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# OPTIMIZATION OF SIGNAL FEATURES UNDER OBJECT'S DYNAMIC TEST

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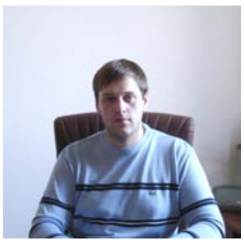

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**Abstract.** The results of investigating the influence of the time constant of acceleration signal transformation or vibration speed into a displacement signal are given. Regularities of displacement signal amplitude change after transformation of acceleration and speed signals have been determined. It is shown that the error of displacement signal amplitude change depends on the transformation time constant for the intended frequency of the input signal. Thus, its minimum value corresponds to the value of the transformation time constant, equal to half an input signal period. The results of displacement measurements obtained by using vibration speed sensors and the results of their comparison with data, obtained by employing the displacement master sensor, are given.

**Keywords:** diagnostics, vibrations, signal spectrum, acceleration signal, speed signal, signal transformation, dynamic displacement.

## 1. Introduction

Research of dynamic construction characteristics by using analysis of vibration parameters is one of the directions of their technical diagnostics. First of all, this concerns large structures, such as aircraft's, bridges, buildings, etc [7, 3]. For excitation of their own or forced vibrations, different types of dynamic influence are applied, such as: blows, car motion, etc. [10, 1]. Thus, one of the major characteristics is dynamic displacement, applied for determining the construction dynamic quality coefficient.

For registration of construction vibration, it is possible to use displacement sensors. However much of them have low sensitivity, limited frequency range, considerable sizes and mass. Considerable problems emerge they are placed on a structure. Speed (induction type) and acceleration (piezo-ceramic type) sensors are therefore more widely spread [4, 5]. These sensors have a highly sensitive and a greater frequency range. They are compact and easy installed on different types of structures. However, the use of acceleration and speed sensors allows a limited set of vibration parameters to be determined. To these parameters, as a rule, belong: frequencies of vibration modes and coefficient of decay [9, 8, 2]. Diagnostics methods are therefore based on the analysis of deviation of parameters' obtained from their theoretical values.

Such a limited set of parameters is conditioned by the need to carry out the transition towards the displacement signal, when using acceleration and speed sensors for dynamic displacement determination. Transition is made be using a standard procedure of a double or single integration. For realization of these procedures, the constant finite integration time is preset. The registered signal frequency remains unknown and the integration constant time is chosen to be sufficiently large (units and tens of seconds). Such an approach is directed towards diminishing the transformation error. However, it results the considerable non-linearity of registered signals transformation, depending on their frequency and diminishing of sensitivity.

The paper considers the influence of the integration time constant on displacement value in the transformation of vibration speed signals into the displacement signal. The procedure of optimizing the transformation of the parameters of speed (acceleration) signals into the displacement signal is considered. It will be also shown, that for the preset input-signal frequency the dependence of displacement change on the value of the integration time constant has a nonlinear character. There is, however, a certain value interval of the integration time constant, for which the displacement value remains practically a constant value.

## 2. Theoretical aspect

As mentioned above, integrating chains (amplifiers) are widely applied for integrating signals of transformers, their output size being proportional to the derivative from the input value – relocation. An ideal integrating chain is described by the following equation [6]

$$U_2 = \frac{k_0}{\tau}\int U_1 dt\,, \qquad (1)$$

where $-U_1$, $U_2$ accordingly, signals in input and output of an integrator; $k_0$ – a proportion coefficient; $\tau$ – time constant, and its frequency characteristic – described by the equation:

$$\left|\dot{S}_i\right| = \frac{k_0}{\omega\tau}\,. \qquad (2)$$

Thus, the frequency characteristic is a hyperbola, and $\varphi$ – a phase angle between the input $U_1$ and output $U_2$ does not depend on the frequency and equals $\varphi = -\pi/2 = -90^0$.

If one considers the simplest integrating passive RC-chain, then supposing that $i_2$ =0, it is possible to write (Fig 1):

$$U_2 = \frac{k_0}{C}\int i dt = \frac{k_0}{C}\int \frac{(U_1 - U_2)}{R} dt = \frac{k_0}{\tau}\int (U_1 - U_2) dt\,, \qquad (3)$$

where $\tau = RC$, and the frequency and phase characteristics of such a chain are:

$$\left|\dot{S}_r\right| = \frac{k_0}{\sqrt{1+(\omega\tau)^2}}\,, \quad \varphi = \mathrm{arctg}(\omega\tau)\,. \qquad (4)$$

With (2) and (4) taken into account, a relative frequency error will be determined as

$$\gamma_\omega = \frac{\left|\dot{S}_r\right| - \left|\dot{S}_i\right|}{\left|\dot{S}_i\right|} = \frac{\omega\tau - \sqrt{1+(\omega\tau)^2}}{\sqrt{1+(\omega\tau)^2}}\,. \qquad (5)$$

Thus, the integrating chain will possess less error, if the time constant $\tau$ is bigger and frequency $\omega$ is higher.

However, the $\tau$ increase results in sensitivity diminishing.

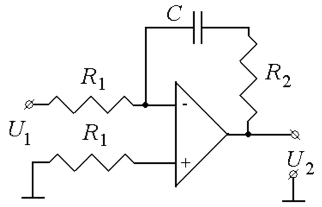
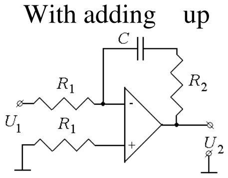
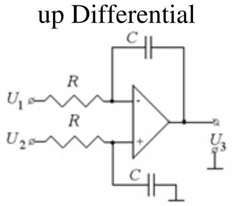
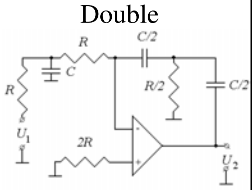



**Fig 1.** Simplest integrating chain

Difficulties with integration for low frequencies are overcome due to application of amplifiers with a deep negative feedback. Some typical charts of integrators on operating amplifiers and transformation equations, given in table, and in figure 2, are typical frequency characteristics of ideal and real integrators.

So that an integrator can function correctly, which depends on the finite value of the $\tau$ time constant, the spectrum of the input signal must lie in the operation frequency range, i.e. it should be higher than an inferior boundary frequency and lower than an upper boundary frequency. However, to provide transmission coefficient constancy in of the entire frequency range, which is important in determining the construction dynamic characteristics, is difficult enough. In other words, there is a question: how at unknown input signal frequency can one preset the integration time constant for conducting transformation and reliable determination of the construction dynamic displacement? In connection with this, we will consider the influence of the integration time constant on the signal amplitude after transformation and the displacement value are obtained.

Typical charts of integrators on operating amplifiers and transformation equations

| Type | Operation executed |
|---|---|
| With adding up  | $U_2 = -\frac{1}{R_1 C}\int U_1 dt + \frac{R_2}{R_1}U_1$ |
| up Differential  | $U_3 = \frac{1}{RC}\int (U_2 - U_1)dt$ |
| Double  | $U_2 = \frac{4}{(RC)^2}\iint U_1 dt$ |

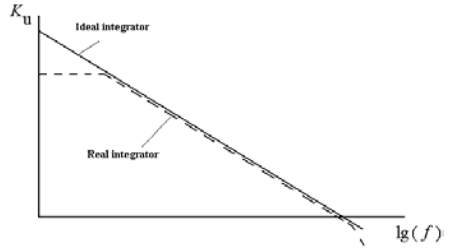
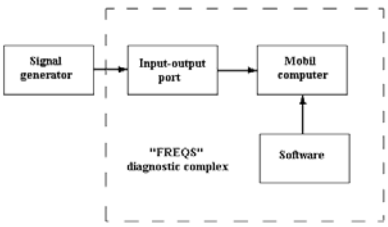



**Fig 2.** Amplitude-frequency characteristics of integrator

## 3. Method of research

Research has been carried out in two stages with the application of the "FREQS" diagnostic complex on the basis of a ACMII mobile computer. The diagnostic complex is intended for registering and processing the vibration (acceleration and speed) signals in the construction dynamic tests. The complex is developed with extensive application of flexible software tools to control the process of signal transformation into digital codes. Processing, analysis and results are presented in a graphic or digital form.

In the first stage of research, the registration and processing of a standard signal of sinusoidal form with $f_1$ preset frequency and $U_1$ amplitude was applied. The signal was provided as an imitation signal of vibration speed and was directly sent to the input of the "FREQS" diagnostic complex (into the input-output port mounted in the mobile computer) (Fig 3; *a*). After recording the signal, spectrum processing was carried out, and frequent transformation into the displacement signal with constructing and processing the dependence of output signal amplitude change (displacement) from integration time was executed.

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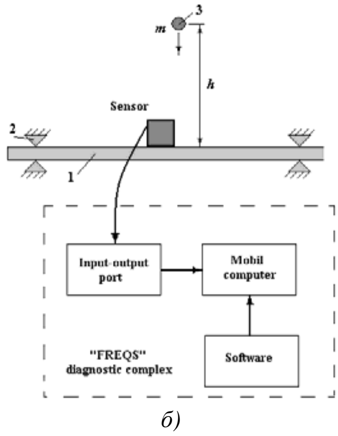



*б)*

**Fig 3.** Structures of using "FREQS" complex in testing signal transformation parameters: 1 – wooden beam; 2 – fastening supports; 3 – sphere, filled with sand

For signal transformation the following integration procedure was applied:

$$U_2(t) = \int_0^t U_1(\tau)d\tau \quad , \quad 0 < \tau \le \delta , \qquad (6)$$

where $\delta$ is integration time, which was changing within the interval $\delta = T_1/16 - 14T_1/16$; $T_1 = 1/f_1$ – period of the registered signal.

At the digital signal processing, the expression (6) is put down as follows:

$$U_2(t_m) = \sum_{i=0}^{m} U_{1i}\Delta t \ , \ t_m = m\Delta t, \ \ 0 < m \le S , \qquad (7)$$

where $U_{1i}$ – values of the amplitude $I$ – samples in the analog-digital transformer output, obtained with the input signal sampling interval $\Delta t$ ; $S = \tau / \Delta t$ .

Signal input into a diagnostic complex is processed with the application of a software package that also supports all the operations of control, the management of the measuring processes, the input information analysis, and the presentation of results in a graphic and digital form.

At the second stage of research, the processing of a vertical decaying vibration speed signal, registered with the application of an induction speed sensor mounted on a beam 1 was applied (Fig 3; *b*). The beam was made of oak and had the following sizes: thickness – 12 mm, width – 30 mm. The beam length between the rigid attachment areas 2 equaled 700 mm (Fig 3; *b*). The beam loading was carried out with the help of a sphere 3 filled with sand, which fell from the permanent height *h*. The mass of the sphere *m* amounted to *m* = 1 N, and the height of its falling *h* – was h = 150 mm. The sensor of vertical vibration speed had the following dimensions: diameter – 29 mm, height – 67 mm. The sensor was fastened to the beam with the help of a screw clamp. The signal was sent from the sensor output into the "FREQS" diagnostic complex input (Fig 3; *b*). After registration of the signal, the following procedures of its transformation into the displacement signal, treatment, analysis, and presentation of results were executed in the way described above.

## 4. Continuous signal research

When researching the continuous signal transformation in the diagnostic complex input, in accordance with figure 3; *a*, the signal of sinusoid form with parameters of amplitude – $U_1$ = 4 B and frequency – $f_1$ = 1.2 Hz was sent. As noted above, its signal was examined as an imitation signal of vibration speed. After the signal was registered, processing and spectrum analysis was carried out. Its transformation into a displacement signal and spectrum analysis was also conducted. In figure 4; *a* and *b*, the registered (speed) signal and its spectrum are shown, and in figure 4; *c* and *d* the displacement signal and its spectrum are shown. The displacement signal, given in figure 4; *c* and *d*, is obtained after conducting a speed signal transformation, according to (7), with time constant having the value equal to half a period of the initial signal $\delta = 1/2f_1 = T_1/2 = 0.417$ s. Figure 4 shows, that transformation of output signal amplitude does not influence its spectrum.

However, when the transformation time constant changes in the range of values $\delta = T_1/16 - 14T_1/16$, as research shows, a nonlinear change in the amplitude of the output signal occurs (Fig 5; *a*). Its dependence bears a bell-shape with the maximal amplitude value $\delta = T_1/2$. It is natural that the dependence of amplitude deviation with respect to percentage from a maximal value has a reverse character (Fig 5; *b*). From the dependencies obtained, it is

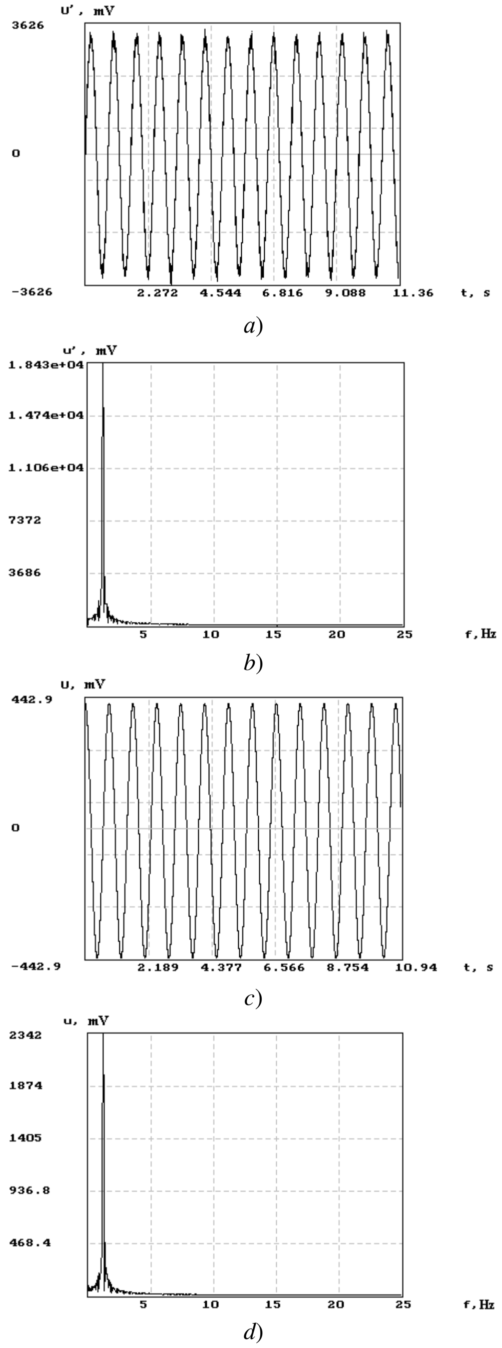
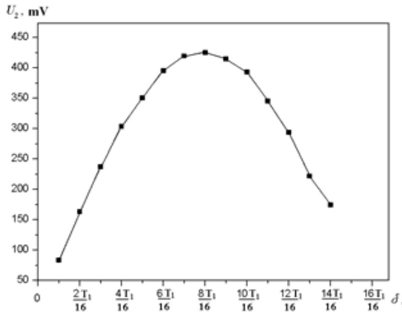



**Fig 4.** Results of the beam decaying vibration signal processing, registered by the induction speed sensor: *a* and *b* – accordingly, vibration speed signal and its spectrum; c and *d* – accordingly, displacement signal and its spectrum. Beam vibration frequency – 1.2 Hz. Integration time constant – $\delta = T_1/2 = 1/2f_1 = 0.417$ s

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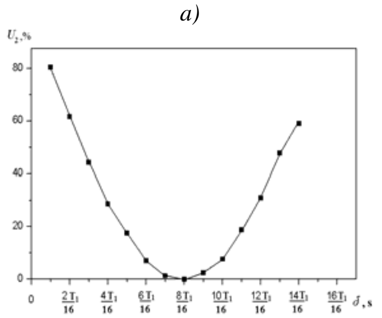



*b)*

**Fig 5.** Change in displacement signal amplitude (*a*) and percentage of deviation from maximal amplitude (*b*) depending on the transformation time constant $\delta$ for a sinusoidal signal with constant amplitude. $T_1$ - period of registered signal

evident that, with the decline or increase in transformation time constant value in relation to the value $\delta = T_1/2$, the decline in the amplitude of the output signal and the extension of its deviation error from maximal value occurs.

The analysis of the dependencies obtained has shown that within the values of the time constant $\delta = 0.4T_1 - 0.6T_1$ the deviation error of the output signal amplitude from the maximal value does not exceed 5%. Its error value is maximally possible in determining dynamic construction displacements, which are calculated at the displacement signal amplitude.

Analogous dependencies are also obtained in conducting a double signal transformation, i.e. when the initial signal is considered an acceleration signal. Thus the second transformation results in further amplitude decline in the output signal but does not influence its spectrum.

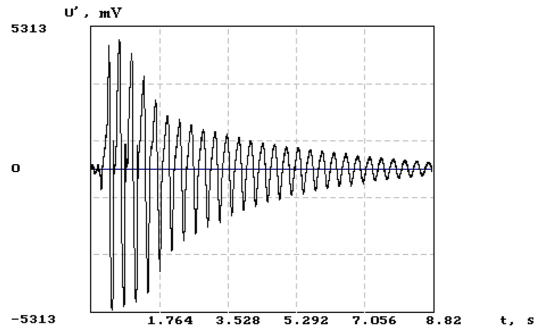
## 5. Decaying signal research

Research of the decaying signals excitation of the beam vibrations was conducted, as shown in figure 3; *b*, and their registration were carried out by means of an induction sensor of vertical vibration speed. After signal registration, processing and spectrum analyses were carried out, and then transformation into a displacement signal and spectrum analysis was conducted. Figure 6; *a* and *b*, shows the registered (speed) signal and its spectrum, and figure 6; *c* and *d,* shows the displacement signal and its spectrum. The displacement signal, shown in figure 6; *c*, was obtained after transforming the speed signal according to (7) with time constant, its value being equal to half a period of the signal registered $\delta = 1/2f_1 = T_1/2 = 0{,}0377$ s.

Figure 6 shows that the transformation of the output signal amplitude does not influence the resonance frequency. The presence of multiple harmonics in the spectrum of the vibration speed signal (Fig 6; *b*), as investigations have shown, corresponds to theoretical calculations and is connected with the peculiarities of the functioning of the induction sensor. However, in the displacement signal spectrum, harmonics are practically absent, which is caused by signal smoothing after conducting the transformation.

Studying the influence of the transformation time constant in the range of values $\delta = T_1/16 - 14T_1/16$ showed that a nonlinear change in the output signal amplitude takes place as well (Fig 7; *a*). The dependence, as in the previous case, appears similar to a bell with the maximal amplitude value at $\delta = T_1/2$. The curve detail in the area of maximal amplitude within the values $6T_1/16 \le \delta \le 11T_1/16$ has a declivity, however. At $\delta < 6T_1/16$ and $\delta > 11T_1/1616$, a sharp drop in the amplitude output signal is observed.

The change in the deviation of the signal amplitude of displacement from its maximal value as a percentage

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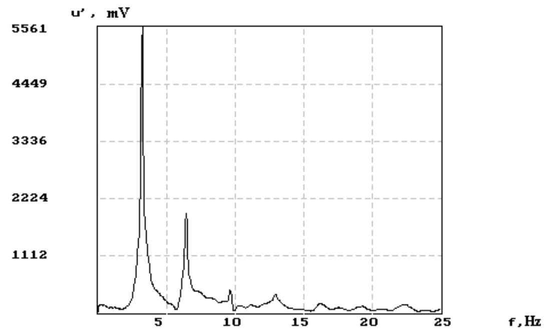


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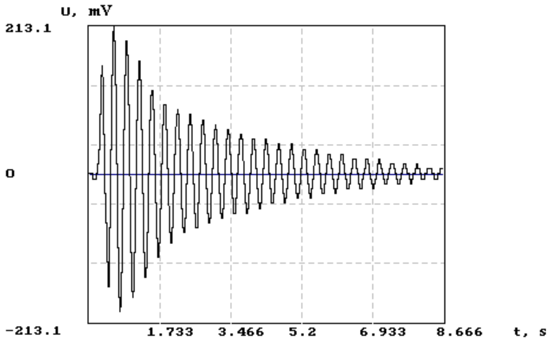


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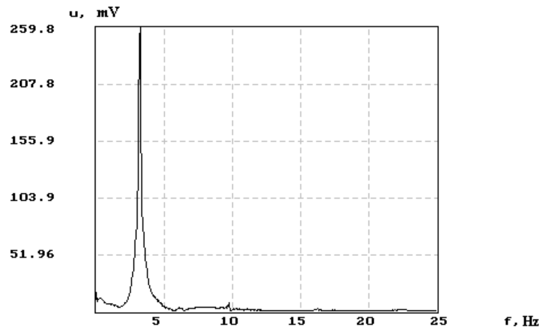
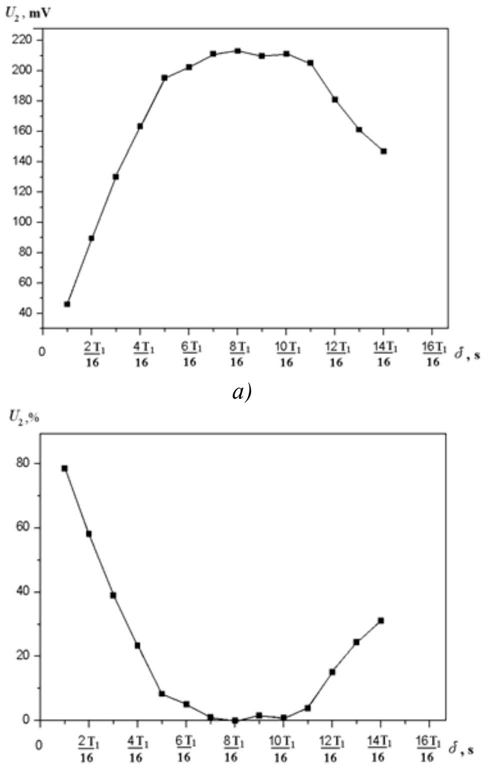



*d)*

**Fig 6.** Results of processing the beam decaying vibration signal registered by the induction speed sensor: *a, b* – respectively, vibration speed signal and its spectrum; *c, d* – respectively, displacement signal and its spectrum. Frequency of beam vibrations is 13.25 Hz. Transformation time constant is $\delta = T/2 = 1/2f$

ratio has analogical conformity to the law (Fig 7; *b*). However, 5 % from a maximal value the greater range of values corresponds to the error of deviation of the amplitude of signal permanent time of transformation – $\delta = 0.38T_1 - 0.7T_1$.



*a)*

*b)*

**Fig 7.** Change in displacement signal amplitude (*a*) and its percentage with deviation from maximal amplitude (*b*) depending on transformation time constant $\delta$ for a sinusoidal decaying signal. $T_1$ – period of registered signal

Analogous conformities to the law are got and during conducting of the double attenuation signal shaping, i.e. when the vibrations of beam were registered with the help of an acceleration sensor. Thus the second transformation similarly results in the further diminishing of output signal amplitude but does not influence its spectrum.

The change of deviation of amplitude of displacement signal from its maximal value in a percentage ratio has analogical conformity (Fig 7; *b*). However, a winder range of the time constant transformation correspond to a 5 % error of signal amplitude deviation from the maximal value is $\delta = 0{,}38T_1 - 0{,}7T_1$.

## 6. Discussion of results

The research carried out shown, while transforming the acceleration or speed signal into the displacement signal its amplitude depends on the value of the transformation time constant. This concerns the processing of both continuous and decaying signals. Analysis of the results obtained shows that time constant, in its turn, is related to the registered signal frequency. Thus, the actual value of the signal amplitude after transformation is determined with a minimum error providing that the value of the time constant corresponds to the value $\delta = T_1/2$, where $T_1$ is a period of input signal. At the same time, there is a range of values of transformation time constant; within its limits, the error value on signal amplitude does not exceed 5%. Its range corresponds to the values $\delta = 0{,}4T_1 - 0{,}6T_1$ for a continuous signal and $\delta = 0.38T_1 - 0.7T_1$ for a decaying signal.

The presence of similar dependencies is obviously conditioned by the following. The transformation (integration) procedure determines the area under to the signal curve (in our case of sinusoidal continuous or decaying signal); its maximal value corresponds to the transition from a positive to a negative amplitude value. It is natural that the part area near the transition value ( $\delta = T_1/2$) is not significant in the common area under investigation signal curve.

At the same time for the continuous signal when $\delta$ increases or decreases the value of an error in the neat transition area part will grow in the process of the common area determination. For the decaying signal, the declivity of the change in output amplitude after the transformation in the maximum area corresponds to a greater range of $\delta$ values. The expansion of the range of $\delta$ values is obviously caused by the presence of the registered signal decaying, i.e. by the decrease in the contribution of positive and negative areas in the area transition into a general signal area.

For diagnostics, the establishment value of the actual amplitude displacement signal is important. This value determines the dynamic construction displacements. Thus the choice of transformation time constant value, in accordance with a basic frequency of the registered acceleration/speed signal, allows one to considerably reduce the displacement determination error, its value having a minimum at $\delta = T_1/2$.

Figure 8 shows a typical result of data processing of the results of measuring displacement by a master sensor of displacements and a sensor of speed. The induction sensor of displacement of WA50 type with a base of maximal linear relocation (displacement) of 50 mm ($\pm$ 25 mm) was used as a master sensor. The frequency range of the sensor work is 0.2 Hertz – 200 Hertz. At maximal output sensor voltage 10 V, which corresponds to the maximal relocation of 50 mm, the WA50 sensor sensitivity amounts to 0.005 mm/mV. As a speed sensor, an induction sensor of vertical vibration speed of SV10Z type with transformation coefficient of 20 V/m/s was used.

Figure 8; *a* shows the dependence of displacement measurements in $x^e - x^\kappa$ coordinates, where, $x^e$ and $x^\kappa$ – are accordingly, the displacements measured by the master sensors and the tested one. Figure 8; *b* and *c* shows, accordingly, the dependencies of absolute and relative errors of displacement measurements for the tested sensor in coordinates $x^e - \Delta x^\kappa_{(1,2)}$, their values being determined as follows:

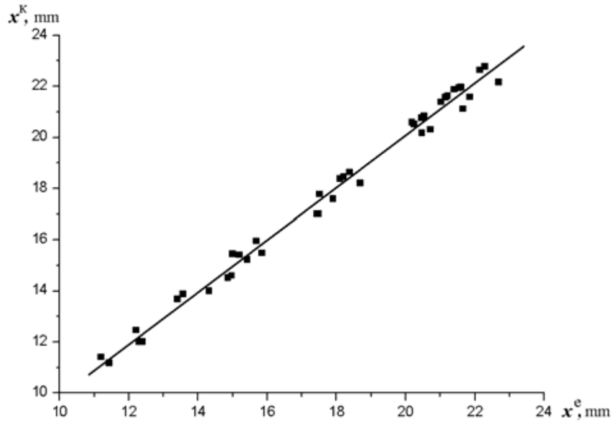
$$\Delta x_1^\kappa = x^e - x^\kappa \ ,$$

$$\Delta x_2^\kappa = \frac{x^e - x^\kappa}{x^e} (\%) \ .$$

The analysis of the dependence shown in figure 8, *a* has shown that it is described in a good way by the following expression:

$$x^\kappa = A + B\, x^e \ , \tag{8}$$

where *A* and *B* are coefficients of approximating expression, their values being equal to: *A* = -0.332 and

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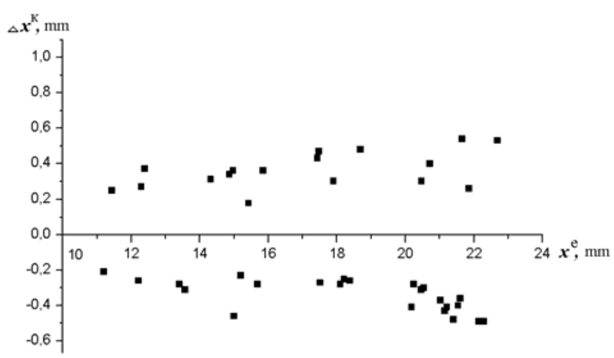


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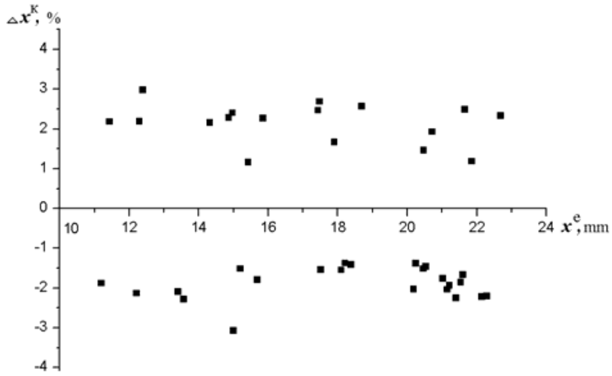


*c)*

**Fig 8.** Results of experimental data processing at displacement measuring by the induction master sensor of displacements and a tested sensor of vibration speed: *a* – dependence of displacements in $x^e$ - $x^\kappa$ co-ordinates (master – tested sensors); *b, c* – accordingly, dependence of absolute and relative error of measuring of displacements by the tested sensor

*B* = 1.021. Thus dispersion for probability p = 0.99512 amounts to $\sigma^2$= 0.361, and the relative error of displacement determination by the vibration–speed sensor does not exceed $\Delta x^\kappa_{2\max} = \pm$ 3.1 %.

## 7. Conclusion

The results that obtained allowed us to define the influence of the integration time constant on the amplitude of the output signal after transforming the signal of acceleration or vibration speed into displacement signal. It was determined that a minimum error corresponds to the value of the transformation time constant, which is equal to half a period of the registered signal. When the transformation time constant increases or decreases the error of the amplitude of the output signal increases. At the same time, it is possible to make a choice of transformation time constant within the preset error of the amplitude of the output signal. The results obtained should be taken into account in developing algorithms for processing vibration signals registered by speed/acceleration sensors when determining dynamic construction displacements.

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**SIGNALŲ CHARAKTERISTIKŲ OPTIMIZAVIMAS OBJEKTŲ DINAMINIŲ BANDYMŲ METU**

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S a n t r a u k a

Pateikti laiko konstantos įtakos greitėjimo signalų arba virpesių greičio signalų virtimo poslinkio signalu tyrimo rezultatai. Nustatyti poslinkio signalo amplitudės pasikeitimo dėsningumai po greitėjimo ir greičio signalų pasikeitimo. Parodyta, kad poslinkio signalo amplitudės pasikeitimo klaida priklauso nuo pasikeitimo laiko konstantos nustatytam įeinančio signalo dažniui. Šiuo atveju jo minimali reikšmė atitinka pasikeitimo laiko konstantos reikšmę, kuri yra lygi pusei įeinančio signalo periodo. Pateikti poslinkių matavimo rezultatai, naudojant virpesių greičio daviklius bei jų palyginimo su duomenimis, kurie buvo gauti etaloniniu poslinkių davikliu, rezultatai.

**Reikšminiai žodžiai:** diagnostika, vibracija, signalų spektras, greitėjimo signalas, greičio signalas, pasikeitimo signalas, dinaminis poslinkis.