APARATURA
BADAWCZA I DYDAKTYCZNA

The prototype of an acoustic communication device for monitoring of water distribution networks

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ABSTRACT:

A plethora of monitoring systems of different technical objects exists nowadays. Some of the solutions are specifically designed for water supply networks. The main objective of the paper is to describe the use of acoustic signal modules for communication in pipeline systems, where water is used as the transmission medium. This idea is proposed as an alternative to methods used in Wireless Sensor Networks (WSNs) nowadays. The paper begins with short introduction to the research problem and WSNs in general. Further sections describe the concept of a node, methods of signal modulation and coding used during the research and a brief description of acoustic node prototype. Results of the preliminary tests together with the major conclusions and future research plans are discussed at the end of the paper.

Prototyp akustycznego urządzenia komunikacyjnego do monitorowania sieci wodociągowych

Słowa kluczowe: bezprzewodowa sieć sensoryczna, komunikacja akustyczna, system monitorujący

STRESZCZENIE:

Obecnie istnieje wiele rozwiązań systemów monitorujących różnorodne obiekty techniczne. Część rozwiązań jest projektowana specjalnie z myślą o sieciach wodociągowych. Głównym celem artykułu jest przedstawienie zastosowania modułów do komunikacji akustycznej wewnątrz rurociągu, w którym medium komunikacyjnym jest woda. Przedstawione rozwiązanie stanowi alternatywę dla obecnie wykorzystywanych metod komunikacji w bezprzewodowych sieciach sensorycznych (WSN). We wstępie krótko scharakteryzowano problem badawczy oraz opisano tematykę bezprzewodowych sieci sensorycznych. Kolejne sekcje opisują koncepcję węzła sieci sensorycznej oraz metody modulacji i kodowania sygnałów wykorzystane podczas badań, jak również przedstawiają prototyp węzła sieci. Końcowe akapity poświęcone zostały wynikom wstępnych badań, najważniejszym wnioskom i planowi dalszych badań.

1. INTRODUCTION

There is a multitude of different solutions used to monitor the health and working conditions of diverse technical objects. The research area described in the paper was narrowed down to WSNs used to monitor water distribution systems.

SmartFlow system [3] designed by the *Future Processing* is an example of an intelligent application for supervising WSNs, dedicated to water distribution networks. It was implemented in the city of Wrocław (Poland) in cooperation with the local water distribution network administrator (MPWiK) and the *Microsoft*. The system collects and processes data sent by radio transmission from wireless nodes deployed inside the pipeline. It analyzes then the data and displays statistics and alarms on the interactive map of the city. According to the *Future Processing*, the system contributed to the reduction of time required to detect the pipeline failure (e.g. leakage) to about 72 h and the yearly water losses by about 500 millions of liters.

An universal PLC-based telemetric module [7] is an example of device used as WSN node. The module consists of a low-power PLC with an embedded RF antenna. The PLC allows to connect and integrate industry-standard sensors, such as devices for pressure, flow or temperature measurement.

Another related solution is a group of microprocessor-based devices with integrated measurement and energy-saving systems, dedicated to use in water distribution networks [2, 8]. While it offers somewhat limited capability compared to the universal PLC-based modules, it is optimized for low power consumption and thus allows longer operation.

WaterWiSe@SG is an experimental WSN introduced in Singapore's water supply network [1]. It was designed to provide monitoring capabilities as well as a subject for further research. The WSN is made of 25 nodes. The node consists of a sensory module (a pressure transducer, a flowmeter and a hydrophone) mounted inside the pipeline and connected by wire with communication module. The communication module consists of a CPU with *Linux* OS, a battery and a solar panel and is placed above ground in near the sensors.

The features of the device includes a detection and localization of leakages by the high-frequency pressure sampling (up to 2 kHz), a fast transmission of data (up to 7.2 Mbps) via high-power USB 802.11b radio (at short distances) or an energy-efficient 3G modem and effectively maintenance-free operation.

The major problem of current solutions is accessibility. Most of the devices used nowadays communicate by wire or wirelessly via electromagnetic (EM) waves. Wireless EM communication requires careful placement of antennae, often in places with reduced accessibility. Deployment of monitoring devices in existing underground pipelines is also a demanding and costly task. An acoustic wave as the communication medium is already widely used e.g. in the oceanography or to control unmanned underwater vehicles (UUVs) [4]. As the acoustic communication system requires no additional external infrastructure, such as an antenna, it could be more easily maintained and deployed, becoming an alternative to EM-based systems.

2. CONCEPT OF AN ACOUSTIC WSN NODE

An acoustic WSN node consists of elements illustrated in Figure 1. The WSN node (1) is enclosed in measurement and diagnostics module (2), together with power source (3) and sensors (4), such as devices measuring the pressure, the flow or the temperature. The node consists of a receiver module, etc. Main elements of receiver module are at least one acoustic receiver (5), an amplifier (6) and a converter (7). A processing module consists of central processing unit (8), further abbreviated as CPU, and converter (9). The major parts of a transmitter module are at least one converter (10), an amplifier (11) and an acoustic transmitter (12).

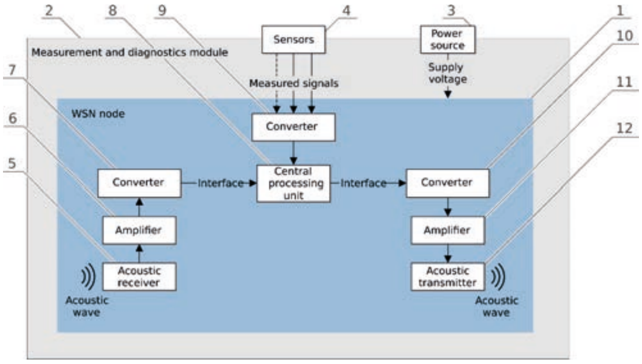


Figure 1 The concept of an acoustic WSN node [4]

The node sends data through water in a pipeline as a modulated acoustic wave. Acoustic receiver, e. g. a piezoelectric element, receives an acoustic signal as a mechanical wave of given properties. The signal is converted to an electrical representation, then it is amplified and converted (demodulated) to be processed by the CPU. The central processing unit receives also the data measured by the sensors. The data are processed and added to a data frame received from the previous node. The CPU modifies the data frame and sends it to the converter (modulator) and further to the amplifier. The electric signal is converted again to the mechanical form (e.g. via inverse piezoelectric effect) and transmitted to the medium as an acoustic wave.

3. SIGNAL MODULATION AND CODING

Two basic digital modulations were used during research: the Amplitude Shift Keying (ASK) and the Phase Shift Keying (PSK).

$$\varphi_{ASK} = \begin{cases} 0, X_n = 0 \\ A_0 cos(\omega_0 t), X_n = 1 \end{cases} \tag{1}$$

$$\varphi_{PSK} = \begin{cases} A_0 sin(\omega_0 t), X_n = 0 \\ -A_0 sin(\omega_0 t), X_n = 1 \end{cases} \tag{2}$$

The ASK modulation is given by the equation (1), where φ_{ASK} is a ASK-modulated signal, A_0 is the carrier amplitude, ω_0 is the carrier angular frequency [rad], $\omega_0 = 2\pi f_0$, t is the time [s] and X_n is the information symbol in nth tact [6]. The PSK modulation is given by the equation (2), where φ_{PSK} is a PSK-modulated signal [6].

For research purposes a simple coding pattern was designed. The pattern is simplified version of the Morse code. The coding pattern revolves around time base (tb) which is the length of the shortest impulse used in a data frame.

A digital one is encoded as a short high pulse with duration of 1 tb, while a long high pulse (3 tb) is assigned to logical zero. Initiation of a transmission (the beginning of a frame) is indicated by the high level pulse of 6 tb length. The transmission ends if the receiver detects low state for at least 3 tb. Between each impulse an interval of low 1 tb pulse is inserted.

Data between nodes is sent as frames with length of 34 characters. The first one indicates the beginning of a frame. Another 8 characters (bits) reference unique 8-bit address of a node. Next 8 bits are the 8-bit address of a sensor or other source of data inside given node. Then there is 16-bit value corresponding to the measurement of the sensor or other parameters that are sent by the node. The last character references the end frame indicator. Figure 2 illustrates an example of the frame.

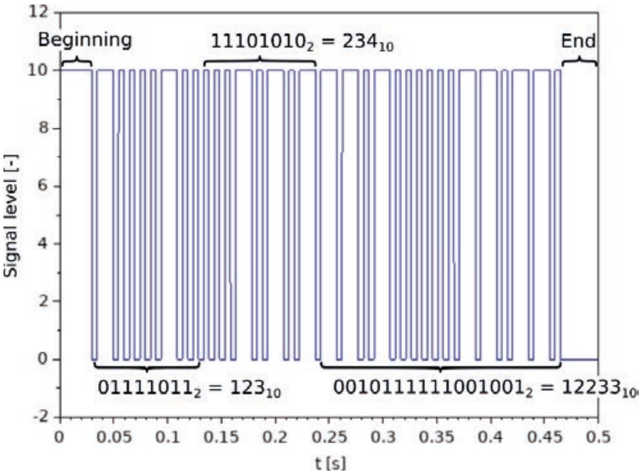


Figure 2 An example of a data frame [4]

4. CONSTRUCTION OF A PROTOTYPE

The prototype is loosely based on the structure of a waterproof ultrasonic transceiver MCUSD14A58S9RS-30C designed for automotive applications, shown in Fig. 3. The transceiver consists of a casing (1) made of milled aluminum alloy with a signal cable (2). The cable is soldered to a PCB (3) without any other electronic components and sealed with a silicon (4). The case is filled with rubber-like substance (5) and synthetic wool (6) used as acoustic dampers. A piezoelectric element (7) is located on the internal face of the casing. The casing also acts as a cathode and vibrating membrane of the transceiver.

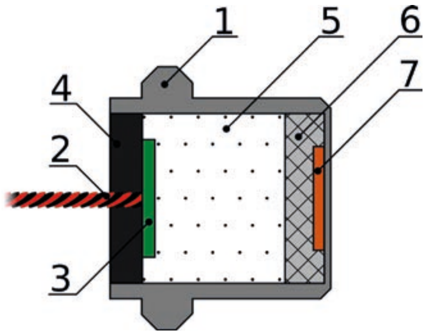


Figure 3 The internal structure of a MCUSD14A58S9RS-30C

The prototype of communication module is shown in Figure 4. To reduce the volume for research purposes, the module was designed to only have necessary components such as a receiver and a transmitter. Signal processing was carried out outside of the main body with use of a digital oscilloscope, a function generator and a PC. The transceiver module consists of two transceiver units (1 and 4) with mounting elements (2) to assure axial propagation of the acoustic waves in water, and a connector (3). The units are mounted together via threaded connections (5) to allow quick replacement and tightness. The body of both units was 3D-printed with ABS using FDM (Fused Deposition Modeling) / FFF (Fused Filament Fabrication) technology with other crucial elements chemically welded using acetone. The manufactured units were positively verified to be waterproof.

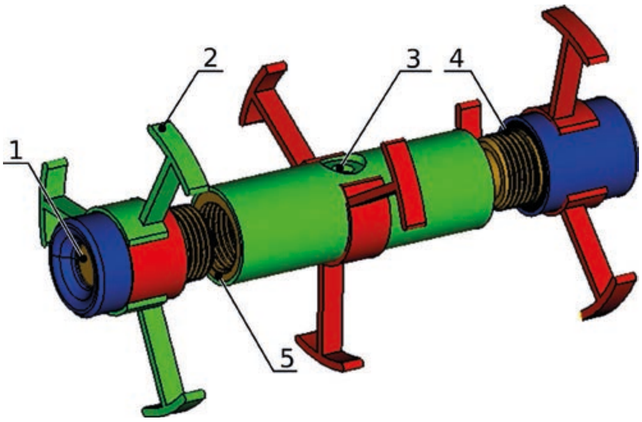


Figure 4 A view of the prototype model assembly [4]

5. VERIFICATION STUDY

The research was conducted in the laboratory with constant temperature of about 25°C. As none of the tests was made in reverberation chamber, some amount of environmental noise (e.g. from the apparatus) was expected. The tests were made mostly in a configurable laboratory stand made of press-fitted polypropylene piping elements as shown in Figure 5.

The general configuration of apparatus used during research can be viewed in Figure 6. A data frame is created offline on a PC and is sent to the arbitrary function generator. The generator creates a carrier wave with an amplitude of 20 V_{pp} and then modulates it using the saved data frame. The resulting signal is then sent to the acoustic transmitter from where it propagates as acoustic waves. The waves are registered by acoustic receiver as an electrical signal, which is then conditioned (i.e. amplified and filtered) to be registered by the digital oscilloscope. The data is then processed offline on a PC.

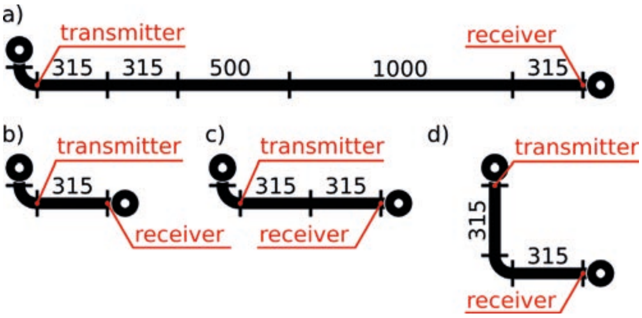


Figure 5 Pipes and pipeline configurations used during the verification process

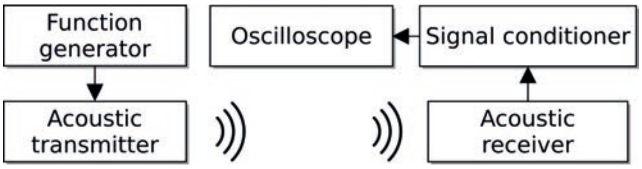


Figure 6 A general configuration of the apparatus

The first tests were carried out in air (Fig. 7) to serve as a reference for further research in aquatic environment. Four transmitters of different types were used: (1) a small 0.25 W speaker, (2) a low-power speaker from a headset, (3) a piezoelectric element with nominal resonant frequency of 18 kHz and (4) a piezoelectric ultrasound transceiver with the nominal frequency of 40 kHz. Each element was mounted inside a 3D-printed waterproof casing, some of which were shown in Figure 4. A professional-grade omnidirectional free field microphone (G.R.A.S. SOUND & VIBRATION 40BE) was used as the receiver.

The 0.25 W speaker (1) has four dominant frequencies of 1.5 kHz, 4 kHz, 8 kHz, 13 kHz. The headset speaker (2) has more flat frequency characteristics with dominant frequencies at 6 kHz, 8 kHz and 15 kHz. The modified 18 kHz piezoelectric element (3) has 3 distinct frequencies: 13 kHz, 33 kHz and 52 kHz. The ultrasonic transceiver (4) has only one resonant frequency of about 41 kHz. The elements were then submerged in glass tank filled with water. Figure 8 illustrates the results of the tests repeated with a hydrophone as the receiver.

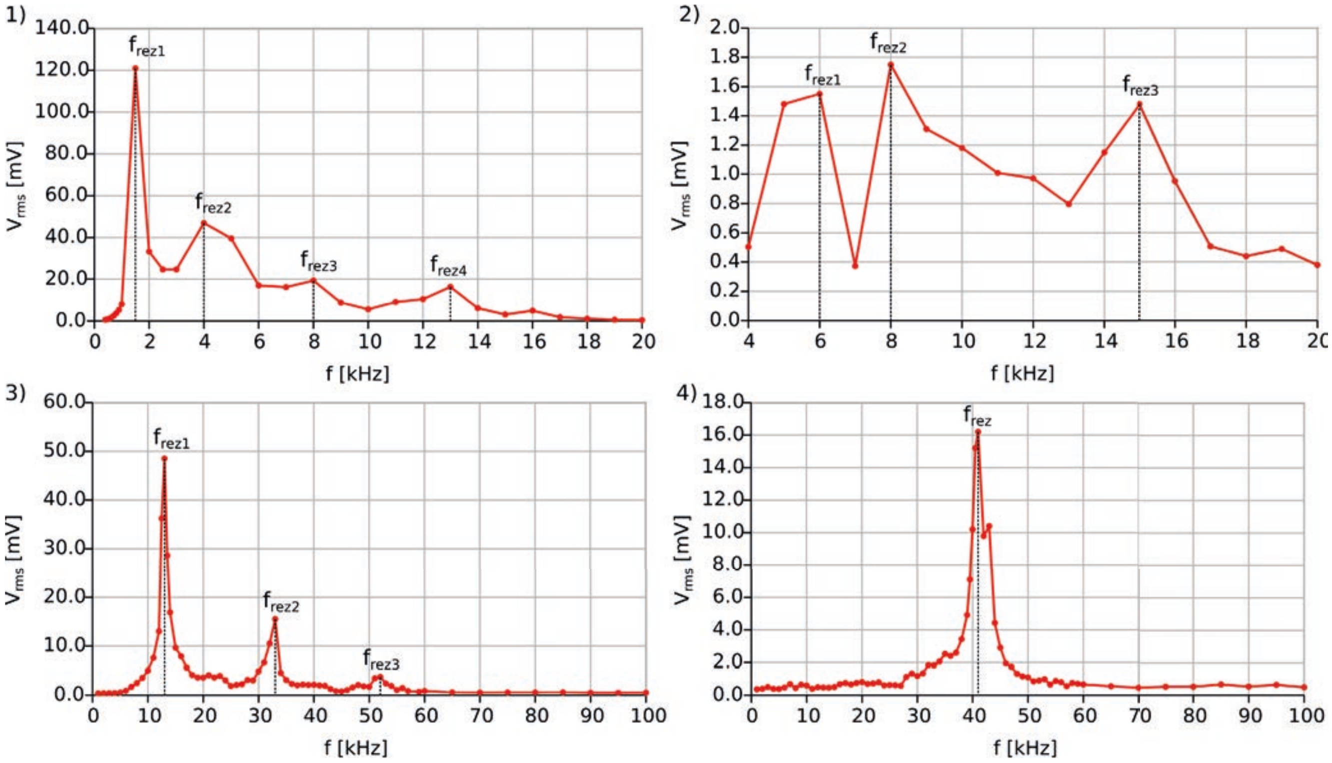


Figure 7 Frequency characteristics registered in air [4]

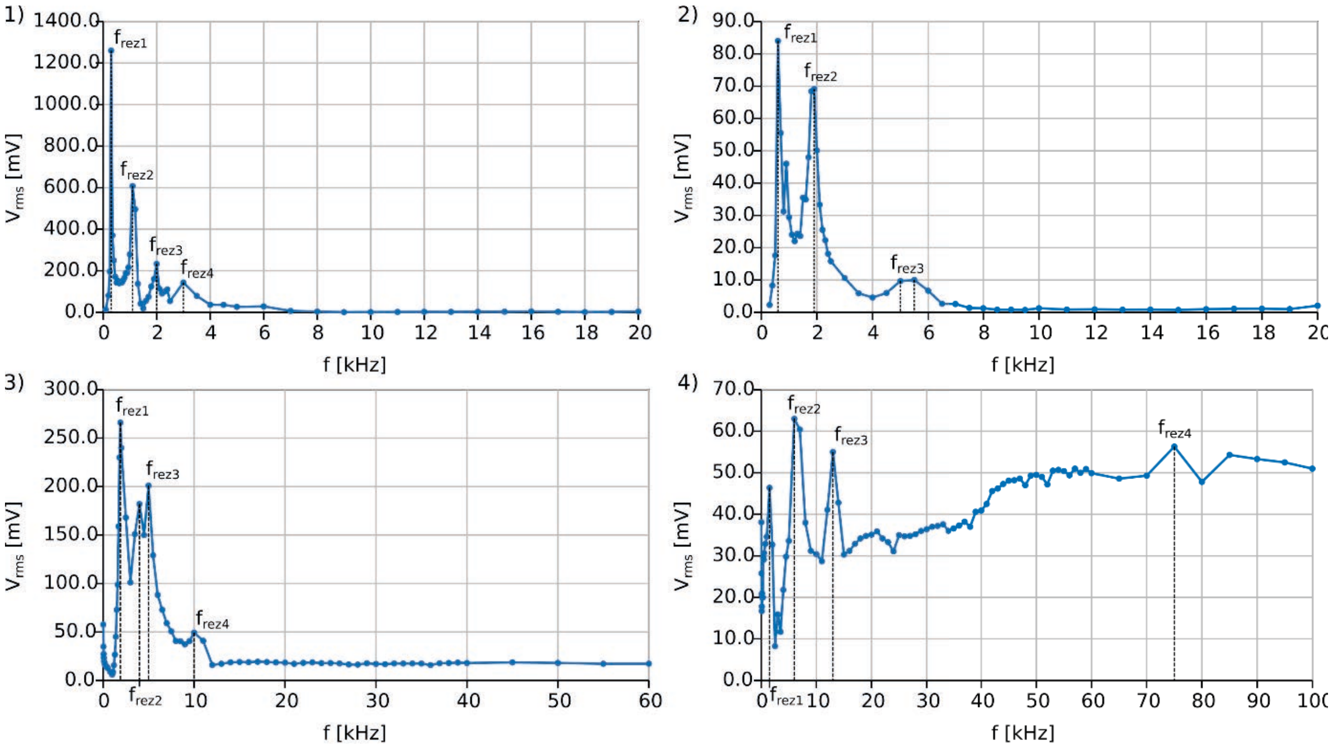


Figure 8 Frequency characteristics registered in water [4]

The characteristics of all transmitters working in audible range of acoustic waves (1, 2 and 3) were narrowed and moved to the lower frequencies. For ultrasonic transceiver (4) the characteristic was flattened and expanded to the higher frequencies.

As the tests in air and in water were carried out using different measurement apparatus (the hydrophone had undetermined gain factor), the further research was conducted to compare the signal strength in both environments. Two pairs of piezoelectric elements of nominal resonant frequencies of 18 kHz and 40 kHz were used with one piezoelectric part acting as the acoustic transmitter and the other as the receiver. The elements were mounted inside a pipeline fragment (32 mm of diameter, polyethylene, press-fitted) with fixed distance of about 290 mm to simulate the influence of cylindrical space of real working environment.

In the first part of the test a pipeline was empty, while in the second it was filled with water. The results for both pairs are shown on Figure 9. In both examples submerging the receiver and the transmitter in water resulted in amplitude gain of about 1.5 to 3 times for 18 kHz (1) and 40 kHz (2) elements, respectively. However the signal in both cases was distorted. For the human-audible 18 kHz element (1) it was shifted to the lower frequencies with augmented resonant frequencies. For ultrasonic devices with the frequency of 40 kHz (2) the resonant frequency was shifted toward higher frequencies and multiplied. The results were similar to the previous presented Figure 7 and 8.

The further experiment was conducted in the pipeline filled with water. To avoid redundant tests only two transmitters were chosen: the 0.25 W speaker for human-audible range and the piezoelectric element with nominal frequency of 40 kHz for the ultrasonic range. The signal was received with the hydrophone in both cases.

The aim of the second experiment was to discover the relation between the amplitude of the received signal and the relative distance between the receiver and the transmitter. The test was carried out for frequencies of 300 Hz (the dominant resonant frequency of the 0.25 W speaker in water) and 1.5 kHz (the non-resonant for speaker as reference), and also for the ultrasonic frequency of 48 kHz (assumed the most effective for a given piezoelectric element). Figure 6a shows the assembled pipeline. Measurements were taken with the relative distance between the receiver and the transmitter starting at 0 mm with subsequent steps of 100 mm ±20 mm to the end of the pipeline or a signal loss. In Figure 11 the results for frequency of 300 Hz (1), 1.5 kHz (2) and 48 kHz (3) were shown. For 1.5 kHz (2) the signal has been lost at a distance of about 1700 mm. For the 48 kHz (3) measurements were taken with powered off preamplifier of the receiver unit. The preamplifier, contrary to the hydrophone, was unable to process ultrasounds. The observed relation is exponential. For 300 Hz (1), however, there are significant distortions of measurements (dots) versus theoretical function (continuous line). The distortions were less severe for the higher frequency of 1.5 kHz (2) and negligible for the 48 kHz piezoelectric transmitter (3). Wave effects such as interference, augmented by the shape of pipeline, are assumed to be the major source of this phenomena.

To estimate the maximal distance of effective data transmission, regression coefficients were determined. The distance was then calculated from transformed regression equation (3).

$$l = log_x\left(\frac{V_{rms}}{a}\right) \tag{3}$$

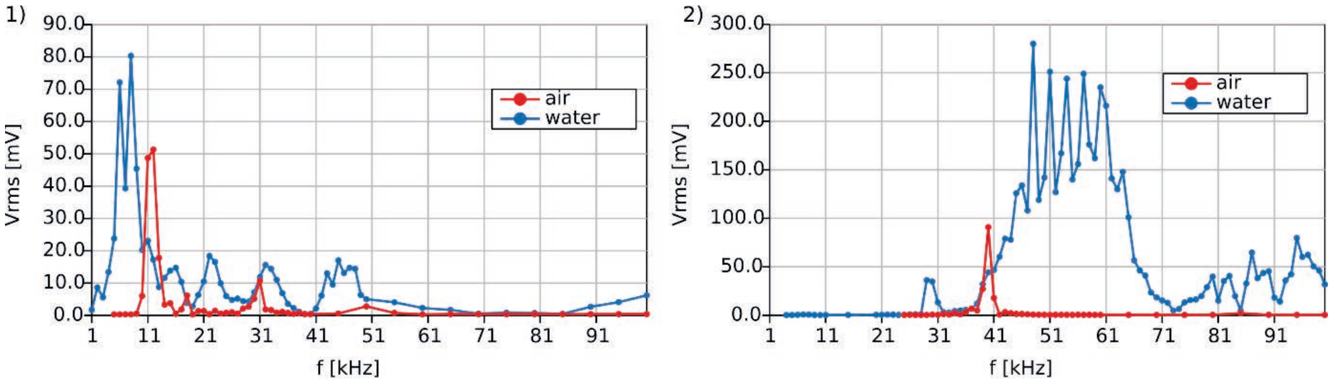


Figure 9 A comparison of the frequency characteristics [4]

A distance of 5686 mm has been calculated with an assumption of 10 mV as a lower amplitude limit for effective communication with the 0.25 W speaker paired with the hydrophone. Concerning unavailability of a precise mathematical model and the nature of the experiment, a distance of 4 m has been assumed as the maximal effective distance of the signal transmission for 0.25 W speaker excited with a voltage of 20 V_{pp} at the resonant frequency of 300 Hz.

Similar calculation was made for the frequency of 48 kHz. The preamplifier, however, has been powered off so amplitude limit of 2 mV was assumed. Concerning the constraints mentioned earlier, the resulting distance of 3388 mm has been floored to 3 m (for the identical signal parameters, excluding frequency).

The last part of the research was dedicated to the acoustic communication. The tests was initiated by verification of the simplified Morse code frame processor (ASK and PSK) in air. The measurement path was assembled as in Figure 6 with fixed distance of 10 mm between the transmitter (the 0.25 W speaker) and the receiver (an omnidirectional free-field microphone).

For the ASK modulation/demodulation a minimal amplitude of 5 V_{pp} was used. The phase deviation of the PSK modulation was conducted at 180 degrees (effectively turning it to a BPSK modulation [6]). The data sent by the acoustic channel was the basic pseudo Morse code frame presented in Figure 2. Figure 11 illustrates the successful reception of an ASK-modulated frame (compare with Fig. 2).

The final phase of the experiment took place in a water-filled pipeline assembled as in Figure 5c. A sine wave with amplitude of 20 V_{pp} was used as an excitation signal. For the ASK modulation the minimal amplitude has been reduced to 0 V_{pp} to counter the noise. For the 0.25 W speaker only ASK signal has been successfully registered (Figure 13) and the PSK signal was significantly distorted.

The research has been continued in the longest pipeline available (Fig. 5a). However, for the 0.25 W speaker signal was distorted too severely to be successfully decoded. The experiment has been repeated with the 40 kHz piezoelectric element as the transmitter and the hydrophone with the preamplifier powered off as the receiver. The carrier frequency of 48 kHz was used. Figure 13 depicts the results of the ASK-modulated signal transmission through the pipeline. The signal of 48 kHz has shown significantly less noise compared to human-audible device with a frequency of 300 Hz (Fig. 12).

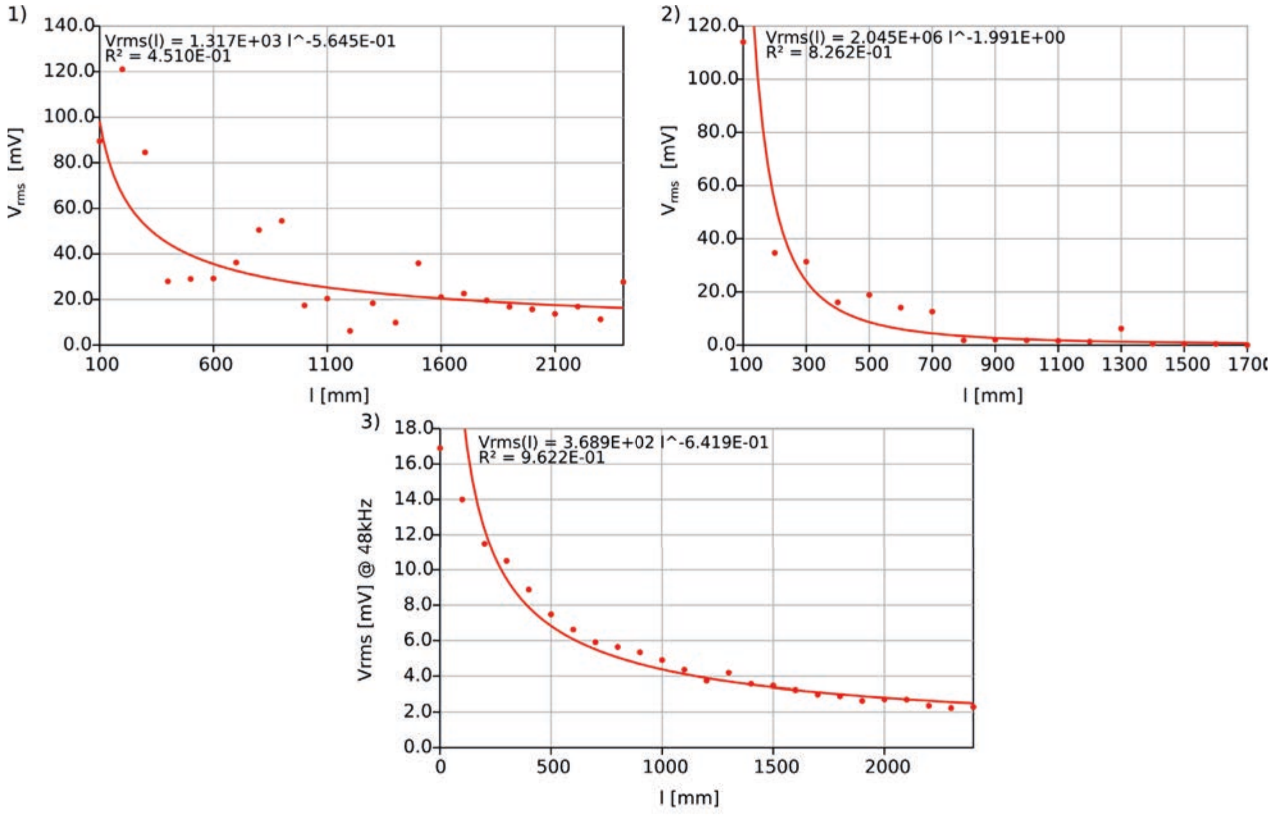
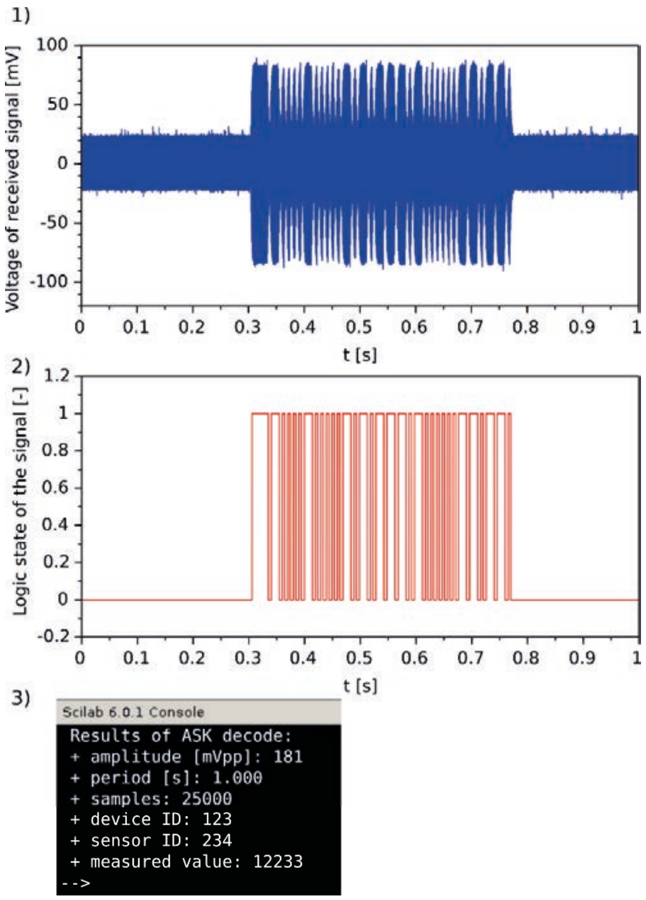


Figure 10 A relation between the signal amplitude and the distance [4]



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Results of ASK decode:
+ amplitude [mVpp]: 181
+ period [s]: 1.000
+ samples: 25000
+ device ID: 123
+ sensor ID: 234
+ measured value: 12233
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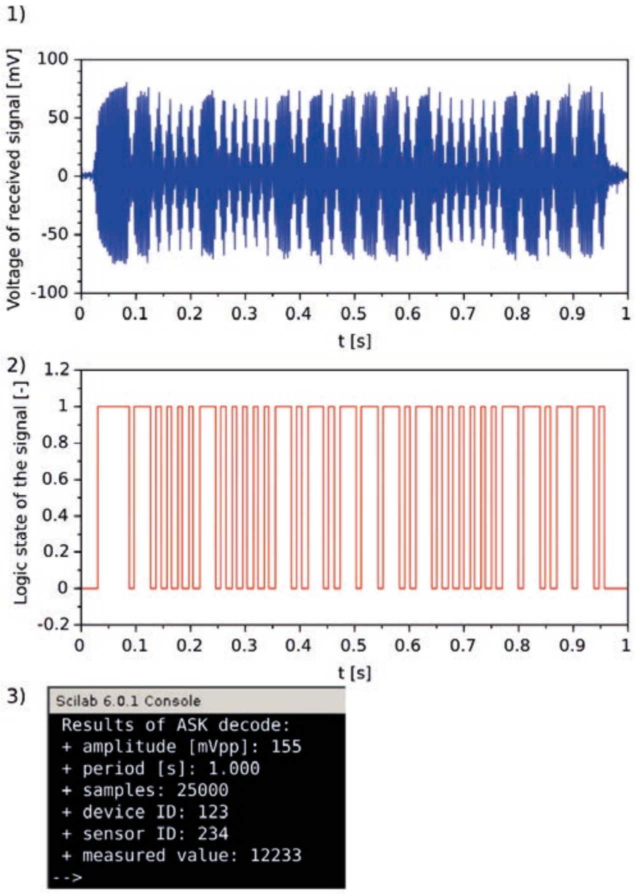
Figure 11 The 300 Hz ASK signal in air before (1) and after demodulation (2) and the result of decoding (3) [4]

6. CONCLUSIONS

The conducted research has shown that short-ranged communication via acoustic waves propagating through water is viable solution in the laboratory conditions. The method of signal coding proposed in the paper has also given satisfactory results for non-industrial applications and the most effective of tested modulations was the ASK modulation. For a pipeline acoustic communication the effective signal reception range increases for lower signal frequency. Thus, low-tone speakers are assumed to be the optimal solution if the signal range is the major criterion. However, the high-frequency signals such as ultrasonic waves, while having the lower effective signal reception range, also have a significantly reduced distortion of the received signal. Usage of both types of transceivers fuses the advantages of relatively long communication range of lower frequencies for straight pipes with the lower noise sensitivity of ultrasonic signals useful in the more intricate pipeline sections. Additionally, the range could be increased by improving the impedance fitting of the transceivers and using matched filtering.

A relatively high nominal excitation voltage of piezoelectric elements restricts their usage in the final product. Using paired piezoelectric elements as the receiver and transmitter unit, however, provides mechanical filtration of non-resonant frequency signals. It eliminates the necessity of additional filters and simplifying the product. The FDM/FFF technology has been found beneficial in the rapid manufacturing of waterproof casings for research purposes, especially for chemically weldable materials, such as ABS filament welded using acetone. The method of an acoustic communication through medium in pipelines is also the subject of a patent application [5].



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Results of ASK decode:
+ amplitude [mVpp]: 155
+ period [s]: 1.000
+ samples: 25000
+ device ID: 123
+ sensor ID: 234
+ measured value: 12233
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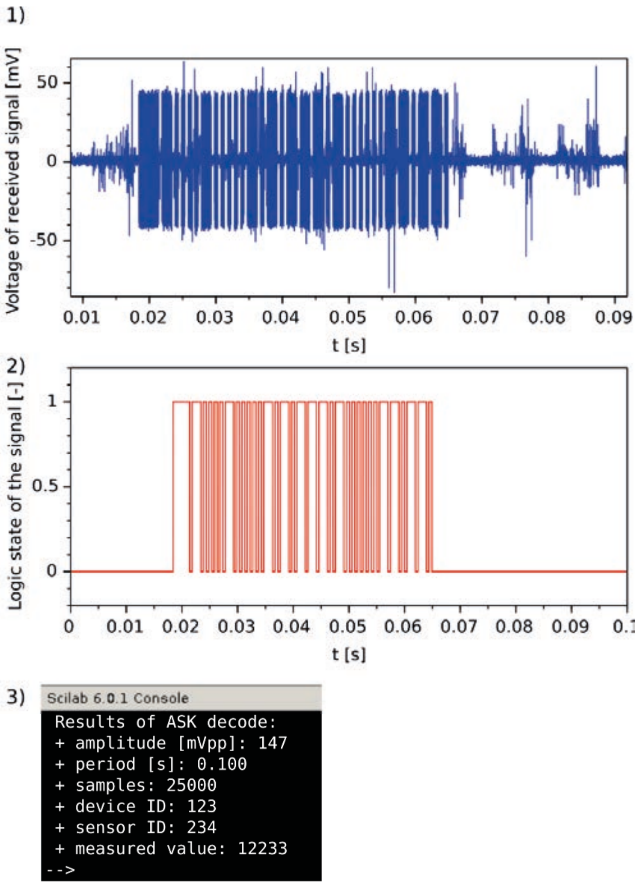
Figure 12 The 300 Hz ASK signal in water before (1) and after demodulation (2) and the result of decoding (3) [4]



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Results of ASK decode:
+ amplitude [mVpp]: 147
+ period [s]: 0.100
+ samples: 25000
+ device ID: 123
+ sensor ID: 234
+ measured value: 12233
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Figure 13 The 48 kHz ASK signal in water before (1) and after demodulation (2) and the result of decoding (3) [4]

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