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PPM-based system for guided waves communication through corrosion resistant multi-wire cables

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Abstract

Novel wireless communication channels are a necessity in applications surrounded by harsh environments, for instance down-hole oil reservoirs. Traditional radio frequency (RF) communication schemes are not capable of transmitting signals through metal enclosures surrounded by corrosive gases and liquids. As an alternative to RF, a pulse position modulation (PPM) guided waves communication system has been developed and evaluated using a corrosion resistant 4H18 multi-wire cable, commonly used to descend electronic gauges in down-hole oil applications, as the communication medium. The system consists of a transmitter and a receiver that utilizes a PZT crystal, for electrical/mechanical coupling, attached to each extreme of the multi-wire cable. The modulator is based on a microcontroller, which transmits60 kHz guided wave pulses, and the demodulator is based on a commercial digital signal processor (DSP) module that performs real time DSP algorithms. Experimental results are presented, which were obtained using a 1m corrosion resistant 4H18multi-wire cable, commonly used with downhole electronic gauges in the oil sector. Although there was significant dispersion and multiple mode excitations of the transmitted guided wave energy pulses, the results show that data rates on the order of 500 bits per second are readily available employing PPM and simple communications techniques.

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*Keywords:*Guided waves; PPM communications; digital signal processing.

1. Introduction

Guided waves can travel large distances with little energy loss in rods-like structures, e.g. single wires and multiple wires cables, compared with the traditional body waves, which makes them appropriate for detecting structural damage over a wide range, and can be excited and received by bonded piezoelectric elements. Consequently, they have been used as an attractive and effective tool for structural health monitoring (SHM) of

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materials, since they can interrogate large structures as stated by Rose (2004) and Cawley et. al. (2009). The main building blocks of an SHM technology are sensors/actuators, data acquisition hardware and a communication platform. In many existing SHM applications, conventional schemes, such as wireless radio communication, have been employed for data transmissions. However, novel wireless communication channels are a necessity in harsh environments, for instance fixed offshore oilrigs and down-hole oil reservoirs as it has been shown by Marsh et. al. (2005). In these types of surroundings making use of existing infrastructure, for instance metal pipes, as a communication channel, is an asset that has been proposed by some researchers, Mijarez et. al. (2013) and Jin et. al. (2013). This work presents a guided wave pulse position modulation (PPM) system that uses a corrosion resistant 4H18 cable, commonly used as wire-line cable in downhole electronic gauges in the oil sector, as a communication channel. Experiments carried out using a multiple-wires 4H18 CAMESA cable, 1 m in length, have successfully detected in real-time PPM guided wave encoded information with data rates on the order of 500 bits per second.

2. Guided waves theory

4H18 cables are made of 4 copper conductors of 7 wires each, which are isolated by a plastic Poly. The cable is armored with 36 special galvanized improved plow steel wires as depicted in Figure 1a. However, due to the complicated characteristics such as inter-wire coupling, dispersive nature, multi-mode presence and mode coupling, an analytical solution that can describe the wave propagation in these multiple-wire cables does not exist. The approach taken to gain insight into the wave propagation in multiple-wire cables is to investigate wave propagation in single wires using a formulation based on the so-called Pochhammer frequency equation of a solid, isotropic, homogenous and traction-free cylindrical rod, which has been discussed in detail by Graff (1975).The solutions of the elastic equation of motion are known, and correspond to three types of modes: longitudinal L(0,m), torsional T(0,m) and flexural F(0,m). By solving the equations, via the commercial package Disperse©, developed by Pavlakovic et. al. (2003), for these vibration modes with known frequencies, the dispersion curves can be obtained. The dispersion curves relate the velocity of the guided wave propagation, to the frequency of the wave and the diameter of the cylinder.4H18 multi-wire cables have small gaps between the strands; hence, the cable was modeled as a rod made of copper 0.61 mm in diameter and surrounded by a 0.61 mm thickness of Poly as depicted in Figure 1b; thereby, the dispersion curves, using the software Disperse, were obtained as shown in Figure 1c.

2.1. Frequency and signal selection

Guided waves used in long range applications require the employment of frequencies below 100 kHz as demonstrated by Cawley et. al. (2003). The selection of a specific point on the dispersion curves depends on the frequency spectrum associated with the transducer source. This is of particular interest considering that PZT elements with normal beam loading and reception, respectively, have been used in this application. Hence, surface pressure loading will excite longitudinal modes and/or flexural modes depending on the applied pressure distributions on the cable surface. As Figure 1c shows, beyond 200 kHz the number of excited modes increase; hence the selection of the modes becomes difficult. Reducing the frequency of excitation will excite fewer guided wave modes; however, it exposes the overall system to greater risk of audio bandwidth interference, leading to a poor signal to noise ratio (SNR). Taking into account these factors, a PPM communication system that use tone pulse pulses of 60 kHz, for powering circular PZT elements, was implemented.

3. PPM guided wave system

The theoretical background of PPM communication systems was established around 50 years ago as it is shown by McAulay (1968);nevertheless, PPM has recently also been of interest in the field of impulse radio and fibre-optic transmission systems as was investigated by Azmia et. al. (2004). PPM is a form of signal modulation in which the message information is modulated in the time-delay between pulses (TDBP) in a sequence of signal pulses. The PPM that is implemented in this work consists of the displacement, of the temporal position of an acoustic pulse, quantified for small time-based values of $\pm\varepsilon$ in relation to a TDBP that is used as a time reference, t_r as implemented by Arnold(1993).

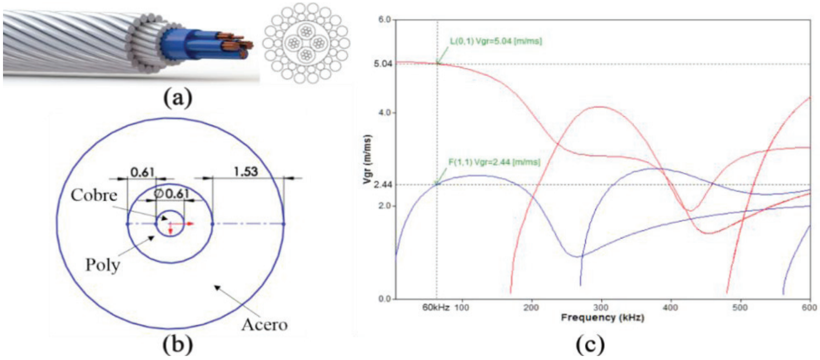

Fig 1. (a) Cable 4H18. (b) Simplified model of the cable 4H18 used to obtain dispersion curves. (c) Dispersion cuerves of a copper rod 0.61 mm in diameter, insolated by a Poly layer of 0.61 mm in thickness, and covered by a steel layer of 1.53 mm in thickness.

For displacements with increment of time +ε, the modulation stands for the logical level 1 (bit 1), and for displacements with decrement of time -ε the modulation represents the logical level 0 (bit 0). Figure 2a shows the example of a sequence of pulses that are not modulated, where each pulse is, exactly, in the center of a time slot, Δt. Figure 2b depicts a sequence of pulses moved ±ε, according to the PPM information, in a sequence of bits 1100.The experiment setup of the PPM guided wave system is comprised of a smart PZT microcontroller-based modulator, a 4H18cable as a communication channel and a DSP-based demodulator as depicted in figure 2c. The actuator/modulator design was based on a microcontroller, a signal booster, a single PZT element and a 9V battery. The PZT crystal was coupled to a copper plate, via silicone glue, and the cooper plate was soldered to the 4H18 cable.

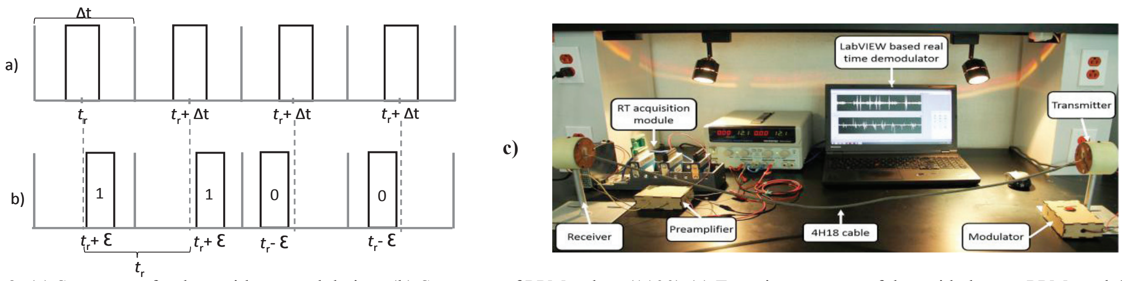

Fig. 2. (a) Sequence of pulses without modulation; (b) Sequence of PPM pulses (1100);(c) Experiment setup of the guided wave PPM modulator and demodulator communication system.

The modulator generated 10-bit frames of guided wave PPM encoded energy pulses. The frame begins with a start pulse, eight pulses of data and a stop pulse. The start and stop pulses are made of 40 square pulses of 60 kHz, i.e. 666µs pulse width each, and data pulses consist of 20 square pulses of 60 kHz, i.e. 333 µs. The time slot, Δt, and the quantified values of ±ε were set to 1998 µs and 999 µs, respectively, equivalent to six times and three times the actual bit representation pulse width. The PPM demodulator instrumentation package, comprises a PZT crystal that make use of the inverse piezoelectric effect; an instrumentation amplifier, which was established as a front-end signal conditioning element; and a National Instruments® PXI with a FPGA based acquisition board, with a sampling rate established to 200 kS/s, which was connected to a personal computer that performed real time signal demodulation using commercial software LabVIEW™. The DSP demodulator performed in real-time, a Finite Impulse Response (FIR) band pass digital filter with a bandwidth of 4 kHz, whose cut-off frequencies were 48 kHz and 62 kHz respectively, i.e. it was designed to operate with the 60 kHz PPM transmitted pulses. Subsequently, an auto-correlation was applied to the filtered signal to increase the SNR. A low pass filter with cut-off frequency tuned to the communication baud rate was executed to smooth out the auto-correlated signal. Finally, the root mean square (rms) value of the new filtered signal was computed to use it as a threshold to generate a continuous square pulse for each acoustic pulse received. The new digital signal was demodulated by the temporal position of the TDBP for each digital bit between the start and stop pulses.

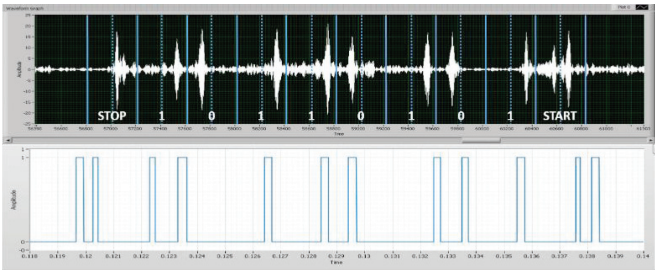

Fig. 3. Demodulation process of the PPM guided wave encoded system in real-time.

4. Experiments and results

The experiment was conducted to identify a transmitted PPM symbol of 8 bits information using the experiment setup shown in Figure 2c. The transmitter and receiver instrumentation were powered simultaneously. For this experiment the transmitter was set to generate continuously every 20ms an 8 bit data PPM symbol, containing the information ABH (1 0 1 0 1 1 0 1). The transmitted PPM symbol was successfully identified in real-time.Figure3depicts the demodulation process applied to identify the symbol in a 1m 4H18 cable, respectively. In the upper graphic, the signal corresponds to the filtered guided waves signals. The lower signal is the result of the signal processing autocorrelation process applied to the filtered signal. The auto-correlated signal was filtered by a low pass FIR filter with cut-off frequency of 55Hz and hamming window, equivalent to the transmission baud rate, and an rms value of the signal was obtained. The amplitudes of the signals were adjusted to the temporary delayed auto-correlated signal, for a proper visualization and identification.

5. Conclusions

A novel guided waves PPM system using multiple-wire 4H18 cables, commonly found as infrastructure in downhole electronic gauges in the oil sector, as communication channel has been designed, implemented and evaluated. Results show that by exploiting the wave-guide effect of multiple-conductors cables acting as communication channel, successful transmissions and reception of 60 kHz encoded PPM information has been attained in real-time. Although the trials have been conducted over small distances, the feasibility of detecting dispersive guided wave energy packets, provided sufficient SNR, has been proved. These results are very encouraging, taking the authors to the next stage of this work, which is to carry out automatic real time PPM demodulation using longer cables.

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