ПРИЛАДОБУДУВАННЯ ТА ІНФОРМАЦІЙНО-ВИМІРЮВАЛЬНА ТЕХНІКА

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THEORETICAL INVESTIGATIONS OF THE ULTRASONIC WAVE GENERATION BY AN ELECTROMAGNETIC ACOUSTIC TRANSDUCER

Background. The article considers the analysis of the electromagnetic acoustic (EMA) converter with controlled angular input of acoustic waves, using parameters influencing the formation of an acoustic wave.
Objective. The aim of the paper is to analyze the formation of an acoustic wave with angular input in the EMA converters of non-destructive testing systems.
Methods. Mathematical modelling was used to investigate the influence of the distance from the yarn-emitters to the control object surface. The influence of various factors (current magnitudes, external magnetic field values, distance from the yarn-emitter and the grating to the control object surface) is investigated with the help of mathematical modeling.
Results. The optimal value of the magnetic induction of an external magnetic field is shown. The calculation of the pressure created by the yarn-emitters and the grating on the controlled object surface was carried out. A formula for the ultrasonic wave input angle was obtained. The formula depends on the parameters of the control environment, the distance between the emitters, the phase shift between the harmonic current signals applied to the adjacent emitters and the harmonic signal frequency. It was found that a change in the angle between the EMA transducer and the surface of the control object leads to a significant deterioration in the acoustic wave generation on the surface of the controlled object.
Conclusions. We investigated the possibility of the angular input of an ultrasonic wave using system of parallel-arranged yarn-emitters. A decrease in the acoustic pressure, with increasing distance from the yarn-emitters to the controlled object surface was observed.

Keywords: EMA transducer; acoustic pressure; non-destructive testing; angular input; ultrasonic wave.

Introduction

Among the studies related to the creation of non-destructive testing equipment, the search for non-contact methods of excitation and recording of ultrasound in solid bodies are important [1]. The progress in this direction has been achieved through the use of electromagnetic-acoustic (EMA) method of generation and reception of ultrasonic vibrations.

Currently, the controlled angular input of an acoustic wave is practically not used in EMA flaw detectors, which substantially limits the areas of their use. At the same time, EMA flaw detectors that have a fixed or discretely switched angle of acoustic wave input are widely used. The problem of controlled angular input of an acoustic wave based on EMA converters can be solved only as a result of the radiation investigation, the formation of a magnetic field [2, 3], and the formation of monitoring pulses [4]. The solution of the task of investigating radiation will increase the reliability and speed of ultrasonic flaw detection.

Problem statement

The aim of the paper is to analyze the formation of an acoustic wave with angular input in EMA converters of non-destructive testing systems.

Analysis of the formation of acoustic vibration with a yarn-emitter

The yarn-emitter with the harmonic current is located at a distance h (Fig. 1) from the elastic, homogeneous, isotropic and linear-conductive half-space 2 [5]:

$$I = I_0 \cos(\omega t) = I_0 \cos(2\pi f t)$$

where I_0 is an amplitude value of the yarn-emitter current; ω is a circular frequency; f is a frequency of a current in a yarn-emitter.

The following measures were assumed [5]: the rigidly fixed yarn-emitter doesn't execute mechanical vibrations, the phase and amplitude of the current in the yarn-emitter is constant throughout its length.

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The yarn-emitter is stretched along the axis along the lines $y = 0$, $z = h$.

The half-space 1 (air) is characterized by electrical conductivity $\delta_1 = 0$, the magnetic permeability $\mu_1 = \mu_2$ and the dielectric permeability $\varepsilon_1 = \varepsilon_0$.

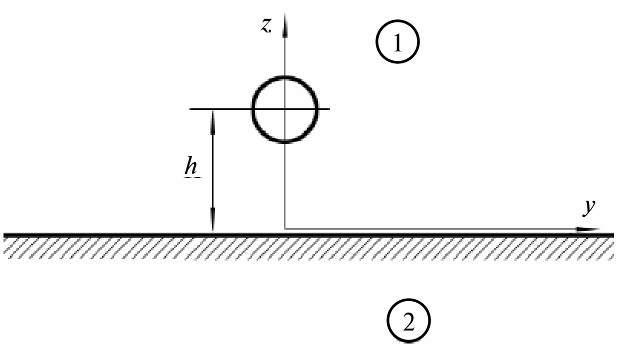

Fig. 1. Location of the yarn-emitter concerning the controlled object

The half-space 2 (iron) has the electrical conductivity $\delta_2 = \delta$, the magnetic permeability of $\mu_2 = \mu_1 \cdot \mu$.

The flowing current I_0 along the yarn-emitter generates eddy currents. The electromagnetic coupling of the primary and induced currents causes pressures on the surface of the half-space 2.

It is known that the efficiency of EMA conversion increases with an external magnetic field [2].

This follows from the theory of ferromagnetism and is explained by the fact that a large contribution to the reduction of ultrasonic vibrations in ferromagnets is caused by losses in eddy currents. They arise during moving domains. The external magnetic field leads to ordering of the domain structure and reduces the ultrasonic attenuation.

In this case, the magnetic field of the currents $(B_{\approx})$ adds to the external constant magnetic field $(B_{=})$, which can be written as [6]

$$B_{\Sigma} = B_{\approx} + B_{=}.$$

A formula describing the law of the distribution of pressures on the surface of the half-space 2 can be written in the following form [6]:

$$p = -\mu_0 \cdot \mu \frac{I_0^2 h^2}{4\pi(h^2 + y^2)^2}(1 + \cos 4\pi \cdot f \cdot t) - \frac{I_0 h B_{=}}{\pi(h^2 + y^2)} \cos 2\pi \cdot f \cdot t$$

where $B_{=}$ is an induction of an external constant magnetic field; h is a distance from center of the yarn-emitter to the controlled object surface; y is a distance from the projection of the thread along the yarn-emitter of controlled object in the direction perpendicular to the projection; $\mu_0 = 4\pi \cdot 10^{-7}$ H/m is a magnetic constant; μ is a magnetic permeability material of the controlled object.

The relation mentioned above establishes the relationship between the acoustic pressure on the surface with the current of the yarn-emitter and its location. The highest acoustic pressure is created directly under the yarn-emitter. With increasing

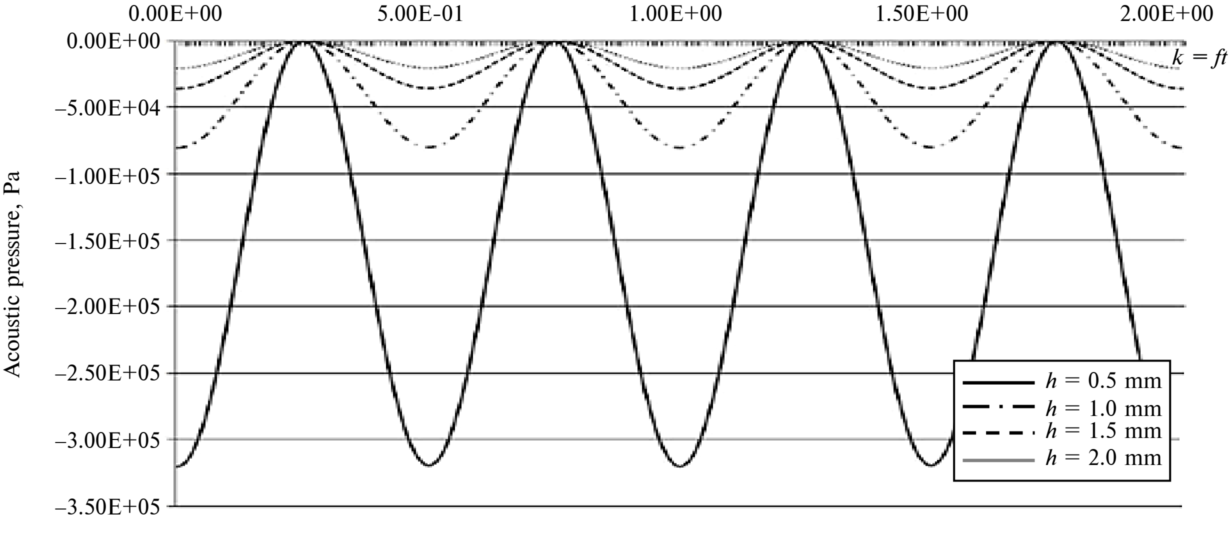

Fig. 2. The family of dependences $p(t)$ for different values on the distance h, $(y = 0)$, $B_{=} = 0{,}3$ T, $I_0 = 2$ A, $f_i = 0{,}5$ MHz

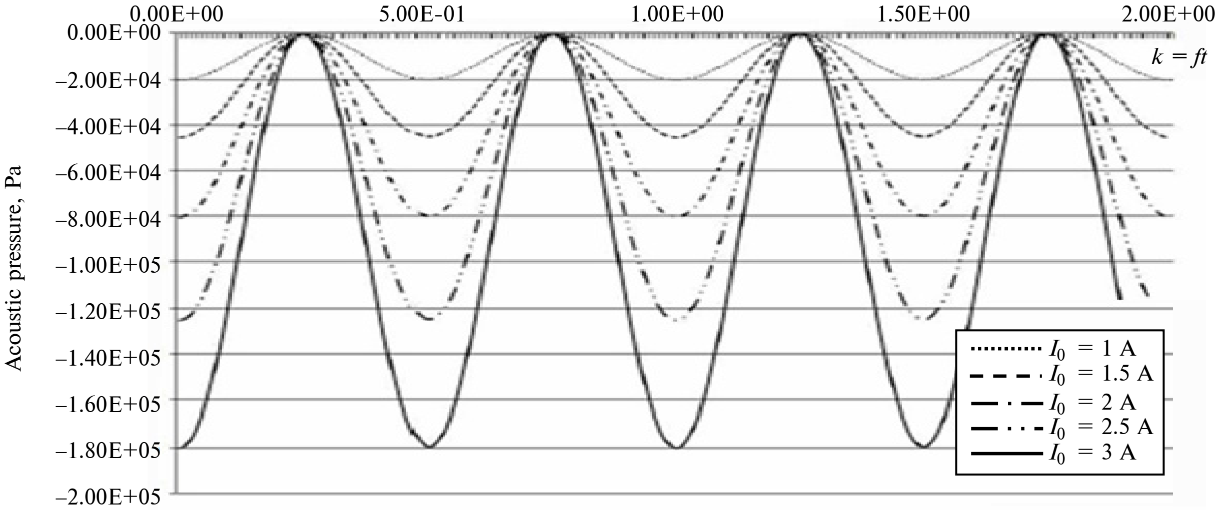

Fig. 3. The family of dependences *p*(*t*) for different amplitude values on current I_0, $(y = 0)$, $B_= = 0,3$ T, $h = 1$ mm, $f_i = 0,5$ MHz

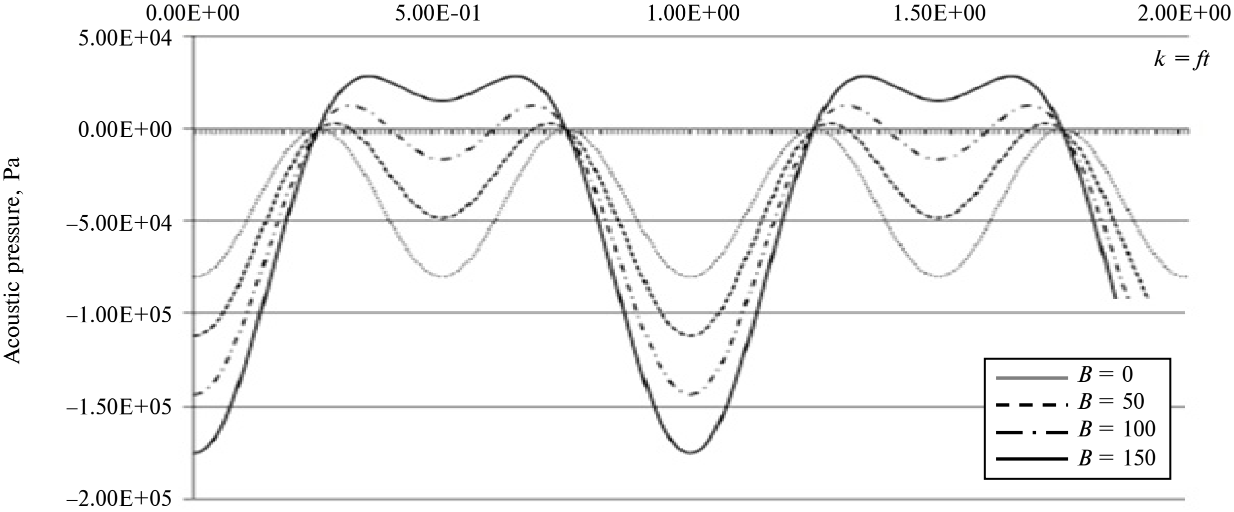

Fig. 4. The family of dependences *p*(*t*) for different values on induction $B_=$, $(y = 0)$, I_0=2 A, $h = 1$ mm, $f_i = 0,5$ MHz

the distance from this line and with increasing distance h, the pressure falls sharply. As the value of the current increases, the pressure increases quadratically. Changed in time, it does not change its value and changes from zero to maximum twice per period of supply current.

Numerous experimental investigations of generation processes and reception of normal waves by EMA method were conducted in Dnipro pipe plant [7]. They revealed the optimal value of the external magnetic field $B_= = 0,3$ T at the control of various objects (pipes and leaf) made from ferromagnetic steel.

The influence of various factors (current values I_0, the values of the external magnetic field $B =$, the distance h from the yarn-emitter to the controlled object) on the created acoustic pressure are presented on diagrams below (Figs. 2–4).

Analysis of the formation of acoustic vibrations based on a system of discrete units

When EMA is triggered [8] by a system of synphased converters (Fig. 5), the width $\Delta y = l = \lambda$; during generating of systems of antiphase transducers

$$\Delta y = l = \lambda/2$$

is a length of the normal wave at the corresponding operating point; $\lambda = \frac{c_c}{f}$ is a phase velocity of the ultrasonic wave; f is an operating frequency of ultrasonic radiation.

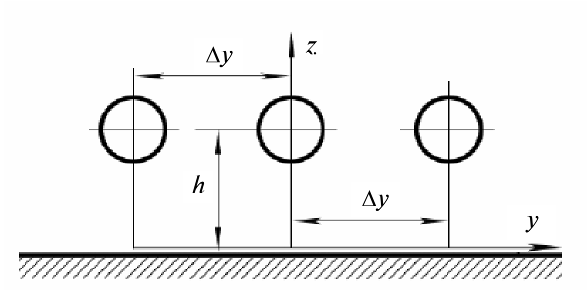

Fig. 5. The location of yarn-emitters

The number of yarn-emitters and their length affects the size of the resulting radiation beam.

The pressure at each point of the surface of the controlled space under the grating will be created by each yarn-emitter, taking into account the distance from the point to the cenetr of each transducer [9]:

$$p_\Sigma(x,y)=\sum_{m=1}^{n} p_m(x,y)$$

$p_\Sigma(x,y)$ is a total pressure created by the grating on the surface of the controlled space at the point with coordinates (x, y); $p_m(x,y)$ is a pressure created on the surface of the controlled space at the

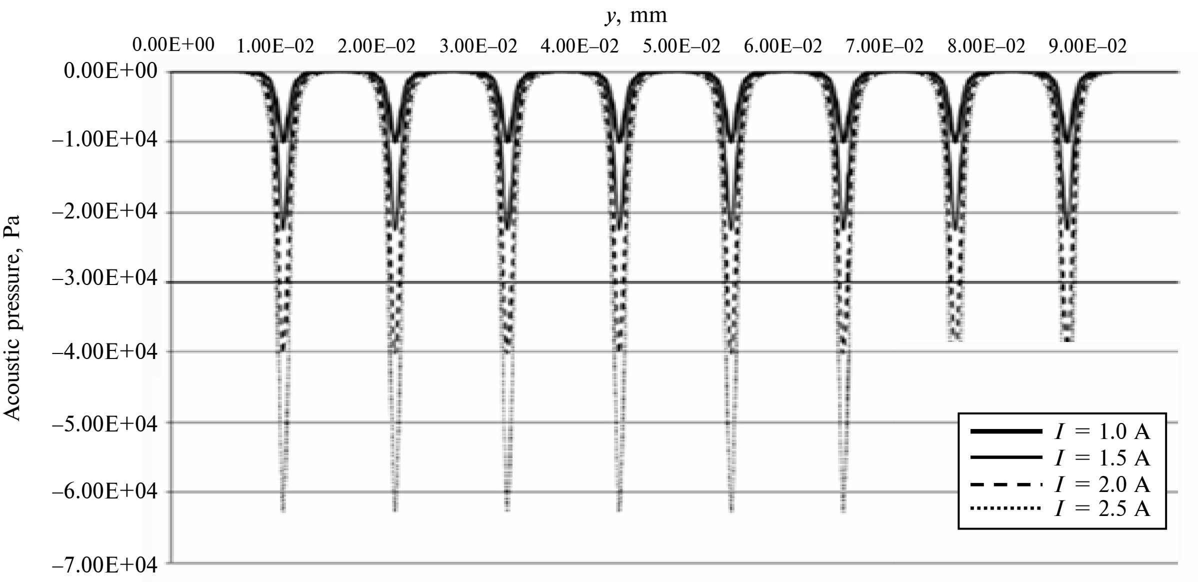

Fig. 6. Dependence of $p_\Sigma(y)$ for different values on current amplitude I_0, $B_= = 0,3$ T, $h = 1$ mm, $f_i = 0,5$ MHz

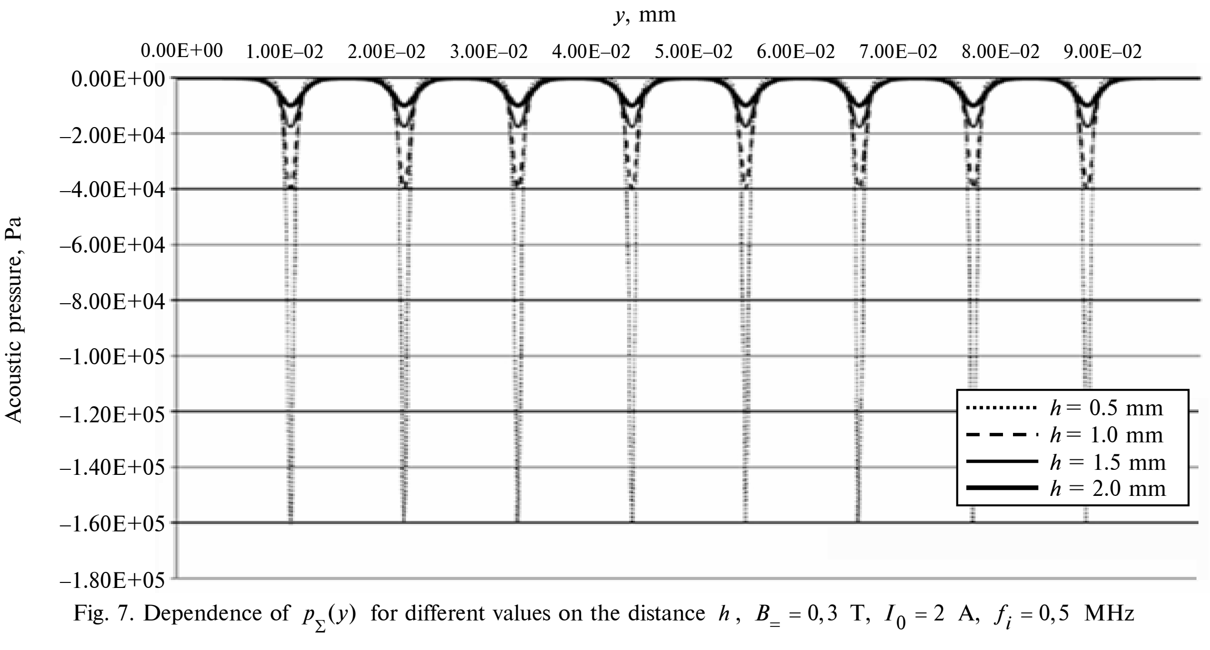

Fig. 7. Dependence of $p_\Sigma(y)$ for different values on the distance h, $B_= = 0,3$ T, $I_0 = 2$ A, $f_i = 0,5$ MHz

point with coordinates (x, y) by use of transducer m, where $m = 1, 2, \ldots, n$.

The average pressure on the controlled object surface limited by the grating can be determined if the magnetic flux passes equally throughout the volume of the triggered surface.

The influence of various factors on the total acoustic pressure p_Σ (Figs. 6–8) was modeled for investigating the process of formation of yarn-emitters' synthesis of acoustic vibrations. The simulation data is the effect of the angle between the transducer and the controlled surface, on the generated acoustic pressure (Fig. 9).

Figs. 6–8 show the diagrams of the formation of the acoustic wave by the grating consisting of yarn-emitters. There is a decrease in acoustic pressure, as the value of the current amplitude I_0 and the distance h increase from the center of the yarn-emitter to the controlled object surface (see Figs. 6, 7). The shape of the pressure distribution changes sharply when the transducer is installed at an angle to the surface (see Fig. 9).

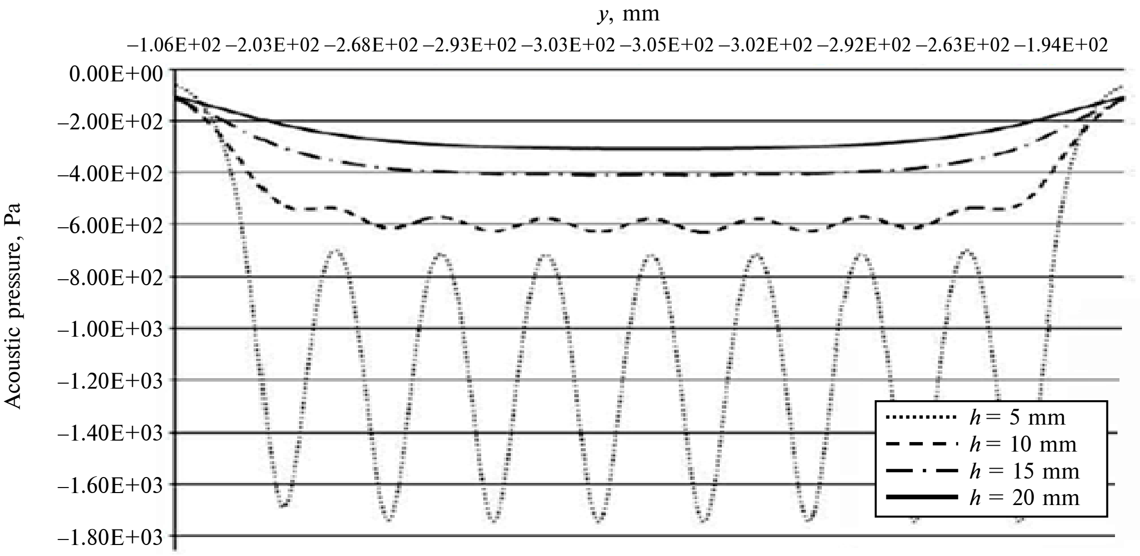

Fig. 8. Dependence of $p_\Sigma(y)$ for large values of distance h, $B_= = 0{,}3$ T, $I_0 = 2$ A, $f_i = 0{,}5$ MHz

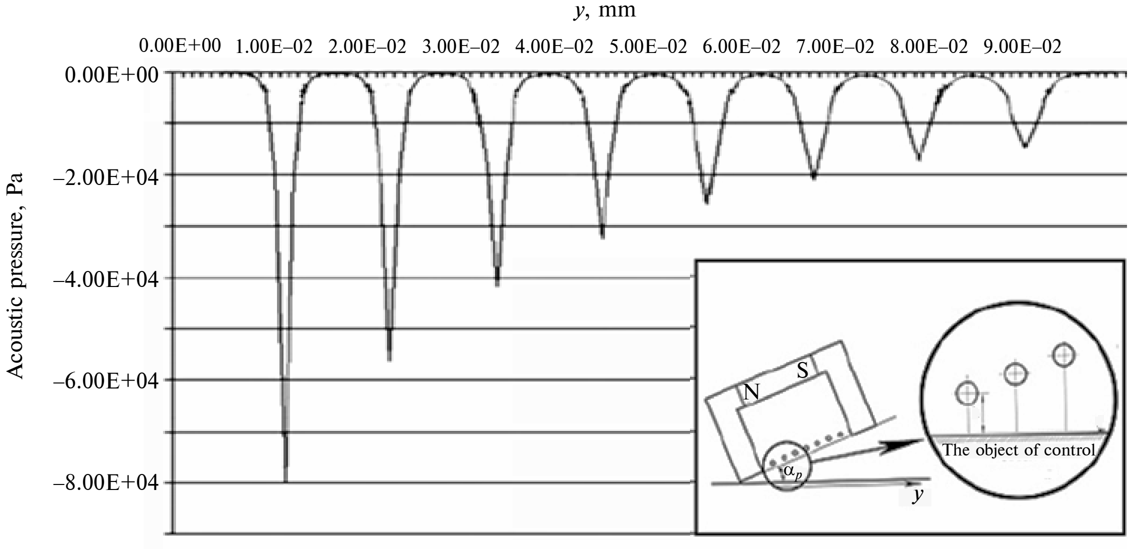

Fig. 9. Dependence of $p_\Sigma(y)$ in the case of a distortion of the sensor by $\alpha_p = 0{,}5^\circ$ in reference to the controlled object surface, $B_= = 0{,}3$ T, $h = 1$ mm, $f_i = 0{,}5$ MHz, $I_0 = 2$ A

Analysis of the formation of the angular input of an ultrasonic wave

Scholarly papers [10—12] show the principle possibility of angular input of ultrasonic vibrations by use of EMA converter, where the basic formulas are obtained. At the same time, the question of the practical application of a smooth control of the input angle of an ultrasonic wave using EMA converters with transducers in the form of a grating of conductors remains open.

It is known [11] that when a plane ultrasonic wave falls along the boundary a forced travelling appears, speed and direction of which depends on the angle of incidence.

In this case, the source of the refracted waves is an oscillating interface, which can be efficiently triggered by using EMA converter built on the basis of a grating of an elementary conductor — radiators located in the same plane (Fig. 10).

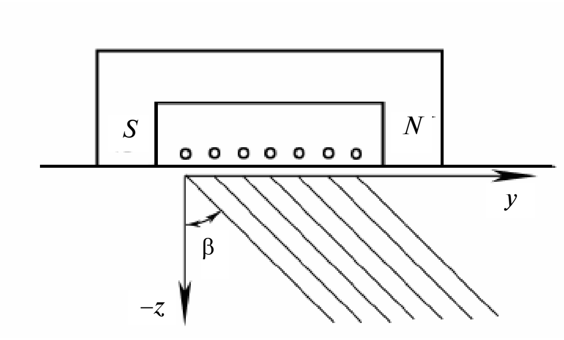

Fig. 10. Angular input of an ultrasonic wave in EMA converter

The component $\frac{\lambda}{l}$ determines the divergence of the radiation beam. In the case $l >> \lambda$, the radiation beam will be low-divergent.

The speed c_2 is determined by the vibration frequency f and $y_{2\pi}$ — a distance between the nearest points of the wave front along the propagation of the travelling wave, phase of oscillations of which differs by 2π [11, 12].

To generate a travelling wave with specified properties, it is necessary that the pressure under each conductor-radiator changes consistently, with the phase displacement $\Delta\varphi$ [12]:

$$\Delta\varphi = \frac{4\pi\cdot\Delta y\cdot f_l\cdot\sin\beta}{c_1}$$

where Δy is a distance between neighbouring yarn-emitters.

A predetermined phase displacement is provided by delaying the supply of a harmonic signal to neighbouring yarn-emitters for a certain time interval Δt.

The working formula for calculating the delay time for the supply of a harmonic signal to neighbouring yarn-emitters to provide a given input angle of the ultrasonic wave b can be written as [12]:

$$\Delta t = \frac{2\cdot\Delta y\cdot\sin\beta}{c_1}$$

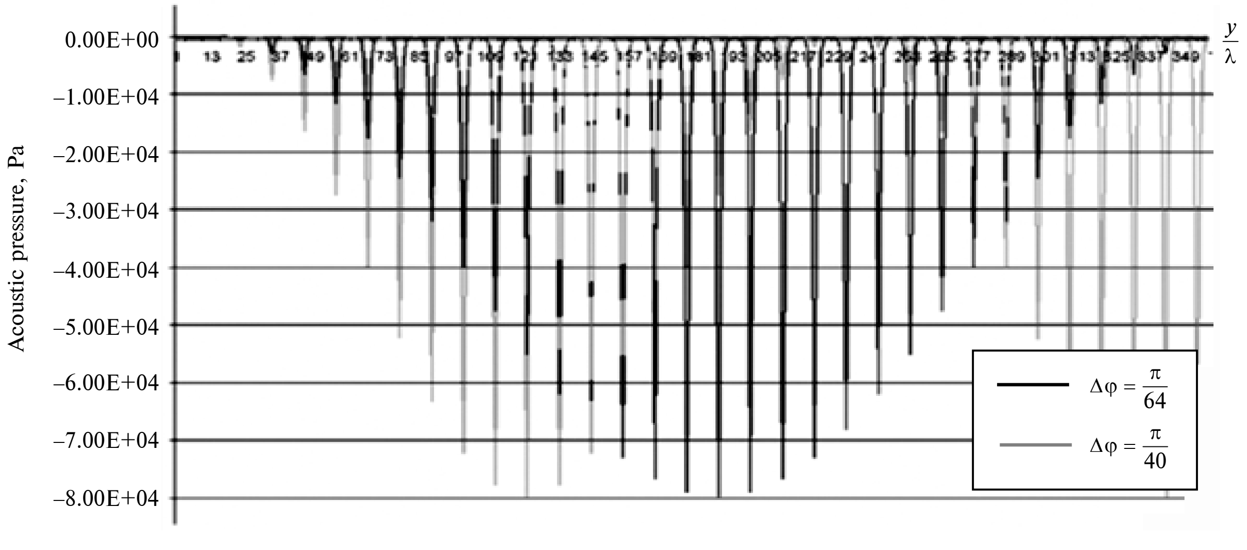

Fig. 11. Dependence of $p_\Sigma(y)$ for different values on $\Delta\varphi$ 32 yarn-emitters $B_= = 0,3$ T, $f_i = 0,5$ MHz, $I_0 = 2$ A, $k = f\cdot t = 1/4$

During examining the digital control system of EMA transducer with an angular input of an ultrasonic wave, it is more convenient to operate not with time intervals, but with a pulse frequency f_T and the number of pulses N_I.

If we assume that the half-period of the current change in the yarn-emitters of EMA converter is the time interval including N_{IT} – a number of setting pulse corresponding to the time interval Δt, then the formula for b can be written as [11, 12]

$$\beta = \arcsin\left(\frac{c_1 \cdot N_{I\varphi}}{2 \cdot \Delta y \cdot f_T}\right).$$

To investigate the process of grating formation of synphase yarn-emitters of acoustic vibrations with angular input different factors (phase displacement $\Delta\varphi$; yarn-emitter current value I_0 distance h from the yarn-emitter and the grating to the controlled object surface; the angle of the sensor α_p comparative to the object surface) to the total acoustic pressure p_Σ (Figs. 11, 12).

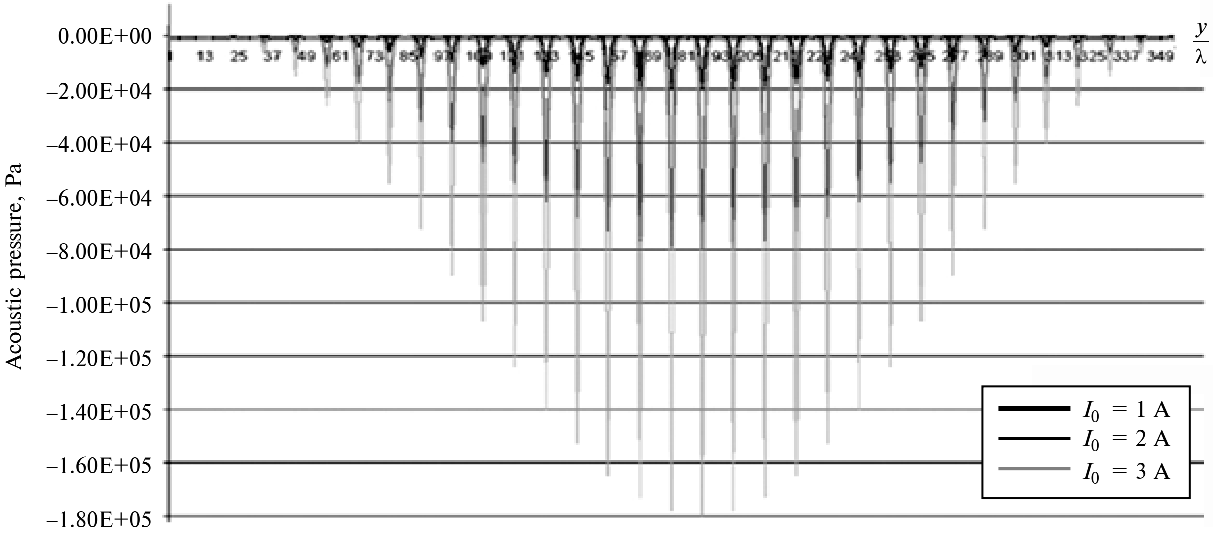

Fig. 12. Dependence of $p_\Sigma(y)$ for current amplitude values on I_0 32 yarn-emitters, $B_= = 0,3$ T, $f_i = 0,5$ MHz, $k = f \cdot t = 1/4$, $\Delta\varphi = \pi/64$

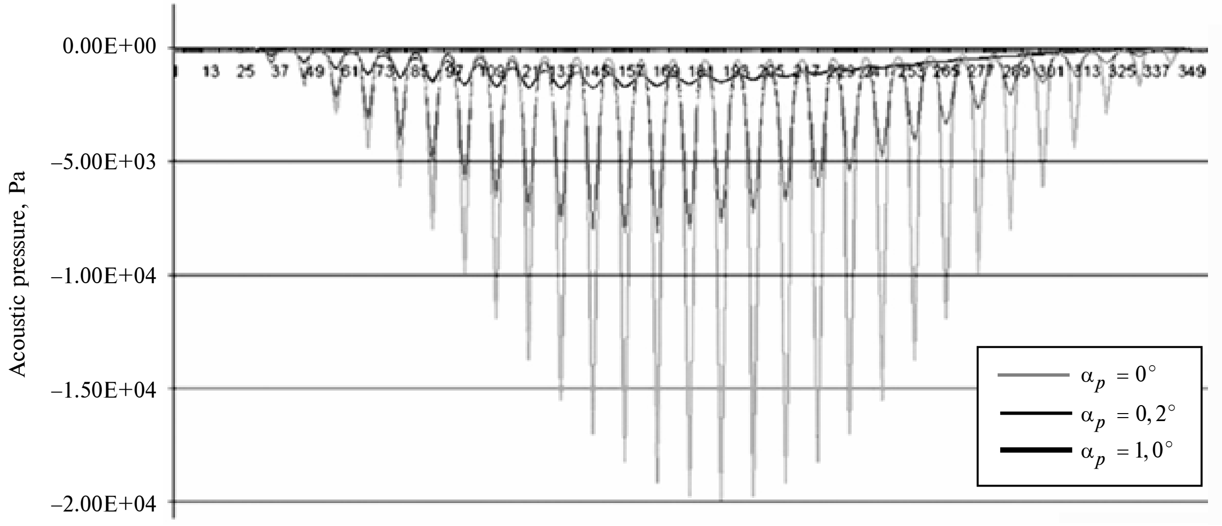

Fig. 13. Dependence of $p_\Sigma(y)$ when the sensor is displaced relative to the surface on 32 yarn-emitter object, $B_= = 0,3$ T, $I_0 = 2$ A, $f_i = 0,5$ Hz, $k = f \cdot t = 1/4$, $\Delta\varphi = \pi/64$

The investigation of the effect of inaccuracy in positioning the radiator grating on the efficiency of generation of the wave at angle to the controlled object surface is of great practical interest. The simulation data show the influence of the angle α_p between the transducer and the controlled surface on the formation of an acoustic wave with an angular input (Fig. 13).

Figs. 11–13 illustrate the distribution of pressures under the yarn-emitters in the phased feeding of probe pulses and their variation from the phase displacement between the yarn-emitters, as well as the current amplitude.

Installation of EMA sensor even at a small angle can lead to the acoustic wave breakdown.

Conclusions

The problem of controlled angular input of an acoustic wave by using EMA converters can be solved only by a joint study of radiation problems, the formation of a magnetic field, and the formation of transmitted pulse.

With the help of mathematical modelling, the influence of various factors (current values, values of the external magnetic field, distance from the yarn-emitter and the grating to the controlled object surface) was investigated. The optimal value of the magnetic induction of an external constant magnetic field is determined to control EMA by a converter. The calculation of the pressures created by the yarn-emitter and the grating on the controlled object surface is considered.

It is shown that without an external magnetic field, the acoustic pressure doesn't change value from zero to maximum twice during the period of current. Under the influence of a strong external magnetic field, the acoustic pressure under the string increases, the shape of the dependence of its magnitude on time changes, positive and negative values appear. The maximum acoustic pressure is created directly under the transducer. At a distance from this line and with increasing distance from the yarn-emitter to the object of control, the pressure falls sharply. Acoustic pressure also depends significantly on the amplitude value of the current in the yarn-emitters.

The possibility of the angular input of an ultrasonic wave with the system of parallel-arranged yarn-emitters was investigated. The distance between the yarn-emitters, the phase displacement between the harmonic current signals fed to neighbouring radiators and harmonic frequencies signal are established on the parameters of the controlled environment for the angle of input of the ultrasonic wave. It is shown that even a slight distortion of EMA sensor leads to a significant deterioration in the generation of the acoustic wave at an angle to the controlled object surface.

Further investigations are proposed to be carried out in the direction of the formation of the angular input of the ultrasonic wave of EMA by a transducer with the given characteristics.

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ТЕОРЕТИЧНІ ДОСЛІДЖЕННЯ ЗБУДЖЕННЯ УЛЬТРАЗВУКОВОЇ ХВИЛІ ЕЛЕКТРОМАГНІТНО-АКУСТИЧНИМ ПЕРЕТВОРЮВАЧЕМ

Проблематика. Стаття присвячена аналізу електромагнітно-акустичного (ЕМА) перетворювача з керованим кутовим введенням акустичної хвилі, виходячи з параметрів, що впливають на формування акустичної хвилі.

Мета дослідження. Метою роботи є аналіз формування акустичної хвилі з кутовим введенням в ЕМА-перетворювачах систем неруйнівного контролю.

Методика реалізації. За допомогою математичного моделювання досліджено вплив відстані від ниток-випромінювачів до поверхні об’єкта контролю. Також за допомогою математичного моделювання досліджено вплив різних факторів (величини струму, значення зовнішнього магнітного поля, відстані від нитки й решітки до поверхні об’єкта контролю) на формування акустичної хвилі.

Результати досліджень. Показано оптимальне значення магнітної індукції зовнішнього постійного магнітного поля. Проведено розрахунок тисків, створюваних ниткою й решіткою на поверхні контрольованого об’єкта. Отримано вираз для кута вводу ультразвукової хвилі, що залежить від параметрів середовища контролю, відстані між нитками-випромінювачами, зсуву фаз між гармонійними струмовими сигналами, які подаються на сусідні випромінювачі, та частоти гармонійного сигналу. Виявлено, що зміна кута між ЕМА-перетворювачем і поверхнею об’єкта контролю призводить до значного погіршення збудження акустичної хвилі на поверхні об’єкта контролю.

Висновки. Досліджено можливість кутового введення ультразвукової хвилі за допомогою системи паралельно розміщених ниток-випромінювачів. Показано різке зниження акустичного тиску при збільшенні відстані від ниток-випромінювачів до поверхні об’єкта контролю.

Ключові слова: електромагнітно-акустичний перетворювач; акустичний тиск; неруйнівний контроль; кутове введення; ультразвукова хвиля.

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ТЕОРЕТИЧЕСКИЕ ИССЛЕДОВАНИЯ ВОЗБУЖДЕНИЯ УЛЬТРАЗВУКОВОЙ ВОЛНЫ ЭЛЕКТРОМАГНИТНО-АКУСТИЧЕСКИМ ПРЕОБРАЗОВАТЕЛЕМ

Проблематика. В статье рассмотрен анализ электромагнитно-акустического (ЭМА) преобразователя с управляемым угловым введением акустической волны, исходя из параметров, влияющих на формирование акустической волны.

Цель исследования. Целью работы является анализ формирования акустической волны с угловым введением в ЭМА-преобразователях систем неразрушающего контроля.

Методика реализации. С помощью математического моделирования исследовано влияние расстояния от ниток-излучателей к поверхности объекта контроля. Также с помощью математического моделирования исследовано влияние различных факторов (величины тока, значение внешнего магнитного поля, расстояния от нити и решетки к поверхности объекта контроля) на формирование акустической волны.

Результаты исследований. Показано оптимальное значение магнитной индукции внешнего постоянного магнитного поля. Проведен расчет давлений, создаваемых нитью и решеткой на поверхности контролируемого объекта. Получено выражение для угла ввода ультразвуковой волны, которое зависит от параметров среды контроля, расстояния между нитями-излучателями, сдвига фаз между гармоническими токовыми сигналами, подаваемыми на соседние излучатели, и частоты гармоничного сигнала. Обнаружено, что изменение угла между ЭМА-преобразователем и поверхностью объекта контроля приводит к значительному ухудшению возбуждения акустической волны на поверхности объекта контроля.

Выводы. Исследована возможность углового введения ультразвуковой волны с помощью системы параллельно расположенных нитей-излучателей. Показано резкое снижение акустического давления при увеличении расстояния от ниток-излучателей к поверхности объекта контроля.

Ключевые слова: электромагнитно-акустический преобразователь; акустическое давление; неразрушающий контроль; угловой ввод; ультразвуковая волна.

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