У системах автоматичного керування існує нагальна потреба вимірювання швидкозмінних нестаціонарних фізичних величин у реальному, чи близько до цього, часі. В цій галузі окремою групою вирізняються задачі вимірювання нестаціонарного тиску рідин чи газів.

Показується, що вимірювання нестаціонарного тиску у реальному, чи близько до цього, часі представляє собою задачу відновлення вхідного сигналу, яка з погляду математики відноситься до класу некоректно поставлених проблем (згідно Ж. Адамара). Отримано розв'язок оберненої задачі вимірювання, що базується на математичній моделі вимірювального перетворення, яке здійснює сенсор тиску. На основі цього розв'язку побудований метод вимірювання, що передбачає вейвлет опрацювання вихідного сигналу сенсора. При цьому в якості базисних функцій вейвлет перетворення запропоновано обирати такі, які є модифікацією імпульсної перехідної функції сенсора.

Подається експериментальне дослідження дієздатності розробленого методу, яке базується на вимірюванні імітованого імпульсу тиску. Імпульс тиску імітується падінням кульки з каліброваною масою на мембрану сенсора. Запропонована вимірювальна схема, для визначення тривалості торкання кульки до мембрани. Перевірка точності методу полягає на порівнянні реальної маси кульки з визначеної за вихідним сигналом сенсора. Запропонований метод показав високу точність, оскільки максимальна відносна похибка визначення маси падаючої кульки становила лише 0,65 %.

Запропонований метод вимірювання нестаціонарного тиску може бути використаний в системах керування в яких необхідне швидкодіюче коригування динамічної похибки вимірювання. Серед інших це системи керування в аерокосмічній техніці, випробувальних комплексах, військовій техніці, наукових дослідженнях

Ключові слова: вимірювання нестаціонарного тиску, обернена задача вимірювання, реальночасовий метод вимірювання, вейвлет перетворення

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CONSTRUCTION AND INVESTIGATION OF A METHOD FOR MEASURING THE NON-STATIONARY PRESSURE USING A WAVELET TRANSFORM

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1. Introduction

At present, numerous highly technological automated control systems face a pressing issue to measure the fast-changing non-stationary physical quantities in real time, or close to that. Among these tasks, there is a separate group of tasks on measuring the non-stationary mechanical magnitudes, namely the pressure of liquids or gases. Such problems are especially relevant in aerospace engineering, testing complexes, military engineering, scientific research [1–4].

However, measuring the non-stationary pressure in real time represents a problem on recovering an input signal, which, from the standpoint of mathematics, refers to the class of ill-posed problems (according to J. Hadamard) [5]. In general, there are methods to solve ill-posed problems [6, 7], or methods to adjust a dynamic measurement error [8, 9]. However, these methods are not applicable to measuring in real time, or close to that, because they are associated with an unacceptably high time cost, or are not precise enough.

Therefore, it is relevant task to construct precise and high-speed real-time methods for measuring the non-stationary pressure.

2. Literature review and problem statement

Measuring the non-stationary pressure poses a specific task, especially if it is a fast-occurring process and measurements must be performed in real time. The methods for measuring the non-stationary pressure that are known at present can be combined into two groups, namely: hardware methods (methods that employ specialized sensors) and methods that involve specialized processing of the output signal (the application of filtering, using the decomposition of the sensor's signal, etc.). Thus, there is a method for measuring the non-stationary pressure that implies the use of a specialized sensor [10], whose structure includes an accelerometer mounted on the membrane to measure its acceleration. A significant disadvantage of this method is the need for a very precise synchronization between the work of the channels that measure the deformation of a sensor's membrane and the measurement of its acceleration using an accelerometer. In addition, such a combined sensor has sophisticated metrological software and requires specialized tools to acquire the metrological characteristics, especially dynamic. In addition, when in operation, the sensor would require proper positioning in order to prevent the parasite components under side fluctuations in the mass of the accelerometer. The above disadvantages are the cause of the method's low precision, which rules out its use for highly technological control systems.

Paper [11] suggests using, to measure the fast-changing pressure, a piezoelectric pressure sensor. Indeed, the piezoelectric sensors that have a high frequency of natural oscillations are suitable for measuring the fast-changing pulse pressure, however, they are not applicable to measure the pressure that exhibits static or slow-changing regions. And this is common for the non-stationary processes. Therefore, it is still a relevant task to devise a method of measurement that could be used at arbitrary non-stationarity of the measured pressure.

There is a known method for measuring the non-stationary pressure [12], which is based on a mixed algorithm applying a wavelet transformation and a variational decomposition. The main disadvantage of this method is the significant duration of the procedure for signal processing and low accuracy, since it does not imply the procedure for recovering an input signal, only "denoising" it. Therefore, the task to measure the non-stationary pressure in real time, or close to that, remains relevant.

There is another method to process a non-stationary signal [13], which is based on the application of wavelet transforms. However, this method, similarly to the previous one, focuses on "cleaning" the signal from noise; its accuracy in the measuring procedure has not been determined. These shortcomings do not make it possible to use this method for measuring procedures, especially those in real time.

At present, there are methods to process signals that exploit a Kalman filter [14, 15]. In this case, the procedure is implemented at the rate of measurement and it does not require the stationarity of the measured signal. However, when employing a Kalman filter, it may face discrepancies as a result of inaccuracies in the source data. This situation makes it impossible to use the methods, which is not acceptable at actual measurements in high-speed systems of automation.

In general, it is obvious that the shortcomings in existing measurement methods do not allow their use in precision high-speed systems; therefore, it is necessary to construct new, more effective methods.

3. The aim and objectives of the study

The aim of this work is to develop a fast method for measuring the non-stationary pressure.

To accomplish the aim, the following tasks have been set:

– to examine correctness of the problem on measuring the non-stationary pressure;

– to solve the inverse measurement problem;

– to investigate a possibility of applying a wavelet transformation of the sensor's output signal to the inverse measurement problem;

– to test the feasibility of the method when measuring the simulated pressure pulse.

4. Theoretical aspects of measurement method

4. 1. Measurement of the non-stationary pressure as an ill-posed problem

When measuring the non-stationary pressure, the piezoelectric or piezoresistive sensors are commonly used [1–4, 16–19]. A transformative function of such sensors can be represented in the form of the convolution integral

$$U(t)=k\int_0^t p(\tau)\cdot e^{-\beta(t-\tau)}\cdot\sin(\eta(t-\tau))d\tau, \tag{1}$$

where U(t) is the sensor's output signal, k is the static factor of sensor transformation, p(t) is the measured pressure, η and β are the frequency of own oscillations and a damping coefficient of fluctuations of the sensor's mechanical part.

Thus, during measurement, we observe signal U(t), and, based on this signal, we need to find the value accepted by pressure p(t). From the standpoint of mathematics, that means solving equation (1). We shall show that, during measurements, it can be an ill-posed procedure.

Write down equation (1) in the following form

$$U(t)=k\int_0^t g(t-\tau)p(\tau)d\tau, \tag{2}$$

where $g(t-\tau)=e^{-\beta(t-\tau)}\sin(\eta(t-\tau))$ is the sensor's pulse transition function.

Equation (2) is an integral equation by Volterra with a symmetric kernel in class $L_2[0, t]$.

Assign function

$$p_i(\tau)=p(\tau)+\sum_{i=1}^{n}\alpha_i\cdot\psi_i(\tau), \tag{3}$$

where p(τ) is the solution to equation (2), or the true value of the measured pressure, α_i is the arbitrary constant, and some functions that are not equal to zero almost everywhere, as well as $\psi_1(\tau)...\psi_n(\tau)$

$$\int_0^t g(t-\tau)\psi_i(\tau)d\tau=0;\quad i=1,\ 2,...,n. \tag{4}$$

Substitute equation (3) in equation (2), we obtain:

$$\int_0^t g(t-\tau)\left[p(\tau)+\sum_{i=1}^{n}\alpha_i\cdot\psi_i(\tau)\right]\mathrm{d}\tau=\int_0^t g(t-\tau)p(\tau)d\tau+$$
$$+\int_0^t g(t-\tau)\sum_{i=1}^{n}\alpha_i\cdot\psi_i(\tau)E\tau=$$
$$=\int_0^t g(t-\tau)p(\tau)\mathrm{d}\tau+\sum_{i=1}^{n}\alpha_i\cdot\int_0^t g(t-\tau)\psi_i(\tau)\mathrm{d}\tau. \tag{5}$$

In expression (5), the second term, based on the assumption made (4), is equal to zero, and, therefore, the entire expression (5) equals U(t). That is, $p_i(\tau)$ can also be treated as the solution to equation (2), that is, as the value for the measured pressure. This means that the input signal can be represented by an infinite number of combinations of the true and external components, which would produce the same output signal, which is observed during measurement.

Therefore, if difference

$$p_i(\tau)-p(\tau)=\Delta(\tau),$$

can be represented as a series of $\sum_{i=1}^{n}\alpha_i\cdot\psi_i(\tau)$, then, based on the obtained actual output signal, the input signal (the purpose of measurement) would be defined ambiguously; hence the measurements are incorrect.

On the other hand, according to the Borel's theorem on convolution [20], equation (2) can be represented, by using a Fourier transform, in the following form

$$H(\omega)\cdot P(\omega)=U(\omega), \tag{6}$$

where $U(\omega)$, $H(\omega)$, $P(\omega)$ are the Fourier images of functions $U(t)$, $g(t-\tau)$, $p(\tau)$, that is, the spectrum an of output signal, the sensor's transfer function, and the spectrum of the input signal, respectively.

Therefore, using a reverse Fourier transform, the solution to equation (2) takes the form

$$p(t)=\frac{1}{2\pi}\int_0^{\infty}\frac{U(\omega)}{H(\omega)}\exp(jt\omega)\mathrm{d}\omega. \tag{7}$$

However, function $H(\omega)$ can be equal to zero at certain points $\omega=\omega_i$, or it could prove to be finite and, beyond a certain interval $\omega_1\leq\omega\leq\omega_2$, can be identical to zero $H(\omega)\equiv 0$.

Then the solution to (2) can be obtained both from function

$$P(\omega)=U(\omega)/H(\omega);\quad \omega\neq\omega_i, \tag{8}$$

and from function

$$P_1(\omega)=P(\omega)+\sum_i a_i\cdot\delta(\omega-\omega_i), \tag{9}$$

and the desired input signal $p(t)$ will be equal to

$$p(t)=\frac{1}{2\pi}\int_0^{\infty}\frac{U(\omega)}{H(\omega)}\exp(jt\omega)\mathrm{d}\omega+\frac{1}{2\pi}\sum_i a_i\cdot\exp(jt\omega_i), \tag{10}$$

where a_i are the arbitrary constants.

Thus, equation (2) will not accept a single solution if the Fourier image of the sensor's transfer function H(ω) is finite, or converts to zero at certain points. Therefore, if the spectrum of input signal P(ω) possesses harmonics with frequencies that coincide with zeros in the transfer function H(ω), then these harmonics do not affect the output signal U(t) and, accordingly, cannot be uniquely recovered from it. Because the transfer functions of actual pressure sensors almost always include zeros, and the length of the spectrum of the input signal, given its non-stationarity, may be arbitrarily wide, then, in terms of this standpoint, the measurements would be incorrect.

In general, it is obvious that an attempt to recover an input signal when measuring the non-stationary pressure may prove to be an incorrect procedure that would require specialized methods to solve it.

4. 2. Solving the inverse measurement problem and the wavelet transformation of the sensor's output signal

To solve the inverse measurement problem, we shall perform a double differentiation of equation (1), we obtain

$$\frac{dU(t)}{dt}=U'(t)=$$
$$=-\beta U(t)+k\int_0^t\eta\cdot e^{-\beta(t-\tau)}p(\tau)\cos\left(\eta(t-\tau)\right)\mathrm{d}\tau; \tag{11}$$

$$\frac{d^2U(t)}{d^2t}=U''(t)=-\beta\cdot U(t)+k\cdot\eta\cdot p(t)-$$
$$-k\cdot\int_0^t\begin{bmatrix}\eta\beta\cdot e^{-\beta(t-\tau)}p(\tau)\cos\left(\eta\cdot(t-\tau)\right)+\\+\eta^2e^{-\beta(t-\tau)}p(\tau)\sin\left(\eta(t-\tau)\right)\end{bmatrix}\mathrm{d}\tau. \tag{12}$$

Taking into consideration (1) and (11), we have

$$U''(t)=-2\cdot\beta\cdot U'(t)+$$
$$+k\cdot\eta\cdot p(t)-(\eta^2+\beta^2)\cdot U(t).$$

We obtain from the last equation

$$p(t)=\frac{U''(t)+2\cdot\beta\cdot U'(t)+(\eta^2+\beta^2)\cdot U(t)}{k\cdot\eta}. \tag{13}$$

Equation (13) is a solution to the inverse problem on measuring the non-stationary pressure and is a basis to construct a measurement method.

Note that the actual output signal is obtained with some error, so its direct differentiation would be an incorrect procedure.

Apply a direct discrete wavelet transform [21, 22] to output signal U(t)

$$C_u(n,m)=\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}U(t)a^{-m/2}\psi(a^{-m}t-n)\mathrm{d}t, \tag{14}$$

where m, n∈Z, Z is the set of real numbers, a is the parameter scale; $\psi(a^{-m}t-n)$ is the basis function.

In turn, the reverse discrete wavelet transformation is carried out based on formula

$$\tilde{U}(t)=K_\psi\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}C_u(m,n)a^{-m/2}\psi(a^{-m}t-n)\mathrm{d}t, \tag{15}$$

where K ψ is the constant defined by basis function ψ.

Then, derivatives from signal (15) are

$$\frac{d\tilde{U}(t)}{dt}=\tilde{U}'(t)=$$
$$=K_\psi\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}C_u(m,n)a^{-m/2}\frac{d\psi(a^{-m}t-n)dt}{dt}, \tag{16}$$

$$\frac{d^2\tilde{U}(t)}{dt^2}=\tilde{U}''(t)=$$
$$=K_\psi\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}C_u(m,n)a^{-m/2}\frac{d^2(\psi(a^{-m}t-n)dt}{dt^2}. \tag{17}$$

That is, the differentiation of the signal derived via a wavelet transform comes down to differentiating the basis function and such a differentiation is robust because the basis function is assigned analytically. Note that differentiating the Fourier series yields the series with inadequately slow convergence.

However, the fundamental problem during wavelet transformation of signals is the choice of a basis function [23]. It is the rational choice of such a function that determines the accuracy and rate of transformation. And when measuring in real time, these settings are crucial. Thus, for the wavelet transformation of measuring signals, we suggest that a base function should be determined based on the physical essence of measurement. When measuring the non-stationary pressure, a sensor output signal can be represented as the integral of product of the input signal and the pulse transition function. Therefore, it is logical to assume that the best basis function for a wavelet transformation of the output signal is a function close to the sensor's pulse transition function.

In equation (1), expression $g(t-\tau)=e^{-\beta(t-\tau)}\sin(\eta(t-\tau))$ is the pulse transition function. The pulse transition function by itself is not a wavelet because

$$\int_{-\infty}^{+\infty} e^{-\beta(t-\tau)}\cdot\sin(\eta(t-\tau))\neq 0.$$

However, if the pulse transition function is to be represented centrosymmetrically in the third quadrant, then we obtain the modified function $\hat{g}(t)$ (Fig. 1).

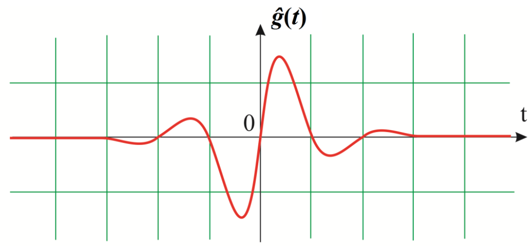

Fig. 1. Modified pulse transition function of the pressure sensor

The modified pulse transition function becomes a wavelet since $\int_{-\infty}^{+\infty}\hat{g}(\tau)d\tau=0,$ and the kernel of the integral equation by Volterra, which is the pulse transition function, belongs in the class $L_2[0, t]$ (a set of functions integrated in a square by [a b]). That is, $\int_{-\infty}^{+\infty}\left[\hat{g}(t)\right]^2 dt<\infty.$

5. Practical implementation and studying the measurement method

Based on the obtained theoretical aspects, the method for measuring the non-stationary pressure using a wavelet transformation is as follows:

– the sensor's output signal U(t) is treated with a direct and reverse wavelet transformation in line with formulae (14) and (15);

– the signal $\tilde{U}(t)$, resulting from a wavelet processing is treated with a double differentiation in line with formulae (16) and (17);

– a value for the measured pressure is determined from formula

$$p(t)=\frac{\tilde{U}''(t)+2\cdot\beta\cdot\tilde{U}'(t)+(\eta^2+\beta^2)\cdot\tilde{U}(t)}{k\cdot\eta}. \quad (18)$$

Note that it is possible to derive the first and second derivatives from a wavelet-treated output signal in parallel.

5. 1. Experimental verification of the constructed measurement method

To check the feasibility of the method we used a piezoresistive sensor (Fig. 2) while the test signal was generated by a pulse pressure force simulator. That is, the dynamic signal in the form of a short pulse was generated by the impact of a metal ball of mass *m*, which falls freely from height H, against the membrane.

Fig. 2. Piezoresistive sensor used to test the feasibility of the method

The experimental set-up (Fig. 3) includes clamper 1, which strictly vertically holds examined sensor 2 with its membrane up, guiding pipe 3, 4 is the interface module E14-140 for data processing and transferring them to monitor 5.

Fig. 3. Set-up of the pulse pressure force simulator

A guiding pipe of length 25 cm is screwed onto a thread section of the sensor's membrane part. At the top of the guiding pipe there is an electromagnet, which keeps a ball of mass 2 g and, when necessary, releases it for free fall on the membrane.

When using a pulse pressure force simulator, a validation procedure of the feasibility of the constructed method for measuring the non-stationary pressure implies determining a value for the mass of a falling ball and comparing this value to the actual one.

To establish the actual duration of contact between the ball and the membrane at impact, the ball was engaged through a flexible electric wire in a specialized circuit (Fig. 4), whose signals were registered by a countdown system at the interface module. As soon as the ball touched the membrane, a line of communication was enabled and an electrical signal from the power supply was registered by the same countdown system. As soon as the ball bounced from membrane, the communication was terminated, the signal disappeared (subsequent impacts of the ball against the membrane were disregarded). The duration of such a signal was equal to the time of contact between the ball and the membrane. In a given experiment, the duration of contact was $t_1=8\times10^{-5}$ s. Since the sensor's natural frequency amounted to 1 kHz, the impact of the ball against the membrane should be correctly interpreted as a short rectangular pulse [24].

This procedure represents an indirect measuring technique. A ball that freely falls from height H simulates a pressure pulse of amplitude

$$p=\frac{4}{\pi R^2}\frac{m\sqrt{2gH}}{t_1}. \quad (19)$$

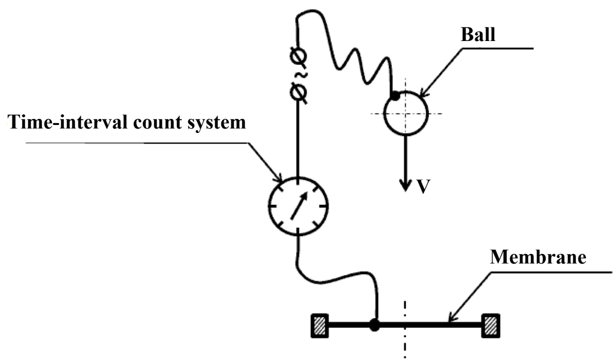

Fig. 4. Schematic of the set-up for determining the duration of contact between a ball and a membrane

If the input source were recovered based on the sensor's output signal, then the mass of the ball that simulated such a pressure pulse would be

$$m=\frac{p\pi R^2 t_1}{4\sqrt{2gH}}. \qquad (20)$$

A value for the amplitude of the simulated pressure pulse p is to be derived in the course of implementation of the measurement method from formula (18). Next, applying (20), we obtain a value for the ball's mass m.

Based on the research result, the sensor's output signal when its membrane was hit by the ball took the form shown in Fig. 5, and the recovered signal from the simulated pressure is shown in Fig. 6.

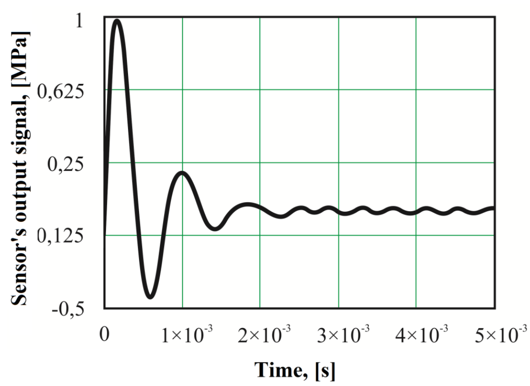

Fig. 5. The sensor's output signal when a ball hits its membrane

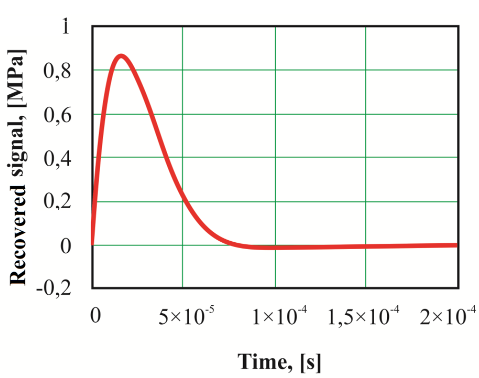

Fig.6. The recovered input signal from the simulated pressure pulse

Based on the results of test repeated 10 times, the simulated pressure pulse amplitude was 0.864 MPa. Because the pulse duration t_1 was 8×10^{-5} s, mass of the falling ball was m=1,987 g. Thus, the maximum relative error in determining the mass of a falling ball was 0.65 %.

6. Analysis of the constructed measurement method

The measurement method that we developed based on the application of the derived solution to inverse problem (13) implies obtaining derivatives from the output signal $\dot{U}(t)$ and $\ddot{U}(t)$. These magnitudes are derived from numerical differentiation of the signal's image wavelet $\tilde{U}(t)$.

Based on the essence of numerical integration, we can record that at time t_i (where $i=1...N$)

$$p(t_i)=\frac{\ddot{U}(t_i)+2\cdot\beta\cdot\Delta t\left(\ddot{U}(t_{i-1})+\ddot{U}(t_i)/2\right)+ +(\eta_0^2+\beta^2)\cdot U(t_i)}{k\cdot\eta_0}. \qquad (21)$$

Thus, to calculate a value for the measured pressure in line with (21), one must know the values for magnitudes $U(t)$ and $\ddot{U}(t)$ at current moment t_i and the value for magnitude $\ddot{U}(t)$ at previous time t_{i-1}.

In line with the developed method of measurement, signal $\ddot{U}(t)$ is obtained by numerical differentiation of the wavelet image of signal $\tilde{U}(t)$ in accordance with (17). That is, by computing the second derivative from the modified pulse transition function (basis function) in advance, performance speed of the method will be determined based on the implementation of arithmetic procedures according to expressions (17), (21). All these procedures are easily implemented when applying known software MathCad or MathLab, etc. There are also techniques to process signals with the possibility of specialized programming that focus on a specific task.

In addition, note that the infinite sums in expression (17) should be replaced with the finite ones, which would affect the accuracy of computing a value for the measured pressure.

7. Discussion of the method to measure the non-stationary pressure

The constructed measurement method implies using a wavelet transform of the sensor's output signal. To improve the accuracy of wavelet processing, we suggested using, as a basis function of wavelet transformation, the sensor's modified pulse transition function.

However, it is important to realize that one must have the sensor's pulse transition function in advance. It is produced by experimental methods. In addition, one experimentally obtains values for the sensor's static coefficient of transformation k, for the frequency of natural oscillations η and for a damping coefficient of the sensor's mechanical part oscillations β. However, it is necessary to understand that the operation of the sensor can change the physical and mechanical parameters of the membrane. This means that it would be necessary to periodically check the value of the frequency of its oscillations, as well as the static coefficient of sensor transformation, and to test its pulse transition function.

In addition, when applying the experimental method for the force simulation of a pressure pulse, it is necessary to ensure a one-time impact of a ball against a membrane, which would require specialized technical solutions in the guiding pipe itself.

It should be noted that the implementation of the method requires appropriate software.

8. Conclusions

1. The work shows that the fundamental equation of measurement will not have a single solution if a Fourier image of the sensor's transfer function is finite, or is converted to zero at certain points. Because transfer functions of actual pressure sensors almost always include zeros, and the length of spectrum of the input signal, given its non-stationarity, can be arbitrarily wide, then measuring the non-stationary pressure based on the derived actual output signal would yield an ambiguous input signal (the purpose of measurement) and therefore the measurements would be incorrect.

2. We have derived a solution to the inverse measurement problem, which is an algebraic equation containing derivatives from the sensor's output signal. For the practical implementation of this equation, the wavelet transforms of the output signal are applied. The work shows the possibility to differentiate a wavelet image of the output signal, which is the basis of the constructed method of measurement. In this case, a proposed basis function of the wavelet transformation is the sensor's modified pulse transition function.

3. When testing experimentally the feasibility of the developed method of measuring using the set-up of a pulse pressure force simulator, error in determining the mass of a falling ball that simulated a pressure pulse was 0.65 %. This result confirms the efficacy of the method.

The research results obtained show the feasibility of the constructed measurement method using a wavelet transformation of the signal, as well as a possibility of its application for the high-speed automation systems that operate in real time.

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Досліджено розподіл рівнів звукового тиску в резонаторах Гельмгольца в широкому діапазоні частот. Проведено комп'ютерне моделювання звукового поля в резонаторі методом кінцевих елементів та експериментальні дослідження.

Встановлено наявність багатьох резонансних частот в резонаторі та показано розподіл максимумів і мінімумів рівнів звукового тиску в об'ємі резонатора. Виявлено, що розподіл резонансних частот резонатора не відповідає гармонійному закону. Це дає змогу розглядати резонансні властивості резонатора аналогічно до коливань мембрани чи дзвона. Друга резонансна частота резонатора в 6–9 раз вище першої резонансної частоти, що відповідає резонансу Гельмгольца. Моделювання звукового поля в резонаторі показало наявність вузлових ліній в розподілі звукового тиску як в об'ємі резонатора так і горлі. Встановлено, що кількість вузлових ліній для перших частот на одиницю менша за номер резонанса.

Спільним для всіх розподілів є те, що при наближенні точки вимірювання до краю горла резонатора рівень звукового тиску зменшується. Також при дослідженнях встановлено, можливість створення резонансу лише в об'ємі резонатора без яскраво виражених вузлових ліній в горлі.

Порівняльний аналіз між експериментальними даними та даними комп'ютерного моделювання показав високий рівень достовірності отриманих результатів. Похибка в визначенні резонансної частоти становила не більше 0,8 %. Даний факт дозволяє в подальшому при визначенні звукового поля в системах резонаторів користуватися комп'ютерним моделюванням замість ресурсозатратних експериментальних досліджень.

Наявність багатьох резонансів в резонаторі Гельмгольца дозволяє проводити побудову широкосмугових приладів, що можуть базуватися на використанні даного типу резонаторів

Ключові слова: резонатор Гельмгольца, резонансні частоти, звукове поле, метод кінцевих елементів

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EXPERIMENTAL STUDY INTO THE HELMHOLTZ RESONATORS' RESONANCE PROPERTIES OVER A BROAD FREQUENCY BAND

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1. Introduction

Research into analysis of human sound sensations began in the mid-19th century [1]. Even though a given work belongs to the field of psychoacoustics, a need arose during its execution to use and register the phenomenon of resonance. It was shown that an elastic body (a string, a stretched membrane) could resonate not only to the sound, equal in height to its natural tone, but also to the overtones. To prove it, sensitive devices were used, namely, glass or metal balls with a narrow neck or tubes – the Helmholtz resonators. In terms of electric acoustics, they represent an acoustic oscillating system, consisting of flexibility, mass, and active resistance. In this case, the flexibility is the air inside the container, the mass is the air that fills the narrow resonator throat, and the attached mass of air adjacent to the end of the throat. The presence of active resistance is predetermined by the friction between air and the walls of the throat and by losses in the oscillatory energy due to the radiation of sound by an open end of the throat [2].

The Helmholtz resonators were used to analyze the spectra of complex sounds before the advent of computing technology, they were also applied in temple structures for the correction of acoustic properties of premises.

One of the areas where resonators could be employed is the construction of focusing systems for acoustic medical instruments or flaw detection devices with simultaneous amplifying properties. In addition, the existence of multiple resonance frequencies in the resonator makes it possible to use them in broadband acoustic systems.