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ACOUSTIC DATA TRANSMISSION SYSTEM FOR OIL PRODUCTION PIPELINE

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Abstract – The optimal operation of an oil well requires the periodic measurement of the downhole pressure. In this work, acoustic waves are used to transmit data from a downhole pressure sensor to surface. The acoustic waves propagate through the wall of the oil production pipeline, making up a wireless transmission system. Binary data is transmitted in two frequencies, using FSK modulation. The transmission faces problems with attenuation and strong distortion caused by multiple reflections at the joints and due to frequency dependency of the sound velocity. A model of wave propagation in pipelines with periodical joints is used to determine an appropriate frequency range of operation. Another model is used to design the acoustic transducer coupled to the pipeline. Successful results have been verified in an experimental set-up. The acoustic attenuation was measured in a 600-m deep oil well. As well as, an acoustic modem was implemented in a 100-m long pipeline with transmission rate of 2 bit/s.

Keywords: *acoustic data transmission, downhole monitoring, pipeline modelling*

1. INTRODUCTION

The operation of an oil well requires periodic measurement of pressure and temperature at the down hole for routine keeping, adjustment of valves to achieve the optimum oil production. Such supervision is done via a permanent downhole sensor (PDS) which measures those variables and sends signals to the surface through electrical cabling. However, deep-water oil production systems are usually longer than 3000-m, resulting in costly wiring installations and maintenance.

Wireless transmission is physically possible with acoustic wave propagation through the steel pipeline elements. Acoustic modems for underwater binary data transmission have been developed successfully for utilization in submarines and sea-work-stations [1]. Acoustic wave propagation has been investigated for tilt and pan control of drilling devices in oil well [2] [3]. Such approach has inspired the present system.

2. SYSTEM DESCRIPTION

Fig. 1 shows the block diagram of the acoustic system control powered by two separated power circuits: (1) low level consumption circuit, based on a Microchip PIC16C71 RISC microcontroller, and (2) a high consumption circuit, based on a Motorola 68HC11 microcontroller, usually idling to save energy. The first is responsible for reception of incoming signals from the top of the pipeline and stay active for the whole life span of the well. The second is responsible for the temperature and pressure outgoing signal transmission from bottom to top of the pipeline through a power acoustic transducer. The microcontroller A receives the incoming signal through an automatic gain control circuit. When such incoming signal is very long in a prescribed frequency – indicating a request to send data – the power battery supply is connected to the system, the microcontroller B wakes up and performs temperature and pressure measurement through the interface of the sensors. Each reading is stored internally as a 12-bit word. This word is serialized with frequency shift keying (FSK), i.e., bit “0” commands the piezoelectric acoustic transducer to vibrate in at frequency F and bit “0” otherwise commands the transducer to vibrate at frequency F + ΔF.

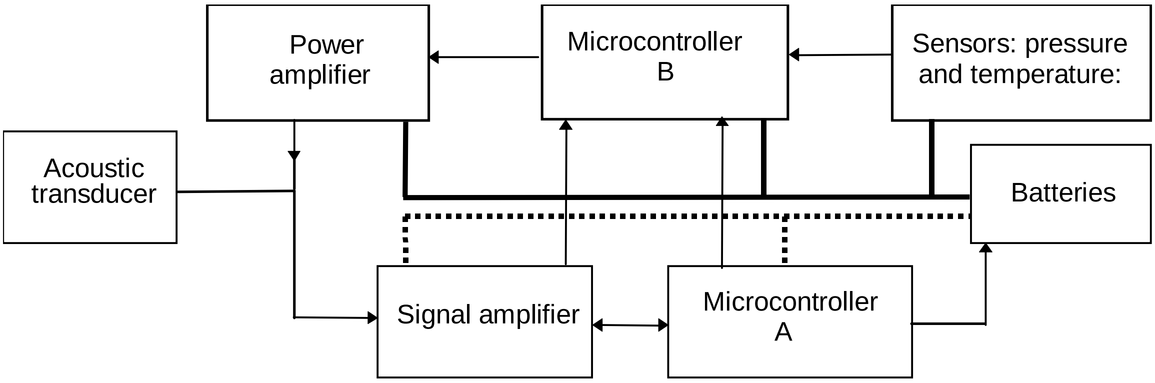

Fig. 1: Block diagram of the acoustic data transmission system

Two critical aspects must be considered in the design of this system: the piezoelectric acoustic transducer, responsible for generating the acoustic waves, and the understanding of the wave propagation through the steel pipeline elements. In addition, operating temperature and pressure (100°C at 300 atm), size (within a cylinder of 30 mm diameter and maximum length of 8-m), and non-interrupted operation of up to 5 years, are challenging requirements. All the care must be given for power consumption optimization, by designing the acoustic transducers and by managing the sleeping state (idling) of electronic circuits. To get out of idling, a wake-up-signal from the top of the pipeline (given by the operating personnel) commands the system, as already described.

2.1. Acoustic Line Transmission Modeling

Fig. 2 illustrates the oil pipeline, an inner tube inside the external jacket where the oil flows. The pipeline is assembled from steel pipes, with length d_1 and cross-sectional area a_1, connected by threaded tool joints, with length d_2 and cross-sectional area a_2. The space between the pipeline and the jacket is filled with water.

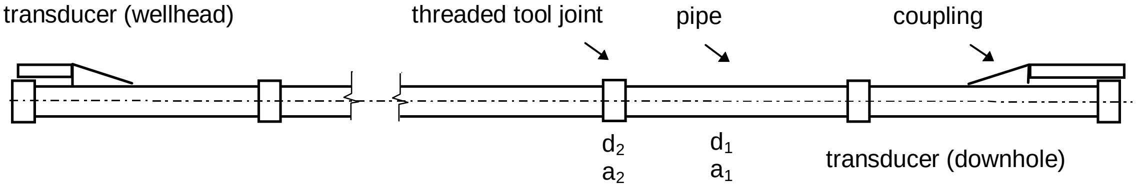

Fig. 2: Oil production pipeline

The acoustic wave propagating on such mechanical structure has phase and group velocities frequency dependency. There is some frequency ranges where the propagation is blocked. Those ranges separate periodically other ranges where the wave can propagate at expenses of high distortion due to the variation of the phase and group velocities with the frequency. The relationship between the angular frequency ω and the wave number k is given by [3]:

$$\cos k(d_1 + d_2) = \cos\left(\frac{\omega d_1}{c_1}\right)\cos\left(\frac{\omega d_2}{c_2}\right) - \frac{1}{2}\left(\frac{a_1}{a_2} + \frac{a_2}{a_1}\right)\sin\left(\frac{\omega d_1}{c_c}\right)\sin\left(\frac{\omega d_2}{c_2}\right)$$

Where: $c_1 = c_2$ = velocity of the extensional wave in steel. The phase velocity is $c_f = \omega / k$, and the group velocity is $c_g = \frac{d\omega}{dk}$

Fig. 3 shows the behavior of the phase velocity for an oil pipeline composed by 9.65-m long pipes. The acoustic waves can propagate in the frequency ranges where the phase velocity is not imaginary. The plot shown in Fig. 3 indicates several bandpass ranges, the 4th range was analyzed in more details, showing a 200 Hz width. The pipe length might vary up to 0.5-m, leading to shifts on the bandpass ranges around 50 Hz. For shorter lengths, the central frequency range is bigger.

2.2. Acoustic Transducer

The connection of the transducer to the pipeline is made by a conic coupling which embraces the pipeline tube, as shown in Fig. 4, through very tight screws and grease. However, in the field, the coupling is shorter and actually welded to the structure. The transducer is sized in accordance to the space between the oil production pipeline and the well jacket. The transducer power ratings are related to the total length of the pipeline and the correspondent attenuation, the first estimate was to build a transducer of 200 W. The specifications for the transducer depend on the operating frequency which are related to the acoustic line transmission bandpass. The structure comprised of transducer, coupling and pipeline is virtually impossible to model with unidimensional assumptions. So, a finite element approach has been used to help to design the transducer frequency response.

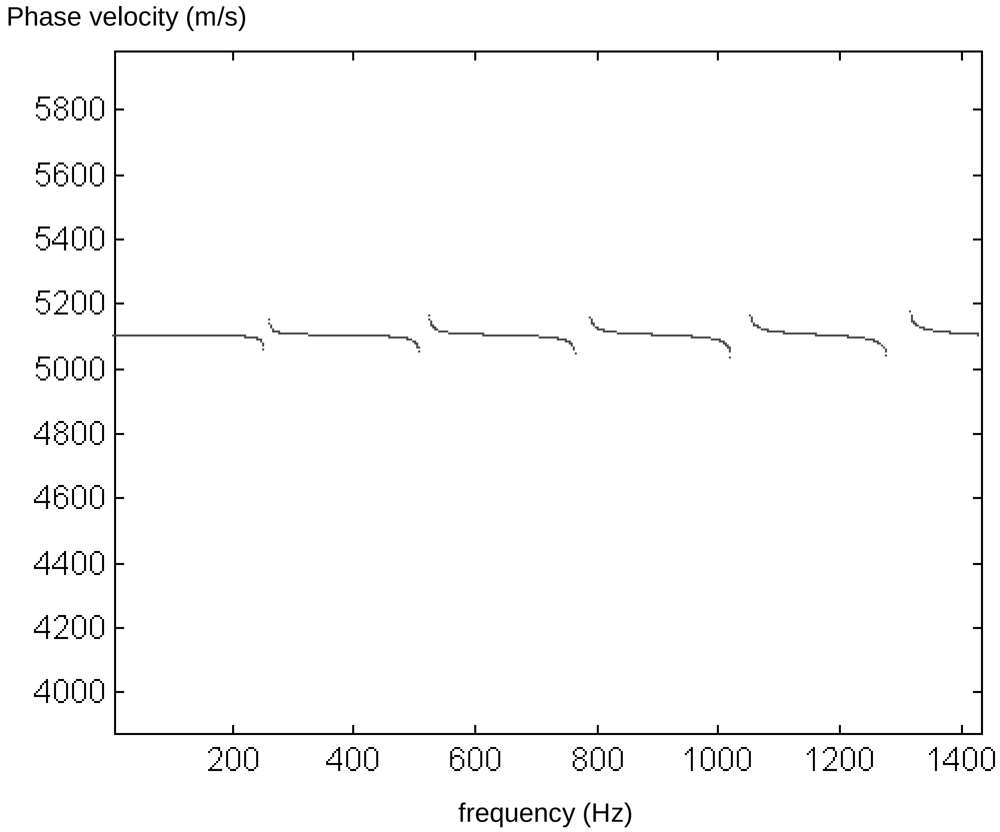

Fig. 3: Phase velocity behavior

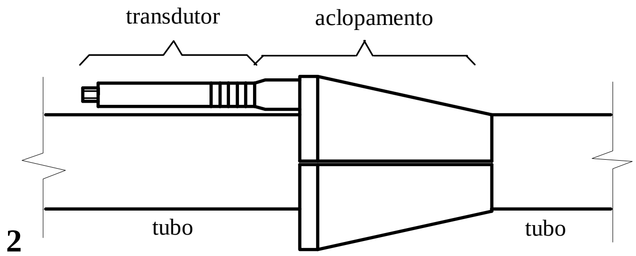

Fig. 4: Coupling of transducer to the pipeline.

Finite elements modeling allow a full-fledged three-dimensional analysis and integration with analytical methods. In this paper, it was used a finite elements model, as seen by Fig. 5, to get the acoustical impedance on the surface of the coupling, in terms of the operating frequency. An analytical *chain matrix* model was used for the piezoelectric transducer, which was coupled to the pipeline [4].

The transducer is arranged in a sandwich construction, with pilled piezoelectric ceramics coupled to two metallic plates on each end, with a central hole for the pre-tension screw adjustment [5], as shown on Fig. 6. The piezoelectric ceramics are connected in parallel, so as to have alternated polarization. The electrical impedance amplitude of the acoustic transducer with varying frequency is shown in Fig. 7. The solid thick line is the experimental verification. The thin solid line is the result of the full finite element modeling, and the dashed line is the result of the FEM combination with the chain matrix. It can be seen a good match for the two models used for the transducer.

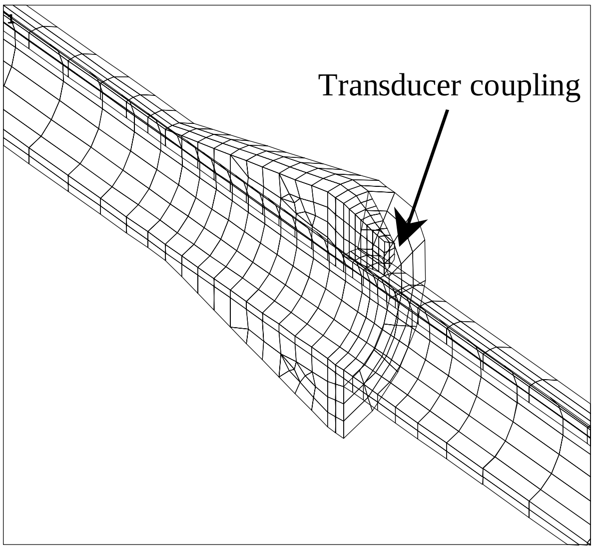

Fig. 5: Finite elements modeling

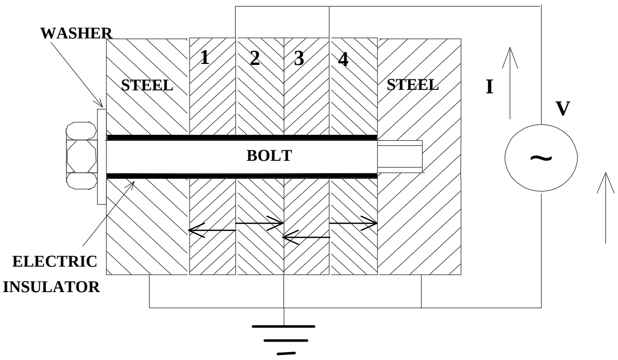

Fig. 6: Piezoelectric transducer

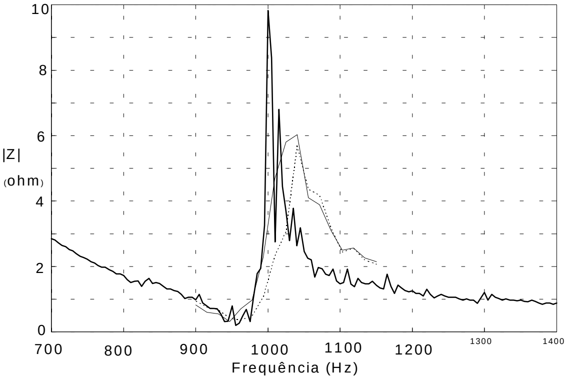

Fig. 7: Frequency response for the piezoelectric transducer coupled to the pipeline

3. EXPERIMENTAL RESULTS

Two field tests were done to determine the attenuation of the acoustic line transmission and to verify the strategy for transmitting the data. The first field test was performed in a “oil-well-school” from Petrobras, at the site of Taquipe, Bahia (Brazil). The acoustic transmission test was done in laboratory, with a 100-m length pipeline.

3.1. Attenuation Test

The FEM model helped to design a transducer operating at 980 Hz. The transducer consists of 16 piezoelectric ceramic disc (PZT-8) connected in parallel and a brass rod on the back-end with a total length of 660 mm, a front-end steel rod with length of 50 mm. The electrical impedance at the operating frequency was measured in the laboratory with a value around 3 kΩ.

The acoustic transmitter was built together to the electronics and related circuitry inside a pressure vessel, and connected to a mandrel at the bottom end side of the pipeline. The system was run with 11 alkaline type-D batteries with no interruption for 24 hours. The individual average battery voltages came from 1.57 V to 1.33 V after the use. The power electronics circuit for activation of the transducers required capacitors with good dynamic response, in order to provide current for the acoustic burst, consisted of 10 cycles at 980 Hz frequency, every 2 seconds.

At the wellhead (top of pipeline), it was used an accelerometer to measure the acoustic wave and an acquisition system with an 8 bit A/D connected to a microcomputer. The signals were acquired at a 20 ksamples/sec to fill an array of 8,192 measures. The pipeline on the “oil-well-school” was progressively increased in depth and for each pipeline length were done 3 acquisitions for the acoustic wave, i.e., the transducer at the bottom was sending the signals, while the accelerometer at the top was receiving with a computer. Several measurements were done for different pipeline lengths, down to 600 meters maximum.

It was observed that although the electrical excitation on the transducer had only 10 cycles, the received signal was very long due to the high Q (quality factor) and to the multiple reflections on the pipeline. Data were analyzed and concluded that after 400 ms after the transmission the signal amplitude was attenuated by 40 dB. The signal attenuation ratio at 980 Hz is 21 dB/km, which is in accordance to the literature [3].

Fig. 8 shows the Fast Fourier Transformation for the acquired signal, with a length referent to 10 pipeline segments. It can be verified a bandpass between 840 Hz and 1,040 Hz, which is in accordance to the simulation studies presented on Fig. 3.

The pipeline segment lengths had a variation from 9.13 to 9.67 meters. The segments used on the field test had 8 units with a length smaller than 9.30 m and 23 units with length larger than 9.67 m. The remaining 28 pipeline segments had lengths between 9.30 and 9.49 m. The threaded tool joints had fix length of 0.161 m.

3.2. Data Transmission Test

A simple modulation technique used to transmit binary data is the Frequency Shift Keying (FSK) that employs two different frequencies, f_1 and f_2. A burst signal at frequency f_1 is emitted when a bit “1” has to be transmitted while frequency f_2 is used for transmitting a bit “0”. The baud rate for such transmission was set to 2 bits/sec, and the error rate was observed to be virtually zeroed after several hours of operation. Note that pipeline length in the laboratory is very small, compared to the real deep-sea installations, and it is expected more distortion and noise for the future experiments. However, those tests were very important to validate and debug the modulation/demodulation strategy.

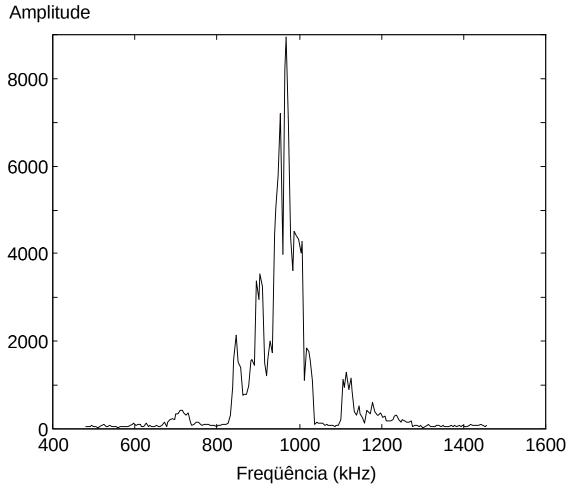

Fig. 8: Frequency spectrum for the signal received from 600-m depth

4. CONCLUSION

The optimal operation of an oil well requires a periodic measurement of the downhole pressure, acoustic waves were used to transmit data from a downhole pressure/ temperature sensor to the surface. Binary data were transmitted in two frequencies, using FSK modulation. A model of wave propagation in pipelines with periodical joints were used to find out an appropriate frequency range of operation and another model to design the acoustic transducer coupled to the pipeline. The numerical model for the acoustic transducer was verified with the experimental results, giving good estimates for resonance, anti-resonance and electrical impedance.

Several experimental evaluations were done in a “oil-well-school” at the site of Taquipe, with an acoustic transducer designed to operate at 980 Hz. The attenuation was measured for the up to 600 meters of pipeline length, indicating the rate of 21 dB/km. The FSK data transmission strategy was evaluated with a 100 meters pipeline, with a baud rate of 2 bits/second, indicating a successful operation. Theoretical and experimental evaluation are still under progress. In near future it is expected to retrofit the transmission system, integrated to a pressure/temperature sensor, for an operating oil well production system.

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