assess the structural health of the structure. However, these global approaches are insensitive to local failures, and may miss the critical growth of local damage. Thus, global SHM approaches need to be supplemented with local approaches to increase their sensitivity.

A well-established local examination technique is to use ultrasonic waves for damage detection in solid materials. Current ultrasonic methods are suitable and often used for manual human inspections. However, commercial ultrasonic equipment usually is supplied by the power grid. Due to its size, weight, and cost, this equipment is usually not suitable for permanent deployment on a structure for continuous monitoring. Shortening the intervals between manual human inspections is not feasible due to the associated labor costs. Thus, a device which is suitable for permanent deployment is needed.

Existing global SHM systems for the short-term inspection of a civil structure usually consist of a central data acquisition device, to which sensors are wired. Such a centralized approach requires running long cables from the data acquisition device to the sensors all over the structure, which is expensive in terms of both time and money. Installation of such a tethered SHM system typically takes up to over 75 % of the total testing time [7]. Considering the costs, Çelebi approximates typical expenses of an SHM system to be $ 1,000 per sensing channel with additional costs of $ 2,000 per channel for the installation [8]. As one alternative, Straser and Kiremidjian [7] demonstrate the feasibility and cost-effectiveness of wireless SHM systems in order to reduce the costs associated with the installation of tethered systems. Wang et al. [9, 10, 11] develop a distributed sensor network, which consists of multiple compact, self-contained data-acquisition and processing devices that run off batteries and that communicate over a wireless connection, which eliminates the need for cabling. Lynch, Wang et al. [12, 13] demonstrate that the performance of this device in field tests is comparable to the performance of a commercial tethered system. Wireless transmission in these cases offers a suitable alternative to avoid running long cables.

Ultrasonic examination techniques differ from the previously described SHM techniques in two major points: firstly, the signals obtained in the SHM techniques typically lie in the Hertz to low Kilohertz range, for which sampling rates on the order of tens to hundreds of Kilohertz are sufficient. Ultrasonic signals, however, by definition are signals with frequencies above 20 kHz and need sampling rates on the order of several Megahertz. Secondly, most SHM systems contain passive devices as far as measurements are concerned, i.e. no test signals are generated, and signals are only acquired. Ultrasonic testing in contrast is an active technique, which requires the generation of sufficiently strong ultrasonic signals in the appropriate frequency range. A strong excitation signal will yield a strong output signal and a good signal-to-noise ratio. However, limited to batteries as power supply, a compromise between signal quality and power requirements must be found.

This study presents a concept for implementing ultrasonic monitoring methods on a small, battery-powered, self-contained device based on a digital signal processor (DSP), which uses a wireless link to communicate with a central server. For the ultrasonic monitoring of surface breaking cracks in steel, Rayleigh waves with a frequency of 1 MHz are used. This paper gives an overview of the functional layout for the device, documenting the current progress towards the development a fully autonomous device. The objectives of this research are: 1) to find suitable components, and to assemble them in an appropriate hardware setup for continuous ultrasonic monitoring; 2) to investigate a method for efficient low-power Rayleigh wave generation and detection using contact transducers to obtain a reasonable signal-to-noise ratio, and to experimentally demonstrate that this method is feasible for crack detection in steel; while 3) adhering to the limits in power supply as imposed by the use of batteries.

To illustrate the feasibility of the proposed ultrasonic measurements, experiments are conducted with a test specimen, in which notches of different depths have been cut. Using commercial equipment and comparable power level as intended for the compact device, the forward scattered field of Rayleigh waves that are scattered at these notches is measured. The signals are only analyzed from a phenomenological point of view; obtaining a quantitative relation between signals and crack dimensions is beyond the scope of this work.

FUNCTIONAL CONCEPT AND HARDWARE LAYOUT OF THE DEVICE

This section describes the basic functional concept and introduces the hardware setup. The functionality of the ultrasonic monitoring device can be split into three main parts: *1) generation* and *2) detection of ultrasonic signals*, and *3) communication with a central server*. Figure 1 shows the basic layout of the device, introducing the separate parts. The parts are assigned to their respective functional part, as indicated by the vertical separation. For the ultrasonic device, a *Texas Instruments* digital signal processor (DSP) is used. Besides a microprocessor, this DSP also includes an analog-digital converter, used for signal detection, a

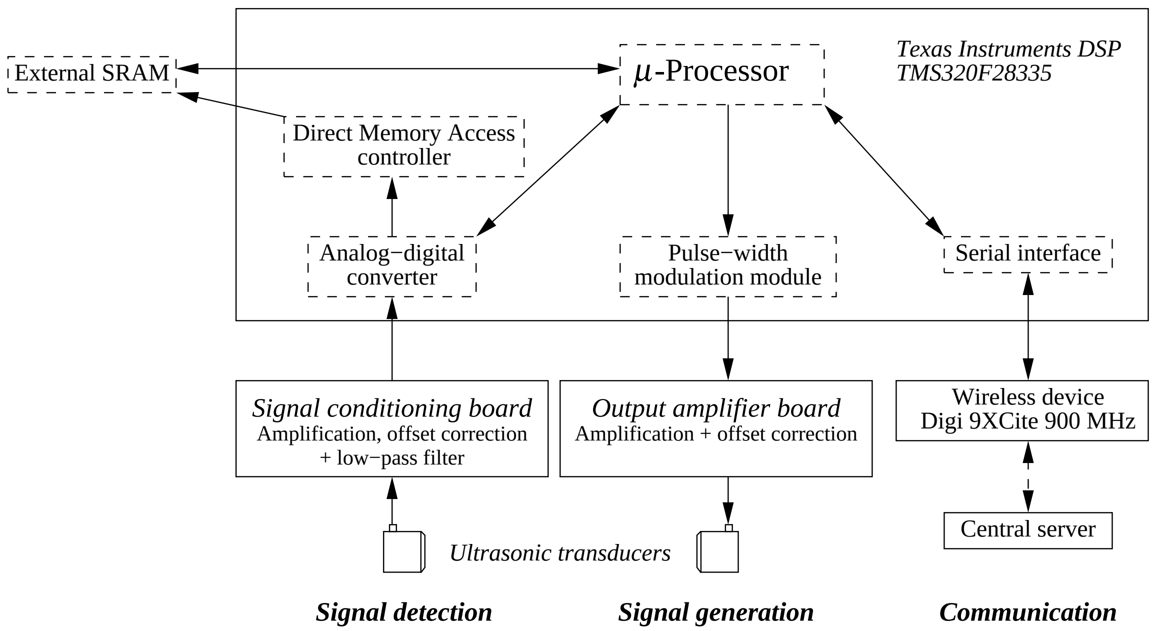


FIGURE 1. Functions and parts of the device. The signal path to the left illustrates the signal detection, the signal path in the middle the signal generation. The wireless device to the right in the figure enables communication with a central server.

pulse-width modulation module, used to generate ultrasonic signals, and a serial interface to which a commercial wireless radio is connected. Commercial ultrasonic contact transducers (*Panametrics A103*) are used to generate and detect ultrasonic waves in the specimen. Conversion between longitudinal and Rayleigh waves is achieved by contact wedges, as will be explained later.

Firstly, consider the *signal generation*: the pulse-width modulation module generates an electric square wave burst signal with a frequency of 1 MHz and a configurable number of cycles. The output alternates between 0 V and 3.3 V. In order to achieve a good signal-to-noise ratio in the output signal, an output amplifier circuit is employed, which is intended to boost the electric output signal to a symmetric level of about ± 18 V, a voltage level which can be supplied by batteries. Feeding a square wave signal into the ultrasonic transducer will yield a sinusoidal output signal, as the transducer acts as narrowband bandpass filter, which only passes frequencies close to its center frequency of 1 MHz.

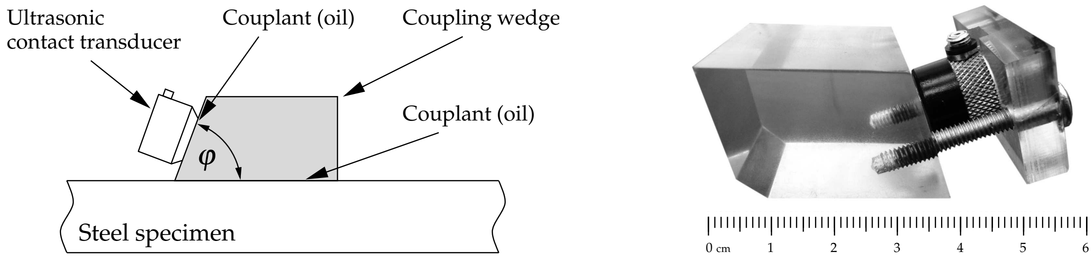
Secondly, consider the *signal detection*: a second contact transducer, attached to a contact wedge, detects the propagating wave field in the specimen in a pitch-catch setup. For the input of ± 18 V, the measured output will be on the order of 300–400 mV. To achieve a good signal-to-noise ratio in the sampled signal, the output of the transducer is amplified and offset corrected in a signal conditioning circuit to span a large portion of the 0–3 V input range of the analog-digital converter (ADC), which also mitigates the influence of sampling errors. The circuit also includes a low-pass filter to prevent aliasing effects in the sampled signal. The ADC runs at a sampling rate of 8.3334 MHz and offers a resolution of 12 bit over its 0–3 V input range. Following the Nyquist-Shannon sampling theorem, this sampling rate is sufficient to fully reconstruct signals from the sampled data if their highest frequency content is below 4.1667 MHz. This sampling rate therefore is sufficient to acquire the band-limited signals from the ultrasonic transducer. A Direct Memory Access (DMA) controller transfers the sampled data from the ADC output registers into the external SRAM, bypassing the CPU for the data transfer. This allows for a reliably fast data transfer and avoids problems that might occur when the CPU is swamped with other tasks.

Lastly, consider the *communication* module: for the wireless communication with a central server, the device includes a commercial *Digi 9XCite OEM RF Module*. This module provides communication with a continuous data stream of up to 38400 bps over a distance of up to 90 m indoors or up to 300 m outdoors line-of-sight with its 2.1 dBi dipole antenna attached. Operating in the 902–928 MHz ISM (industrial, scientific and medical) radio band with a transmit power of 4 mW, the wireless device can operate in North America, Australia and Israel without the need for an individual license. Compared to 2.4 GHz devices, which can be used worldwide, 900 MHz devices typically offer longer range communication while consuming less power [14]. Communication between the wireless module and the microprocessor uses the UART (universal asynchronous receiver/transmitter) interface of the DSP and a serial data transfer protocol. The use of this standardized protocol renders a specific driver for the communication unnecessary and so enhances the portability of the approach.

ULTRASONIC MEASUREMENTS AND PRELIMINARY RESULTS

Rayleigh wave generation using contact wedges

To generate Rayleigh waves, commercial *Panametrics A103* narrowband ultrasonic contact transducers are attached to coupling wedges, as shown in Figure 2. Contact methods are preferable over non-contact methods for the intended application of the ultrasonic device, as they allow for efficient energy transmission, and are less prone to errors caused by environ-



(a) Setup for Rayleigh wave generation **(b)** Wedge with attached transducer

FIGURE 2. Generation of Rayleigh waves using a contact transducer and a coupling wedge.

mental influences as long as a sufficiently tight mechanical contact between transducer and wedge, and also between wedge and specimen is ensured. The contact transducers generate longitudinal waves. If the angle φ of the front surface of the wedge is cut at the appropriate angle, the longitudinal waves in the wedge are converted into Rayleigh surface waves in steel. Neglecting the thin couplant oil layers, *Snell's law* directly yields the necessary angle φ:

$$\sin\varphi = \frac{c_{\mathrm{L}}^{\mathrm{W}}}{c_{\mathrm{S}}^{\mathrm{R}}}, \tag{1}$$

where $c_{\mathrm{L}}^{\mathrm{W}} = 2750\,\mathrm{m/s}$ is the longitudinal wave speed in the wedge, and $c_{\mathrm{S}}^{\mathrm{R}} = 2963\,\mathrm{m/s}$ the Rayleigh wave speed in steel. The resulting angle is $\varphi = 68.1^\circ$. It can be shown, that this contact wedge method in theory only gives rise to a Rayleigh wave in steel, but not to bulk waves. Note that the longitudinal wave speed in the wedge material must be lower than the Rayleigh wave speed in steel. Plexiglass, which is used for the wedges, is one of the materials which fulfill this condition. This material additionally features a low attenuation.

Comparing the principle schematic in Figure 2a to the picture in Figure 2b, note that the opposite end of the wedge is not cut at a right angle to the bottom surface. This is to mitigate spurious signals that arise from reflections inside the wedges.

Test specimen and measurement setup

To demonstrate the feasibility of the intended ultrasonic measurement device with the power restrictions as imposed by the use of batteries, measurements of a test specimen are taken, using commercial off-the-shelf ultrasonic equipment. For the test specimen, notches of different depths have been cut into a steel plate (241 mm × 152 mm × 25.3 mm) using electrical discharge manufacturing (EDM) to simulate surface breaking cracks. Table 1 lists the dimensions of the notches. The height of the the steel plate is much larger than the Rayleigh wave length of 2.9 mm for a 1 MHz ultrasonic wave in steel, which justifies the assumption of an elastic half space for the propagation of Rayleigh surface waves. The notches' positions on the steel plate allow for an examination of one notch at a time without interference from reflections from edges or other notches.

TABLE 1. Dimensions of the notches cut into the test specimen (measured using calipers)

No.	Depth D (mm)	Width w (mm)	Length l (mm)
1	0.5	0.58	9.3
2	1.2	0.58	9.4
3	2.3	0.63	9.3
4	3.2	0.70	9.3

To examine the forward scattered wave field of an incident Rayleigh wave at a notch, two transducers together with their coupling wedges are set up on both sides of a notch in a pitch-catch setup. For the wave generation, a *Agilent 33250A* signal generator generates a 1 MHz sine wave burst, which is amplified by a *ENI 325LA RF Power amplifier* to an output level of ± 15 V before being fed into the transducer. This output level is slightly higher than the resulting output for the ± 18 V square wave signal, though it can also easily be achieved be extending the battery supply. On the detection side, the amplifier that is included in a *Panametrics 5058PR pulser/receiver* amplifies the signals received by the transducer to the desired level of -1.5 V to 1.5 V. This range corresponds to the input range of the analog-digital converter (ADC) when the DC offset is neglected. The amplifier gain during the measurements does not exceed 20 dB. The amplified signal is fed into a *Tektronix TDS 5034 digital storage oscilloscope* which digitizes and saves the data with a sampling rate of 500 MS/s. For an analysis of the influence of the lower ADC sampling rate, the recorded signal could be later downsampled to match the sampling rate of the ADC.

Measurement results

As an example for signals obtained from different notches, Figure 3 compares the signal from the undamaged specimen (Fig. 3a) to the signal detected from the 1.2 mm deep notch (Fig. 3b). Several propagation paths can be distinguished: *after 31* μs, the direct Rayleigh wave arrives, which creeps along the rim and the sides of the notch; *after 47* μs, a signal that arises from the conversion of the Rayleigh wave to a shear wave at the bottom of the notch is detected. This signal is reflected at the bottom of the steel plate and converted back to a Rayleigh wave at the notch. *After 55* μs, a creeping Rayleigh wave signal is detected that arises from reflections inside the wedge. The mode converted shear wave is not only reflected at the bottom surface of the steel plate, but also at the top, so that *after 63* μs a double-reflected (bottom-surface-bottom) mode converted wave arrives. Note that the Rayleigh wave arising from the reflection inside the wedge is most prominent for the undamaged specimen and is negligible compared to the amplitudes of the other signals for the 1.2 mm deep notch. Though not shown here, note that the same effects are observed for the other notches as well.

Comparing the plots as obtained from both measurements, it can be seen that the ampli-

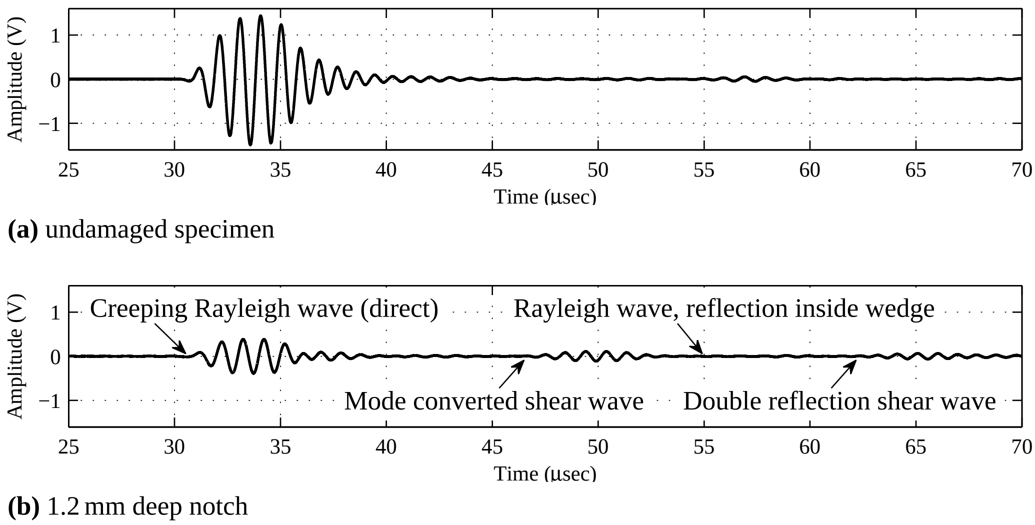


FIGURE 3. Ultrasonic measurement signals in the time domain for different notch depths, taken with commercial ultrasonic equipment.

TABLE 2. Amplitude ratios, direct signal over mode converted reflected signal

Measurement no.		Notch depth			
	undamaged	0.5 mm	1.2 mm	2.3 mm	3.2 mm
1	72.8	52.5	3.47	2.61	6.28
2	62.1	45.8	3.77	2.64	8.62

tude of the creeping Rayleigh wave decreases and the amplitude of the mode converted shear wave increases with increasing notch depth. This indicates that the amplitude ratio of these two signals, defined as the ratio of the maximum absolute values of the respective signal bursts, might be used to assess the severity of damage. Table 2 lists the amplitude ratios for different notch depths as found during two sets of measurements. The results are comparable between both measurements. The only outlier is the 3.2 mm deep notch, for which the amplitude ratios unexpectedly increase. It is assumed, that the geometry of the notch is different from the other notches due to imperfections in the EDM process, which leads to a different wave scattering pattern. Nevertheless, the obtained results show that the intended power levels are sufficient for ultrasonic monitoring, and the numeric results support the assumption that the amplitude ratios may be used to assess the severity of surface breaking damage in steel.

CONCLUSIONS

This study examines the applicability of continuous ultrasonic monitoring of surface breaking damage in steel using a small, battery-powered, self-contained device. It documents the current progress towards an autonomous device. Rayleigh waves with a frequency of 1 MHz are used for the ultrasonic monitoring. A concept for the design of a device for generating and detecting these waves is proposed. The sampling rate of 8.3334 MHz provided by the conceptual device is sufficiently high to digitize the band limited output signal of the narrowband transducer, as well as to acquire all information provided in these signals.

This study also presents a contact wedge method to generate Rayleigh surface waves in steel. Rayleigh waves have the advantage of a lower geometric attenuation over bulk waves, as their energy is confined to a small layer at the surface. The method presented for Rayleigh wave generation is very efficient, which enables ultrasonic measurements even when the possible excitation voltages are limited by the use of battery supply. The measurements taken with commercial ultrasonic equipment show that the proposed ultrasonic examination technique is applicable. This study includes a mainly phenomenological analysis of the measured forward-scattered wave field. For future work towards a completely autonomous damage assessment, methods which allow for a strict and reliable quantitative assessment of the severity of damage have to be examined.

Communication of the device with a central server is realized using a wireless connection, which can send data over a distance of up to 300m. The wireless transmission channel eliminates the need to run long cables on the structure, which saves a considerable amount of time and money.

This study shows that continuous ultrasonic monitoring using a compact, battery-supplied device is possible. In future work, signal processing algorithms and efficient power saving technologies will be taken into consideration. The device implementation and validation will also be reported in the near future.

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