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ACOUSTIC METHODS FOR MEASURING THE THICKNESS OF DEPOSITS ON THE INNER WALL OF PIPELINES

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Abstract. Wax deposits on the inner walls of pipelines and technological equipment are a serious problem in the petroleum industry. This is not a new problem and it appeared at the dawn of oil production, but it still remains relevant, especially today, when most of petroleum fields are moving to a late stage of their development. Wax deposits lead to complications in the transportation of petroleum products, which leads to economic losses, and deposits can also cause equipment failure.For timely planning and implementation of treatment activities, information on the current thickness of wax deposits is required. However, there is currently no simple and effective method for measuring thickness of deposits.The paper considers the existing acoustic methods for measuring the thickness of deposits: through-transmission method, echo-method andmethod based on attenuation of acoustic signal. Experimental studies were carried out to determine the applicability of the proposed methods. An analysis of the literature was carried out and we proposed a new method for measuring the thickness of wax deposits, based on the analysis parameters of frequency of natural vibrations of the pipeline wall.An experimental study and computer modeling have been carried out, confirming the existence of a relationship between the resonant frequency of the pipeline wall oscillations and the thickness of the deposits. This dependence can be used as the basis for a new device for measuring the thickness of wax deposits.

Keywords

non-destructive test; acoustic methods; thickness measuring; wax deposits; technological equipment

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Научная статья

АКУСТИЧЕСКИЕ МЕТОДЫ ИЗМЕРЕНИЯ ТОЛЩИНЫ ОТЛОЖЕНИЙ НА ВНУТРЕННЕЙ СТЕНКЕ ТРУБОПРОВОДОВ

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Аннотация. Асфальтосмолопарафиновые отложения на внутренних стенках трубопроводов и технологического оборудования представляют серьезную проблему в нефтяной отрасли. Данной проблема не является новой и появилась на заре становления нефтедобычи, однако она не теряет своей актуальности, особенно сейчас, когда большинство месторождений нефти и нефтепродуктов переходят на позднюю стадию своей разработки. Асфальтосмолопарафиновые отложения приводят к осложнениям транспортировки нефти и нефтепродуктов, что в свою очередь приводит к экономическим потерям, а также отложения могут выступать причинами выхода оборудования из строя. Для своевременного планирования и проведения очистных мероприятий необходима информация о текущей толщине парафиновых отложений. Тем не менее, на настоящий момент не существует простого и эффективного метода измерения толщины отложений. В статье рассмотрены существующие акустические методы измерения толщины отложений – методы прохождения, отражения и методы, основанные на затухании акустического сигнала. Проведены экспериментальные исследования с целью определения применимости предложенных методов. Проведен анализ литературы и предложен новый метод измерения толщины отложений, основанный на изучении параметров резонансной частоты колебаний стенки трубопровода. Проведено экспериментальное исследование и компьютерное моделирование, подтверждающие наличие зависимости между резонансной частотой колебаний стенки трубопровода и толщиной парафиновых отложений. Данная зависимость может быть положена в основу нового прибора измерения толщины асфальтосмолопарафиновых отложений.

Ключевые слова

неразрушающий контроль; акустические методы; измерение толщины; асфальтосмолопарафиновые отложения; технологическое оборудование

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Introduction

The process of oil extraction and transportation are complicated by a quantity of problems: the formation of oil emulsions, wax deposits, inorganic salts, the presence of various mechanical impurities in petroleum, and corrosion damage [1]. One of the most common problems is wax precipitation on the inner walls of pipelines and technological equipments. This problem appeared more than 100 years ago, but it still remains relevant [2].

An ordinary and obvious consequence of the wax sedimentations is a decrease the cross size of the pipeline, figure 1. This leads to the breakaway of equipments from the normal operating mode (reduction of throughput, increase in pressure in the head of the pipeline) and, as a result, to economic losses and a reduction in overhaul periods [3, 4]. Wax deposits on the bottom of reservoirs can reach 1.5–2.0 meters in 3–5 years, which significantly reduces the volume of the reservoirs themselves [5]. In addition to pipelines and tanks for storing petroleum products, wax deposits reduce the efficiency of pumps and other technological equipments, and are also the causes of their breakdowns [6].

Every year, countries spend a lot of money on pigging pipelines from wax deposits. Information on the current thickness of wax deposits is required for planning and apropos implementation of treatment activities [7–9]. Proper planning will save resources and prevent emergencies caused by wax deposits.

Currently, there are many solutions have been proposed to determine the thickness of wax deposits. Exists direct methods, by introducing a device into the pipelines and operating on the prin-

Figure 1. Wax deposits [5]

Рисунок 1. Парафиновые отложения [5] ciple of direct measurement [10], and indirect methods using various physical phenomena. «Massive» deposits can be detected by a decrease in equipment performance. The problem lies in the measurement of deposits of whatever thickness. One of the most common methods is the pressure drop method [11, 12]. There are also many solutions based on thermal conductivity and heat transfer [13, 14]. There is a quantitative assessment of the wax deposits by the volume of displaced liquid (LD-LD) [4, 12]. The direction of measurement wax thickness using ionizing radiation is promising [15–17]. Advantages of ionizing radiation methods are accurate and non-contact. However, because this methods use radiation, they are expensive, require special implementation conditions, and these methods are dangerous to health, radiation safety rules must be keep up.

The currently existing methods for measuring the thickness of wax deposits have certain disadvantages, which makes it difficult to apply them in any industry. In some cases is required to destruct the pipeline, another methods need to stop transportation of oil, some methods have a complicated implementation scheme. Formed a list of requirements to the method for determining the thickness of wax deposits:

— the method must be non-destructive, i.e. not violate the integrity of the pipelines or technological equipments;

— the method must be implemented with one-way access to the object of study;

— technically complex and expensive equipment for control are not required;

— should be used simple algorithms for processing control results.

An analysis of the existing methods of control showed that acoustic methods of non-destructive testing are suitable for implementation this tasks.

Materials and methods

Acoustic methods of non-destructive testing are based on the analysis and processing of mechanical wave's witch generating or occurring in the test object. For further research were selected active methods of acoustic control. These methods are based on the generating and reception of mechanical oscillations and waves.

Through-transmission method

The through-transmission method is based on the generated of acoustic waves in the study object and the analysis of the parameters of the waves that have passed through the study object. One of the analysis parameters can be the signal intensity [18, 19].

There is a solution for pipes [20] that proposes to measure the intensity (amplitude) of ultrasonic waves transmitted through the pipe and compare it with the intensity of ultrasonic waves transmitted through the same pipe filled with the same product but without deposits. An analysis of the attenuation of the wave intensity will tell about the thickness of the deposits.

To test the applicability of through-transmission method for wax deposits, an experiment was carried out according to the scheme in figure 2. Ultrasonic waves were passed through a pipe ∅91×6 mm filled with oil, and through the same pipe, but with wax deposits 3 mm thick.

Echo methods

Echo methods are based on the generating of acoustic waves in the test object and the analysis of the parameters of waves reflected from the bottom surface or from defects [18, 19].

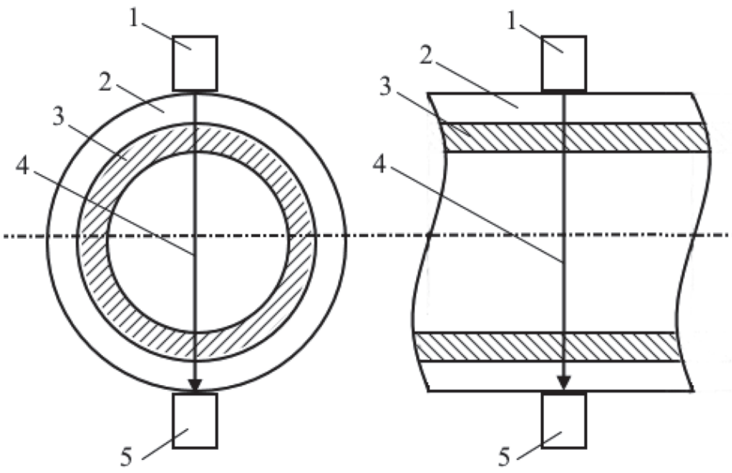
There is a solution [21] that proposes to analyze multiple reflected ultrasonic signals. Among of incoming signals from the pipeline wall, distinguished signals that have passed into the wax deposits and reflected from their bottom. If we know velocity of sound in wax sediments and the transit time of the wave, it is possible to calculate the thickness of the wax deposits.

To test this method, an experiment was carried out according to the scheme in figure 3. In a sample of steel, 59 mm thick, ultrasonic wave were generating and the receiving waves were analyzed. The measurements were carried out with a sample without wax deposits and with deposits with a thickness of 3 and 6 mm.

Attenuation

There is a solution [22] that proposes to analyze the attenuation curve of a multiple reflected signal. By comparing the curves for samples without deposits, samples with deposits of known thickness and the curve obtained by measuring the object of study, a conclusion is made about the thickness of the deposits.

To test this approach, an experiment was carried out according to the scheme in figure 4. In a sample of steel, 12 mm thick, ultrasonic waves were generated and multiple reflections were recorded by the receiver. The measurements were carried out for the sample without deposits and with wax deposits of thickness 3, 6, and 9 mm.

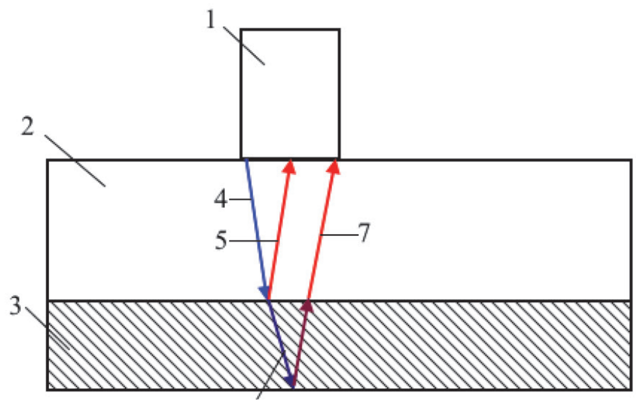


1 — transmitter, 2 — wall of pipe, 3 — wax deposits, 4 — acoustic wave direction, 5 — receiver

1 — излучатель, 2 — стенка трубы, 3 — отложения, 4 — направление акустической волны, 5 — приемник

Figure 2. Through-transmission method

Рисунок 2. Схема метода прохождения



1 — transducer, 2 — sample of steel, 3 — wax deposits, 4 — direct wave, 5 — reflected wave in steel, 6 — direct wave in wax, 7 — reflected wave from wax

1 — излучатель и приемник, 2 — образец из стали, 3 — отложения, 4 — прямая волна, 5 — отраженная волна в металле, 6 — прямая волна в парафине, 7 — отраженная волна из парафина

Figure 3. Echo methods

Рисунок 3. Схема метода отражения

Measuring wax deposits

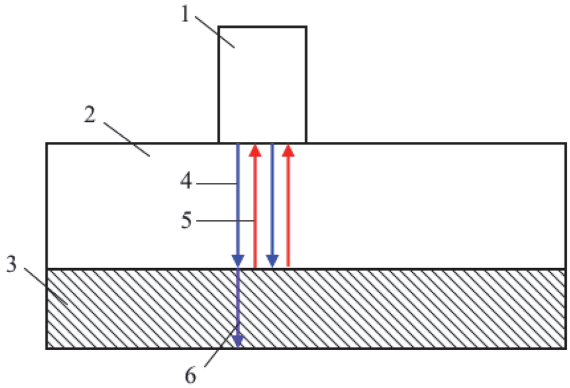
Additionally, experiments were carried out to study the transit of an ultrasonic wave in wax deposits according to the scheme in Fig. 5. Measurements were taken for wax deposits with thicknesses of 3, 5, 7 and 10 mm.

To carry out all the experiments used ultrasonic flaw detectors of models USD-50 (KROPUS), A1212 Master Light (AKS), piezoelectric transducers for 1.25 MHz, 2.5 MHz and 5 MHz, samples for setting flaw detectors, calibration blocks, and wax deposits from operating oil pipeline.

Local method of free oscillations

A preliminary study of the material and previous studies using acoustic methods of non-destructive testing showed the need to find a new solution for measuring the thickness of wax deposits. The analysis of existing methods of acoustic control showed that the method of natural oscillations is suitable for solving the problem. It consists in generated of free oscillations in the local area of the study object and measurement of their parameters [23].

The hypothesis was put forward: the presence of wax deposits on the inner walls of the study

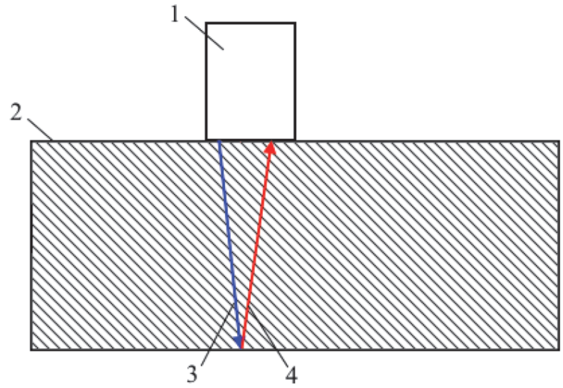


1 — transducer, 2 — sample of steel, 3 — wax deposits, 4 — direct wave, 5 — reflected wave in steel, 6 — ultrasonic wave in wax

1 — излучатель и приемник, 2 — образец из стали, 3 — отложения, 4 — прямая волна, 5 — отраженная волна в металле, 6 — звуковая волна прошедшая в парафин

Figure 4. Attenuation method

Рисунок 4. Схема с измерением затухания



1 — transducer, 2 — wax deposits, 3 — direct wave, 4 — reflected wave

1 — преобразователь, 2 — парафиновые отложения, 3 — прямая волна, 4 — отраженная волна

Figure 5. Measuring wax deposits

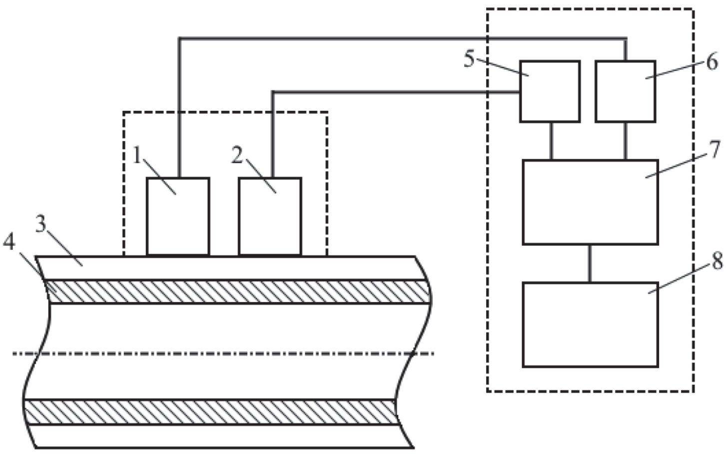
Рисунок 5. Схема измерения распространения звука в отложениях

object will affect on the frequency of its natural oscillations.

To test this hypothesis, an experiment was carried out according to the scheme in figure 6.

On the local area of the pipeline Ø91x6 mm, free oscillations were generated by a mechanical impulse. The oscillations of the pipeline were recorded, processed, and then the frequency response was analyzed.

A total of 700 measurements were carried out, 100 measurements on a pipeline section without wax deposits and 600 measurements on the same pipeline section with wax deposits of thickness 2.5 to 15 mm.



1 — vibroacoustic generator, 2 — receiver, 3 — wall of pipe, 4 — wax deposits, 5 — amplifier, 6 — generator, 7 –controller, 8 — indicator

1 — возбудитель колебаний, 2 — приемник, 3 — стенка трубы, 4 — отложения, 5 — усилитель, 6 — генератор, 7 — контроллер, 8 — индикатор

Figure 6. Method of free oscillations

Рисунок 6. Схема измерения свободных колебаний

Modeling

To confirm the hypothesis about the relationship between the frequency of free oscillations of the study object and the thickness of wax deposits on its inner wall and confirm experimental studies, computer simulation was carried out in the T-Flex CAD software package.

A study was made of oscillations of a square steel plate embedded along the edges, 12 mm thick, 150x150 mm in size. Oscillations of the plate without wax deposits and with deposits of thickness 2 to 14 mm are simulated.

Results and discussion

Through-transmission method

The results of the measurement in the research of the through-transmission method are shown on figure 7. In figure 7, a number 2 marks the signal of the transmitted wave, followed by a series of reverberations in the pipe wall. Number 1 marks the signal of an acoustic wave transmitted along the wall (creeping wave) of the pipeline.

Figure 7, b shows the flaw detector screen during measurements with 3 mm thickness of wax deposit. With increased amplification of the flaw detector, only the signal of the creeping wave can be seen. The wave passing through the pipe does not reach the receiver of acoustic oscillation.

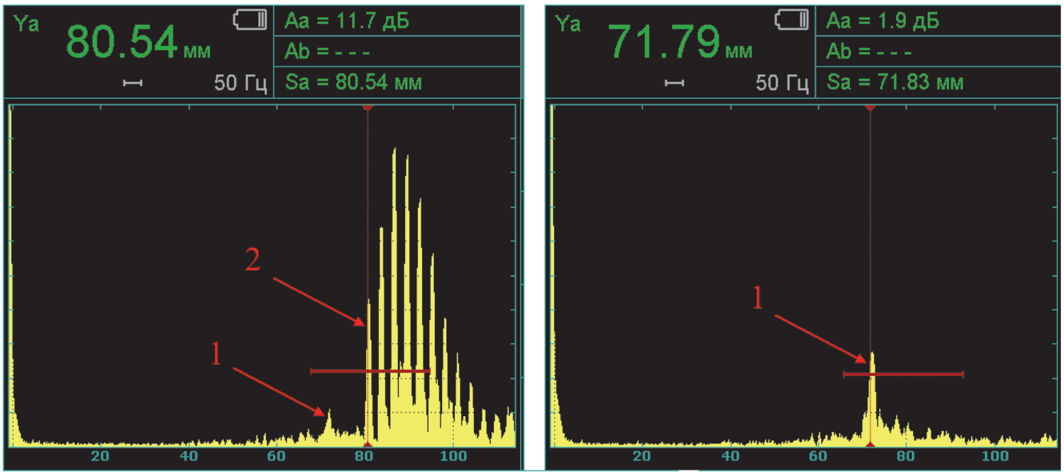
The experiment showed that wax deposits strongly absorb the ultrasonic wave and even with a deposit thickness of 3 mm, this method does not give positive results.

Echo method

The results of the measurement in the research of the echo method are shown on Fig.8. With the normal amplification of the flaw detector, the signal from the reflection of wax has the noise level and it is not distinguishable. With a high amplification of the flaw detector, interfering signals become noticeable, such as additional waves resulting from transformation during reflections (mark 2, figure 8). The signal from wax deposits 3 mm thick can be distinguished against the noise background (mark 3). The signal from deposits 6 mm thick is already below the noise level (mark 4).

Echo methods can be applied in practice, but they require the development of special information processing algorithms. It is necessary to programmatically highlight the signals from wax against the background of strong reverberations in steel. This approach is described in [24].

However, these methods have a significant limitation. To calculate the thickness of the wax deposits, it is necessary to know the velocity of sound waves in the deposits, which is not known in advance [25]. The composition of wax varies depending on the geographical location, as well as over time [26]. The second limitation is that the deposit must have a plane-parallel surface so that the reflected signal can return to the transducer. In fact, the deposit surface can be of any shape.



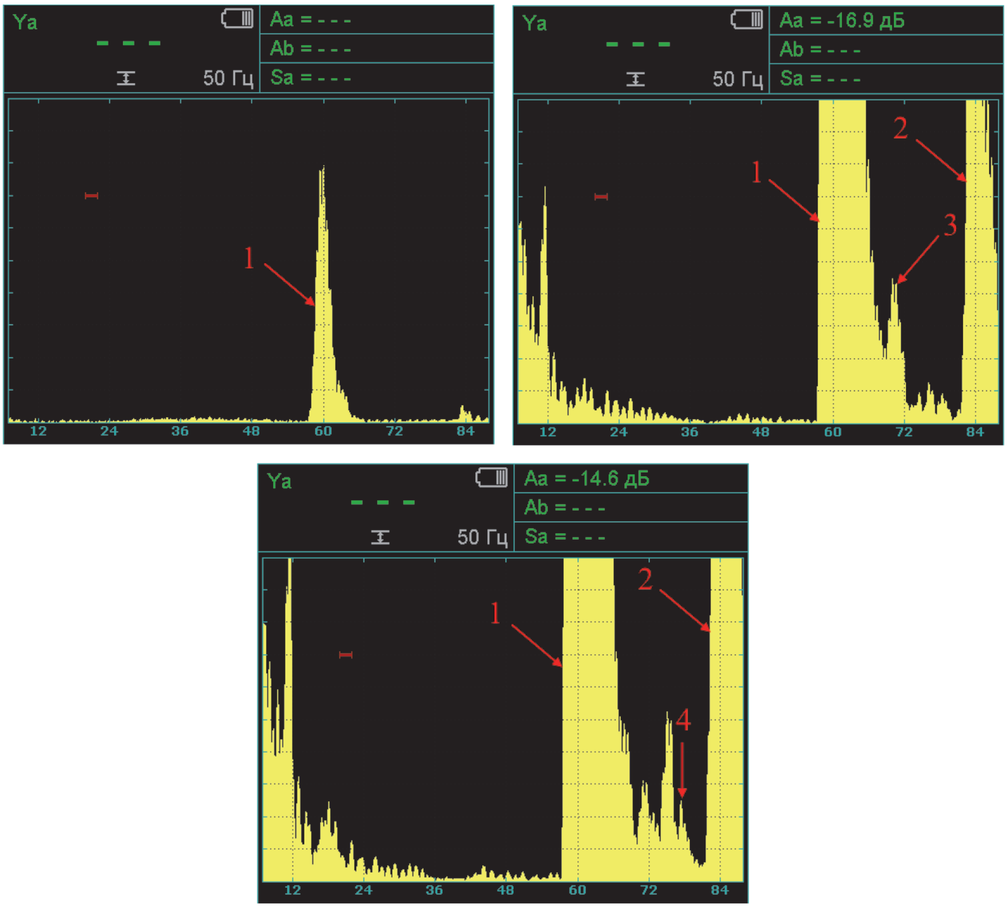
a) b)

a) creeping wave, b) transmitted wave

a) сигнал огибающей волны, b) сигнал прошедшей волны

Figure 7. Results of the through-transmission method

Рисунок 7. Результаты метода прохождения



1 — signal of bottom of steel sample, 2 — signal of interference wave, 3 — signal from wax deposits 3 mm thick, 4 — signal from wax deposits 6 mm thick

1 — донный сигнал от стального образца, 2 — сигнал помехи от трансформации волны, 3 — сигнал от отложений толщиной 3 мм, 4 — сигнал от отложений толщиной 6 мм

Figure 8. Results of echo method

Рисунок 8. Результаты метода отражения

Attenuation

The results of the measurement when studying the method based on attenuation shown on figure 9. The experiment showed that when wax deposits appear, the first reflected signal practically does not change, 4th the reflected signal is attenuated by 1.5 dB. With a further increase of wax deposits, no changes occur.

The attenuation of the signal is not affected by the thickness, but by the composition of the wax deposits. The reflection coefficient by energy at the interface between two media, when the wave is normal incidence, can be found using the formula [27]:

$$R = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2, \qquad (1)$$

where Z — acoustic impedance, can fined by formula (2):

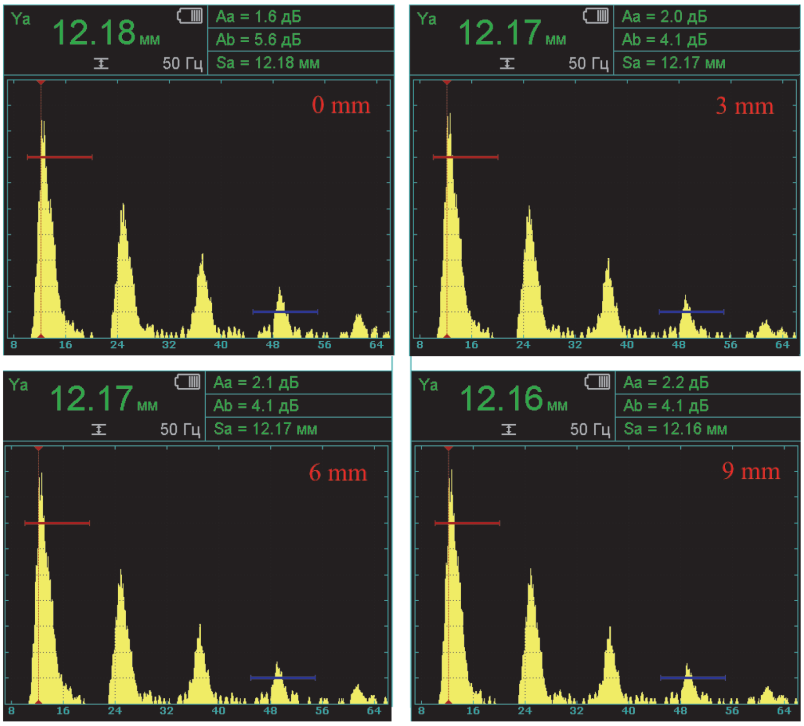
$$Z = \rho C, \qquad (2)$$

where ρ — density of medium; C — velocity of sound in medium.

As can be seen from the formula, the density of the medium and the velocity of sound, and not the thickness of the medium, affects the transmission and reflection of waves. The attenuation method can be used to determine the composition of the medium, rather than the thickness of the wax deposits [24].

Measuring wax deposits

The results of the measurement propagation of ultrasonic waves in wax deposits shown on figure 10. Under the condition of plane-parallel surfaces, the wax thickness was reliably measured up to 7 mm. It should be noted that the measurements are carried out at a high amplification of the flaw de-

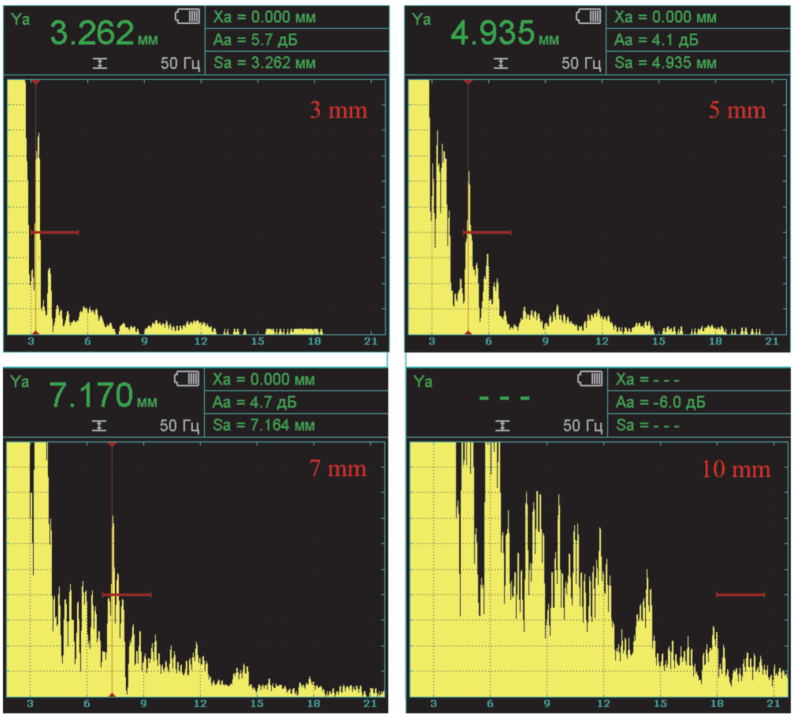


At the top right of each image shown the thickness of the wax deposits, mm

Справа сверху каждого изображения указана толщина отложений парафина в мм

Figure 9. Results of the method based on attenuation

Рисунок 9. Результаты метода, основанного на затухании



At the top right of each image shown the thickness of the wax deposits, in mm

Справа сверху каждого изображения указана толщина отложений парафина в мм

Figure 10. Results of measurement propagation of ultrasonic waves in wax deposits

Рисунок 10. Результаты измерения парафина tector. The 10 mm thick wax deposits signal cannot be distinguished from noise signals.

These results confirm the large attenuation of ultrasonic waves in wax deposits, which limits the use of traditional methods of ultrasonic testing.

Similar results with the attenuation of ultrasonic waves were obtained in the study [28]. The attenuation of the ultrasonic wave occurs due to the difference in propagation velocities in asphaltenes, resins and paraffins, the presence of sand, mud, clay, corrosion products and other substances contained in wax deposits.

Local method of free oscillations

The 700 measurements carried out were checked for the presence of rough fault according to the Charlier criterion. Results that did not meet the criteria were eliminated. Separate series of measurements were checked for belonging to the normal distribution by a graphical method and by calculating the coefficient of skewness and kurtosis. All series of measurements belong to the normal distribution.

The average values in each individual series of measurements were calculated and the analysis of the dependence of the frequency of natural oscillations of the pipeline on the thickness of deposits was carried out using the least squares regression. The Pearson correlation coefficient was R_{xy} = –0.998, which indicates an inversely proportional dependence of the frequency of natural oscillations on the thickness of the deposits.

An assumption is put forward about the presence of a linear relationship between the indicated quantities of the form: $y = ax + b$. Regression analysis was carried out to find the coefficients a and b. The resulting coefficients are a = –6.149, b = 1945.044.

The regression equation takes the form (3)

$$y = -6.149x + 1945.044. \quad (3)$$

On figure 11 shows a graph of the dependence of the oscillation frequency of a local section of the pipeline on the thickness of wax deposits based on the results of an experimental research.

Regression analysis showed that the coefficient of determination is R^2 = 0.996.

The conducted experiment and analysis of the obtained results confirmed the existence of dependence between the frequency of natural oscillations of the pipeline section and the thickness of deposits on its inner walls. The dependence is inversely proportional, and with an increase in the thickness of wax deposits, the oscillation frequency decreases. This dependence can be used as the basis for the method of measuring the thickness of wax deposits.

Modeling

Modeling in the T-Flex CAD software package using finite element analysis for a given test object showed the value of the natural oscillation frequency f_m = 4518.26 Hz.

Analytical solutions for a given test object can be found by the formula (4):

$$\omega = \frac{2\pi^2(m+\frac{1}{3})^2}{a^2}\sqrt{\frac{D}{\rho h}}, \quad (4)$$

where D — bending stiffness, h — steel thickness, p — density, a — size of test object along the OX axis and OY axis, m — whole numbers 1, 2, 3 … [29].

The bending stiffness is found by the formula (5):

$$D = \frac{Eh^3}{12(1-\mu^2)}, \quad (5)$$

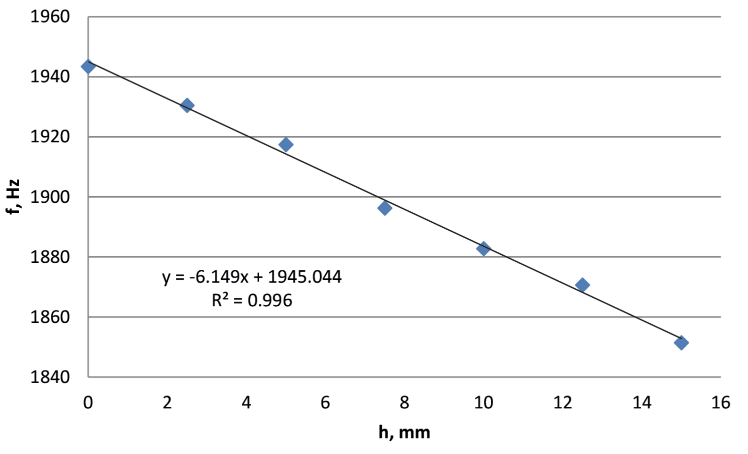


Figure 11. Results of local method of free oscillations

Рисунок 11. Результаты экспериментального исследования where E — elastic modulus, μ — Poisson's ratio, h — steel thickness.

The analytical solution is $f_p = 4674.73$ Hz. The error of modeling and analytical solution is (6):

$$\delta = \frac{|f_м - f_р|}{f_м} \cdot 100\% = 3{,}46\ \% \qquad (6)$$

Further modeling of oscillations with wax deposits from 2 to 14 mm, as expected, showed a decrease in the oscillation frequency with increasing deposit thickness. The simulation results are shown in figures 12 and 13.

The graph on figure 13 shows a linear dependence of the wall oscillation frequency y on the deposit thickness x: $y = ax + b$.

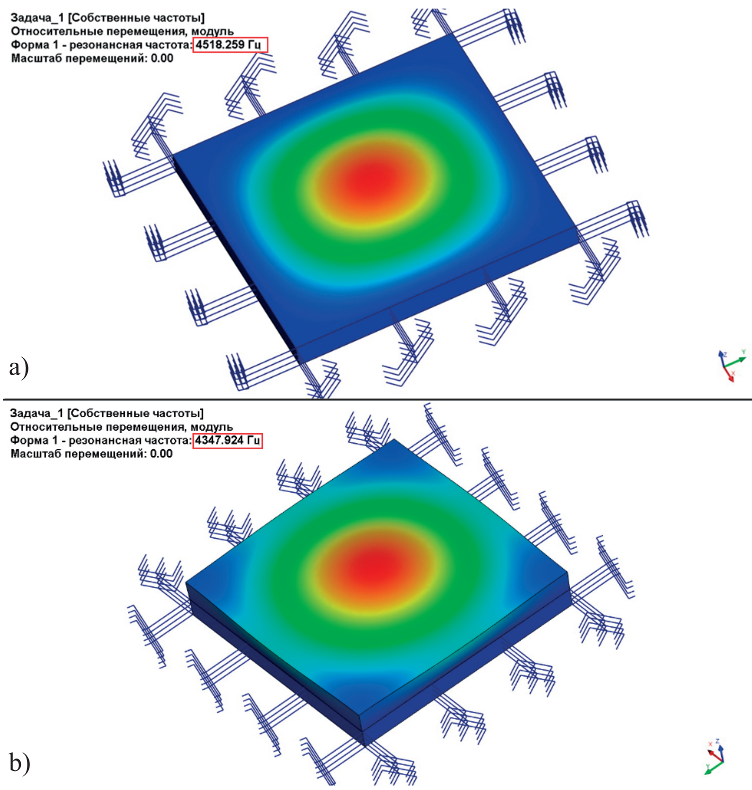
To find the coefficients of the equation a and b, a regression analysis was carried out. Based on the results of the analysis, the following coefficients were obtained $a = -11.885$, $b = 4507.506$.

And the regression equation takes the form (6):

$$y = -11.885x + 4507.506. \qquad (6)$$

Regression analysis showed that the coefficient of determination is $R^2 = 0{,}989$.

Computer modeling confirms the conducted experimental researches on the presence of dependence of the frequency of natural vibrations of the test object on the thickness of wax deposits.



a) a steel plate without deposits.
б) with wax deposits 14 mm thick

а) пластина без отложений;
b) с отложениями толщиной 14 мм

Figure 12. Results of modeling

Рисунок 12. Результаты моделирования

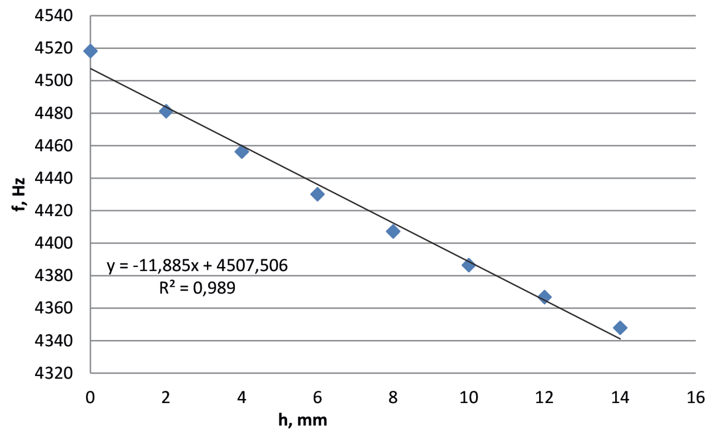


Figure 13. Results of modeling

Рисунок 13. Результаты моделирования

Conclusion

Acoustic methods of non-destructive testing have advantages over other methods of measuring wax deposits. They can be implemented with one-way access and do not violate the integrity of the test object.

The conducted experimental studies show that traditional ultrasonic methods of non-destructive testing using directional wave have limitations that make their application difficult. Two main obstacles can be distinguished — the large attenuation and an unknown velocity of acoustic waves in wax sediments. Attenuation prevents the use of ultrasound at large thicknesses of deposits, and not knowing the velocity (due to the unknown composition of deposits) does not allow calculating the path of the acoustic wave.

The dependence of oscillations of the local section of the test object on the thickness of wax deposits, confirmed by the results of experiments and computer simulation, can be used as the basis for measuring the thickness of deposits on the inner walls of pipelines. The dependence is inversely proportional and with the increase of deposits, the resonant frequency of oscillations of the test object decreases.

This dependence requires further study to identify additional parameters and develop a reliable mathematical model.

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