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ON A CERTAIN IDENTIFICATION METHOD FOR STAND SIMULATION TESTS

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In the paper the identification method, called the averaging method, is presented. Information on the tested object is obtained from a number of experiments made under similar conditions. The possibility of applying this method in stand simulation tests securing the conditions for the necessary experiments is pointed out. The method of forming the input signals for simulation tests appropriate for the presented identification method is described. An example of synthesis the input signals in the tests of a single-bucket excavator, real experiments being replaced with the computer ones, is discussed.

1. Introduction

In stand simulation tests efforts are made to reproduce in the laboratory the same working conditions as those to which a tested object would be subject in real operation [2, 6]. Reproduction of these conditions is understood here as securing the similarity of signals measured in the chosen points of the object on the test stand to those occuring in normal service. The similarity measure of the signals, i.e.: stresses, strains, displacements or accelerations, is the simulation error which is a function of differences between signals.

At the preliminary stage of the tests the aim is to form the input signals $x_k(t)$ in the stand so that the output signals $y_i(t)$ would be sufficiently similar to the reference signals, Fig.1. Assessment of the input signals is equivalent to solving the classical problem of dynamics where, on the basis of the known effects (output signals), the corresponding causes (input signals) are sought. To this end it is necessary to identifity the object properties. Identification is carried out on the grounds of information obtained during the stand tests. Full identification of structure, masses, elasticity and damping coefficients is not necessary; it is only important to find the relation between the input and output signals.

The method of forming the input signals depends on the information on the object obtained during identification. Many methods of solving this problem are known. One of them is the identification of frequency characteristics and the corresponding synthesis of the input signals carried out in the frequency domain [3, 6]. Another one is the identification carried

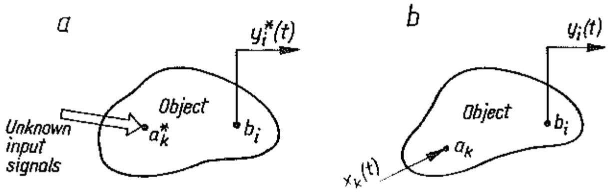

FIG. 1. Signals under service conditions (a), and on the test stand (b).

out with functions in the time domain. The examples are: identification of a hysteresis loop [1], identification of a transfer function with the use of isoperimetric conditions [9], or identification of impulse characteristics, use being made of the isoperimetric conditions [8].

Although a number of methods of forming the signals necessary for simulation tests already exist, a new and different identification method will now be proposed. This new method results from the possibility of repeating the experiments to collect more information useful for identification, what is characteristic for stand testing. The method proposed in this paper, called the averaging method, is a method of this kind. Also the corresponding method of input signals synthesis is presented.

2. FORMATION OF THE INPUT SIGNALS BY THE METHOD OF SYNTHESIS IN THE TIME DOMAIN

Let us imagine an object during the stand test as a system in which input signals are the forcing signals and output signals are the response ones (Fig.2). Let us introduce the transfer function $g_{ik}(t)$; the relation between signals can be written down as follows:

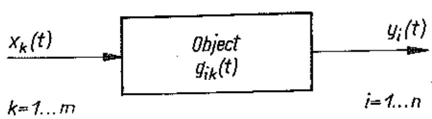

FIG. 2. Relation between signals on the test stand.

$$y_i(t) = \sum_{k=1}^{m} g_{ik}(t)\, x_k(t)\,, \qquad i = 1, ..., n\,. \tag{2.1}$$

The forcing signals $x_k(t)$ should be chosen so as to minimize the simulation error; therefore, they are calculated from the condition of minimum of this error. We shall understand the absolute simulation error as a function of squares of differences between the reference signals and the output signals:

$$\delta(t) = \sum_{i=1}^{n} [y_i^*(t) - y_i(t)]^2\,, \tag{2.2}$$

or, taking into account the relation between signals (2.1),

$$\delta(t) = \sum_{i=1}^{n} \left[y_i^*(t) - \sum_{k=1}^{m} g_{ik}(t)\, x_k(t) \right]^2 . \tag{2.3}$$

The relative error can be obtained by averaging in the time interval (t_1, t_2),

$$\varepsilon = \frac{1}{\varepsilon_0} \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} \delta(t)\, dt , \tag{2.4}$$

where the reference function has the form

$$\varepsilon_0 = \frac{1}{t_2 - t_1} \sum_{i=1}^{n} \int_{t_1}^{t_2} [y_i^*(t)]^2 \, dt . \tag{2.5}$$

Using the Euler–Lagrange conditions [9] for the simulation error minimum we obtain the system of equations

$$\frac{d}{dt} \left[\frac{\partial \delta(t)}{\partial \dot{x}_k(t)} \right] - \frac{\partial \delta(t)}{\partial x_k(t)} = 0 , \qquad k = 1, ..., m . \tag{2.6}$$

From this system we can find the functions $x_k(t)$ which are the extremals yielding the minimum of the simulation error

$$\sum_{i=1}^{n} \left[y_i^*(t) - \sum_{k=1}^{m} g_{ik}(t)\, x_k(t) \right] g_{i\nu}(t) = 0 , \qquad \nu = 1, ..., m . \tag{2.7}$$

Solution of the system (2.7), which is linear with respect to the sought signals $x_k(t)$, written in a matrix form is as follows:

$$[x_k(t)] = \left[\sum_{i=1}^{n} g_{j\nu}(t)\, g_{jk}(t) \right]^{-1} [g_{i\nu}(t)]^T [y_i^*(t)] , \tag{2.8}$$

$$k, \nu = 1, ..., m , \qquad i = 1, ..., n .$$

The input signals found in this way ensure the minimum simulation error in the time domain. The presented method of finding the input signals is convenient when their number is smaller than the number of the reproduced output signals: $m < n$.

In the case when the numbers of these signals are equal, $m = n$, the condition for minimum error is vanishing of all components of the sum (2.3), what leads to the system of equations

$$y_i^*(t) - \sum_{k=1}^{m} g_{ik}(t)\, x_k(t) = 0 , \qquad i = 1, ..., n . \tag{2.9}$$

Its solution in the matrix form is the following:

$$(2.10)\qquad [x_k(t)] = [g_{ik}(t)]^{-1}[y_i^*(t)]\,, \qquad i = 1,...,n\,, \quad k = 1,...,m\,. \qquad (m = n)\,.$$

In the case of $m > n$, i.e. when the number of input signals is greater than the number of the reproduced output signals, the condition of minimum error is also Eq.(2.9), where some of the input signals $x_k(t)$ for $k = n+1,...,m$ have been arbitrarily chosen, and the remaining ones are

$$(2.11)\qquad [x_\nu(t)] = [g_{i\nu}(t)]^{-1}\left[y_i^*(t) - \sum_{k=n+1}^{m} g_{ik}(t)\, x_k(t)\right], \qquad \nu = 1,...,n\,, \quad i = 1,...,n\,.$$

It is possible to use the presented method of synthesis of the input signals [(1)] after identification of the transfer functions which appear in the equations of the method.

3. Identification by the averaging method

Identification of the transfer function $g_{ik}(t)$ is carried out with the use of information obtained in the experiments made at the test stand. This information consists of the measured and recorded time functions, $x_k(t)$ and $y_k(t)$. The transfer functions should be chosen so as to ensure the similarity between the signals in the model relation (2.1) and in the real relations during the stand experiments. The measure of similarity can be the error which is the function of differences between signals in the model and in the experiment.

It is not possible to find the transfer functions which yield the minimum of this error from the results of a single experiment. A single experiment gives too little information. The problem, however, may be solved with the use of the condition of minimalization of the error averaged for a greater number of experiments. This is the essence of the method of averaging. Averaging is carried out in the set of realizations on the grounds of the results of a number of experiments carried out on the test stand. The averaged absolute error for $\vartheta = 1,...,s$ realizations of the signals is the following:

$$(3.1)\qquad \delta_s(t) = \frac{1}{s}\sum_{\vartheta=1}^{s}\sum_{i=1}^{n}\left[y_{i\vartheta}(t) - \sum_{k=1}^{m} g_{ik}(t)\, x_{k\vartheta}(t)\right]^2,$$

(1) The method of syntesis in the time domain is analogous to the method of synthesis in the frequency domain presented in [3].

where $y_{i\vartheta}(t)$, $x_{k\vartheta}(t)$ are the signals measured during the experiment ϑ. The relative error averaged in the time interval $< t_1, t_2 >$ is

$$\varepsilon = \frac{1}{\varepsilon_0} \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} \delta_s(t)\, dt\,, \tag{3.2}$$

where the reference function has the form

$$\varepsilon_0 = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} \sum_{\vartheta=1}^{s} \sum_{i=1}^{n} [y_{i\vartheta}(t)]^2\, dt\,. \tag{3.3}$$

By using the Euler–Lagrange conditions for minimum error

$$\frac{d}{dt}\left[\frac{\partial \delta_s(t)}{\partial \dot{g}_{ik}(t)}\right] - \frac{\partial \delta_s(t)}{\partial g_{ik}(t)} = 0\,, \qquad i = 1, ..., n\,, \qquad k = 1, ..., m\,, \tag{3.4}$$

the system of equations with unknown transfer functions $g_{ik}(t)$ is obtained for each $i = 1, ..., n$:

$$\sum_{\vartheta=1}^{s} \left[y_{i\vartheta}(t) - \sum_{k=1}^{m} g_{ik}(t)\, x_{k\vartheta}(t) \right] x_{\nu\vartheta}(t) = 0\,, \qquad \nu = 1, ..., m\,. \tag{3.5}$$

The solutions of the equations system (3.5) are the sought transfer functions. The equations are linear with respect to $g_{ik}(t)$. If the equations are not linearly dependent, the system will have a unique solution. Linear independence of the equations results from the influence of nonlinear properties of the object during experiments, and from the fact that the input signals are not fully repeatable. The differences between the input signals in subsequent realizations of the experiment are random or can be introduced intentionally [2]. This lack of full repeatibility of the input signals in time during the experiments is a necessary condition for application of the averaging method in the identification process. For the same reasons, application of the results of only one experiment does not give positive effects, but leads to an indeterminate set of equations and makes it impossible to find the unknown transfer functions.

Let us introduce a symbolic notation for the operation of averaging and substitute

$$\begin{aligned} \sum_{\vartheta=1}^{s} y_{i\vartheta}(t)\, x_{\nu\vartheta}(t) &= E\{y_i(t)\, x_\nu(t)\}\,, \\ \sum_{\vartheta=1}^{s} x_{k\vartheta}(t)\, x_{\nu\vartheta}(t) &= E\{x_k(t)\, x_\nu(t)\}\,. \end{aligned} \tag{3.6}$$

Equations (3.5) for each $i = 1, ..., n$ will be have the form

$$E\{y_i(t)\, x_\nu(t)\} - \sum_{k=1}^{m} g_{ik}(t)\, E\{x_k(t)\, x_\nu(t)\} = 0\,, \qquad \nu = 1, ..., m\,. \tag{3.7}$$

The solution can be written in a matrix form. The column matrix of the transfer functions $g_{ik}(t)$ for each $i = 1, ..., n$ is as follows:

$$[g_{ik}(t)] = [E\{x_k(t)\, x_\nu(t)\}]^{-1}\, [E\{y_i(t)\, x_\nu(t)\}]\,, \qquad k = 1, ..., m\,, \qquad \nu = 1, ..., m\,. \tag{3.8}$$

For example, for $m = 2$ the transfer functions found according to Eq.(3.8) are

$$\begin{aligned} g_{i1}(t) &= \frac{1}{W_0}\,[E\{x_2(t)\, x_2(t)\}E\{y_i(t)\, x_1(t)\} \\ &\qquad - E\{x_2(t)\, x_1(t)\}E\{y_i(t)\, x_2(t)\}]\,, \\ g_{i2}(t) &= \frac{1}{W_0}\,[-E\{x_1(t)\, x_2(t)\}E\{y_i(t)\, x_1(t)\} \\ &\qquad + E\{x_1(t)\, x_1(t)\}E\{y_i(t)\, x_2(t)\}]\,, \end{aligned} \tag{3.9}$$

where the following notation has been used:

$$W_0 = E\{x_1(t)x_1(t)\}E\{x_2(t)x_2(t)\} - E\{x_1(t)x_2(t)\}E\{x_2(t)x_1(t)\}. \tag{3.10}$$

Assuming $s = 2$, i.e. averaging the results of two experiments, the transfer functions (3.9) will be obtained in the following form:

$$\begin{aligned} g_{i1}(t) &= \frac{y_{i1}(t)\, x_{22}(t) - y_{i2}(t)\, x_{21}(t)}{x_{11}(t)\, x_{22}(t) - x_{12}(t)\, x_{21}(t)}\,, \\ g_{i2}(t) &= \frac{y_{i2}(t)\, x_{11}(t) - y_{i1}(t)\, x_{12}(t)}{x_{11}(t)\, x_{22}(t) - x_{12}(t)\, x_{21}(t)}\,. \end{aligned} \tag{3.11}$$

The special case of the process of forming the input signals for $m = n$, i.e. when the number of the formed input signals is equal to the number of the reproduced output signals, creates conditions for direct identification of elements of the inverse matrix. After substitution in the relation (2.10)

$$[\bar{g}_{ki}(t)] = [g_{ik}(t)]^{-1}\,, \tag{3.12}$$

it will take the form

$$[x_k(t)] = [\bar{g}_{ki}(t)]\, [y_i^*(t)], \qquad i = 1, ..., m\,, \qquad k = 1, ..., m\,, \tag{3.13}$$

where $g_{ki}(t)$ are the transfer functions of the new inverse model (Fig.3), in which the forcing signals are the output signals and the resulting, forced signals are the input ones. These functions, found by means of the method of averaging for each $k = 1, ..., n$ are

$$(3.14)\quad [\bar{g}_{ki}(t)] = [E\{y_i(t)\, y_\nu(t)\}]^{-1}\, [E\{x_k(t)\, y_\nu(t)\}]\,, \qquad \nu = 1, ..., m$$

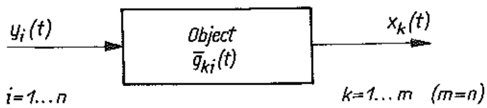

FIG. 3. Relation between signals in the inverse model.

In this manner, synthesis of the signals does not necessitate inversion of the matrix, what reduces the number of necessary calculations. Nevertheless, the necessity of inverting the matrix in the process of identification (3.14) still remains. This is a different matrix, however, what sometimes may simplify the procedure.

4. Conditions of forming the input signals

A substantial problem in the processes of forming the input signals and identification of the transfer functions is the possibility of obtaining singular matrices. Vanishing of denominators of certain expressions makes them indeterminate and, consequently, the transfer functions and input signals are impossible to assess for those time values for which the matrix singularity occurs. In such a case the corresponding transfer functions and input signals may be evaluated by extrapolation from the neighbouring intervals.

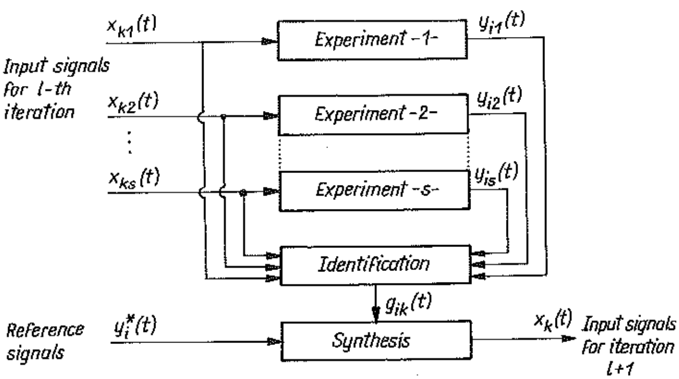

FIG. 4. Scheme of input signal generation (for a single iteration step).

The majority of real mechanical systems for which input signals forming is carried out exhibit nonlinear properties. The presented methods of synthesis and identification are, however, applicable to linear systems only. To make their application to nonlinear systems possible it is assumed that in some neighbourhood of the signals used for identification the system is linear, i.e. the superposition rule is valid. However, due to nonlinear properties of objects, the accurate solution of the problem of forming the input signals necessitates the iteration procedures [6]. In each iteration step, on the basis of signals measured during the experiment made in this step, identification of properties of an object is carried out. The criterion for assuming the proper number of iteration steps is that the solution of the problem should remain in the assumed range of linearity of the object properties. This is a drawback of the method of averaging, since it may require a large number of experiments (Fig.4).

Another inconvenience in the application of the presented method is the necessity of simultaneous recording of all the input and output signals in the system. Even small phase shifts, resulting from inaccurate measurement, recording or processing of signals, can significantly influence the results. It seems, however, that the present measuring technology makes it possible to satisfy the required precision conditions.

5. Example of application of the averaging method in simulation tests

In the presented example the object of simulation tests is a hydraulic single-bucket excavator. The program of simulation tests consists in reproducing in the stand the time functions of forces acting on the bucket tip in the soil excavation process. Hence, these forces measured in the excavation process, $P_1(t)$ and $P_2(t)$, are the reference signals (Fig.5).

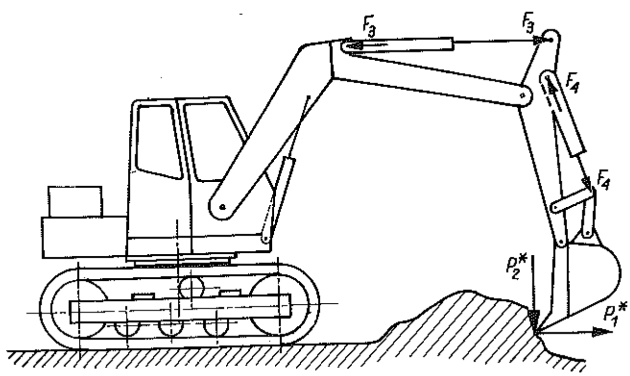

Fig. 5. Excavator under service conditions.

During the real work of an excavator the elements of its attachment boom, arm, bucket change their mutual positions in a broad range, according to the operation cycle. On the stand, however, the bucket tip is fixed, and the displacements of the attachment elements are possible only within a small range resulting from their deformations (Fig.6).

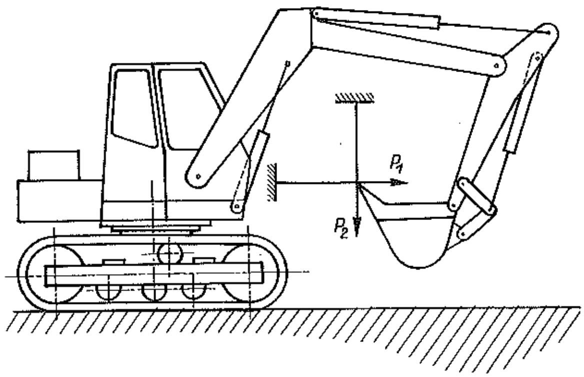

FIG. 6. Excavator on the simulation test stand.

It has been assumed that the input signals are the forces $F_3(t)$, $F_4(t)$ exerted by the hydraulic cylinders of the arm and the bucket, and the output signals are the forces $P_1(t)$ and $P_2(t)$. Then, the mathematical model of the excavator on the stand is a system with two input signals ($m = 2$) and two output signals ($n = 2$, Fig.7), governed by the following equations (2.1):

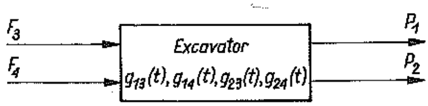

FIG. 7. Input and output signals for mathematical model of the excavator.

$$(5.1) \qquad \begin{aligned} P_1(t) &= g_{13}(t)\, F_3(t) + g_{14}(t)\, F_4(t), \\ P_2(t) &= g_{23}(t)\, F_3(t) + g_{24}(t)\, F_4(t), \end{aligned}$$

or, taking into account Eqs.(3.13), in the inverse form

$$(5.2) \qquad \begin{aligned} F_3(t) &= \bar{g}_{31}(t)\, P_1(t) + \bar{g}_{32}(t)\, P_2(t), \\ F_4(t) &= \bar{g}_{41}(t)\, P_1(t) + \bar{g}_{42}(t)\, P_2(t). \end{aligned}$$

Using the averaging method for the results of two experiments ($s = 2$) carried out on the test stand we can find the transfer functions of the model according to Eq.(3.14). This leads to

$$
\begin{aligned}
\bar{g}_{31}(t) &= \frac{1}{W_0}\left[F_{31}(t)\,P_{22}(t) - F_{32}(t)\,P_{21}(t)\right],\\
\bar{g}_{32}(t) &= \frac{1}{W_0}\left[F_{32}(t)\,P_{11}(t) - F_{31}(t)\,P_{12}(t)\right],\\
\bar{g}_{41}(t) &= \frac{1}{W_0}\left[F_{41}(t)\,P_{22}(t) - F_{42}(t)\,P_{21}(t)\right],\\
\bar{g}_{42}(t) &= \frac{1}{W_0}\left[F_{42}(t)\,P_{11}(t) - F_{41}(t)\,P_{12}(t)\right],
\end{aligned}
\tag{5.3}
$$

where

$$
W_0 = P_{11}(t)\,P_{22}(t) - P_{12}(t)\,P_{21}(t). \tag{5.4}
$$

The sought forcing signals which yield the minimum simulation errors are calculated according to formulae (2.10) which now will have the form

$$
\begin{aligned}
F_3(t) &= \bar{g}_{31}(t)\,P_1^*(t) + \bar{g}_{32}(t)\,P_2^*(t),\\
F_4(t) &= \bar{g}_{41}(t)\,P_1^*(t) + \bar{g}_{42}(t)\,P_2^*(t).
\end{aligned}
\tag{5.5}
$$

Having measured the output signals $P_1(t)$ and $P_2(t)$ obtained on the stand for the input signals (5.5), we can find the simulation error according to Eq.(2.4), which takes now the form

$$
\varepsilon = \frac{\int_{t_1}^{t_2} \left\{[P_1^*(t) - P_1(t)]^2 + [P_2^*(t) - P_2(t)]^2\right\} dt}{\int_{t_1}^{t_2} \left\{[P_1^*(t)]^2 + [P_2^*(t)]^2\right\} dt}. \tag{5.6}
$$

During the tests the hydraulic cylinders which drive the arm and bucket of the excavator are replaced with the electro-hydraulic actuators [6] equipped with control system suitable for simulation. It is also possible to use the standard cylinders of the excavator and apply special electro-hydraulic values in their alimentation circuits. A suitable control system should be provided then; this can be a digital control system equipped with a universal computer [5, 7].

In the considered example real experiments have been replaced with the computer ones, in which dynamic equations of the mathematic model of the excavator in the digging process and on the test stand have been solved.

The model of the excavator (Fig.8), which has been reduced to the mechanical part, is a system of four stiff masses coupled by articulated joints. The masses are: undercarriage with an operator cab, arm and bucket with the excavated soil. In the model, six reduced flexible elements with elastic-damping properties have been introduced. Planar movement of masses has been assumed and six independent coordinates have been assumed to describe it [4, 5]. Three of them: x_0, y_0, φ_1 describe the undercarriage displacements. Their values change in narrow intervals resulting from deformations of the flexible elements. Three coordinates: φ_2, φ_3, φ_4 describe the relative motions of the boom, arm and bucket. Their values vary in large ranges which result from the desired motion of the excavator attachment and from the deformations of the flexible elements which connect the hydraulic cylinders with the boom, arm and bucket.

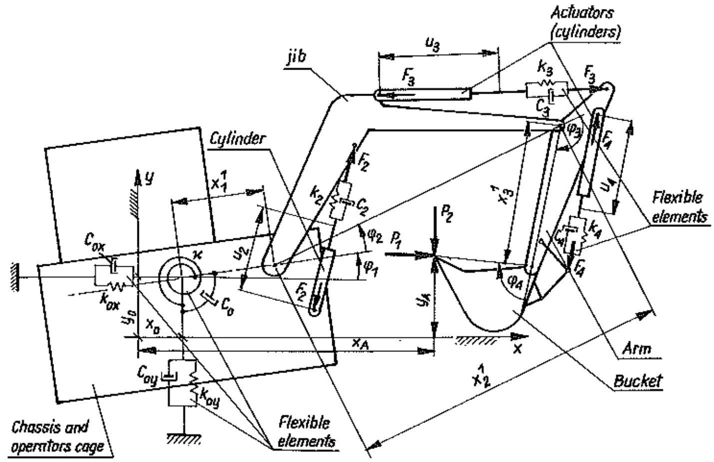

FIG. 8. Model of mechanical elements of the excavator.

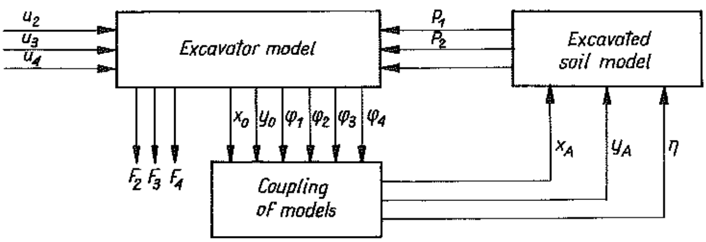

FIG. 9. Signals in the excavation soil experiment.

In the computer experiment which replaces the soil excavation process the input signals are the displacements u_2, u_3, u_4 of the cylinder pistons (kinematic input) and the forces P_1, P_2 of the excavated soil reaction. The output signals are $x_0, y_0, \varphi_1, \varphi_2, \varphi_3, \varphi_4$ and the forces F_2, F_3 and F_4 of cylinder reactions. Forces P_1 and P_2 and the coefficient ϑ which describes the bucket filling ratio are the output signals of the model of excavated soil(2)[5]. The output signals of the latter model are the coordinates x_A, y_A and η which describe the bucket position as a function of the coordinates $x_0, y_0, \varphi_1, \varphi_2, \varphi_3$ and φ_4, (Fig.9).

In the equations of the model the motion is decomposed into the principal motion and perturbation motion. The principal motion is the desired part of displacements of the system, whereas the perturbation motion consists of the vibrations resulting from the flexibility of the object elements. Motion of the

(2)The model of the soil excavation process was described in more detail in [5].

excavator elements without flexible elements deformations is understood as the principal motion, therefore, only three coordinates will have the principal and perturbation motion components:

$$\begin{aligned} \varphi_2 &= \varphi_2^0 + \varepsilon\varphi_2 \,, \\ \varphi_3 &= \varphi_3^0 + \varepsilon\varphi_3 \,, \\ \varphi_4 &= \varphi_4^0 + \varepsilon\varphi_4 \,, \end{aligned} \tag{5.7}$$

whereas the remaining coordinates will have only small, perturbation components,

$$\begin{aligned} x_0 &= \varepsilon x_0 \,, \\ y_0 &= \varepsilon y_0 \,, \\ \varphi_1 &= \varepsilon\varphi_1 \,, \end{aligned} \tag{5.8}$$

where $\varphi_2^0, \varphi_3^0, \varphi_4^0$ – principal motion components, $\varepsilon\varphi_2, \varepsilon\varphi_3, \varepsilon\varphi_4, \varepsilon x_0, \varepsilon y_0, \varepsilon\varphi_1$ – perturbation motion components. Such decomposition allows for linearization of the equations of the perturbation motion, for which the principal motion is the vibration excitation; the disturbance motion does not influence the principal motion.

The principal motion equations and the equations of constraints which result from the object geometry are as follows:

$$\begin{aligned} &\ddot{\varphi}_2^0 A_{22} + \ddot{\varphi}_3^0 A_{23} + \ddot{\varphi}_4^0 A_{24} \\ &\qquad = B_2 + F_2^0 D_2 - F_3^0 A_3 - P_1 x_2^1 \sin\varphi_2^0 + P_2 x_2^1 \cos\varphi_2^0 \,, \\ &\ddot{\varphi}_2^0 A_{32} + \ddot{\varphi}_3^0 A_{33} + \ddot{\varphi}_4^0 A_{34} = B_3 + F_3^0 D_3 - F_4^0 D_4 \\ &\qquad - P_1 x_3^1 \sin\left(\varphi_2^0 + \varphi_3^0\right) + P_2 x_3^1 \cos\left(\varphi_2^0 + \varphi_3^0\right) \,, \\ &\ddot{\varphi}_2^0 A_{42} + \ddot{\varphi}_3^0 A_{43} + \ddot{\varphi}_4^0 A_{44} = B_4 + F_4^0 D_4 \\ &\qquad - P_1 x_4^1 \sin\left(\varphi_2^0 + \varphi_3^0 + \varphi_4^0\right) + P_2 x_4^1 \cos\left(\varphi_2^0 + \varphi_3^0 + \varphi_4^0\right) \,, \\ &a_2^2 + b_2^2 - 2a_2 b_2 \cos\left(\alpha_2 + \beta_2 + \varphi_2^0\right) - u_2^2 = 0 \,, \\ &a_3^2 + b_3^2 - 2a_3 b_3 \cos\left(\alpha_3 + \beta_3 - \varphi_3^0 - \Pi\right) - u_3^2 = 0 \,, \\ &a_4^2 + b_4^2 - 2a_4 b_4 \cos\left(\alpha_4 + \beta_4 - \varphi_4^0 - \Pi\right) - u_4^2 = 0 \,, \end{aligned} \tag{5.9}$$

and the perturbation motion equations after linearization are

$$\begin{aligned} \varepsilon\ddot{\varphi}_1 a_{11} &= -b_{11} - c_0 \varepsilon\dot{\varphi}_1 - \kappa\varepsilon\varphi_1 + P_1 d_{11} + P_2 d_{12} \,, \\ \varepsilon\ddot{\varphi}_2 a_{12} &= -\left(c_{22} + d_{22}^2 c_2\right)\varepsilon\dot{\varphi}_2 - \left(b_{22} + k_{22}^2 d_2^2\right)\varepsilon\varphi_2 - F_2^0 d_{22} \,, \\ \varepsilon\ddot{\varphi}_3 a_{33} &= -\left(c_{33} + d_{33}^2 c_3\right)\varepsilon\dot{\varphi}_3 - \left(b_{33} + k_3 d_{33}^2\right)\varepsilon\varphi_3 - F_3^0 d_{33} \,, \\ \varepsilon\ddot{\varphi}_4 a_{44} &= -d_{44}^2 c_4 \varepsilon\dot{\varphi}_4 - \left(b_{44} + k_4 d_{44}^2\right)\varepsilon\varphi_4 - F_4^0 d_{44} \,, \\ \varepsilon\ddot{x}_0 a_{55} &= -b_{55} - c_{0x}\varepsilon\dot{x}_0 - k_{0x}\varepsilon x_0 + P_1 \,, \\ \varepsilon\ddot{y}_0 a_{66} &= -b_{66} - c_{0y}\varepsilon\dot{y}_0 - k_{0y} + P_2 \,. \end{aligned} \tag{5.10}$$

The forces extered by the cylinders, which are the sums of forces resulting from the principal and the perturbation motions are found from the formulae

$$\text{(5.11)}\qquad \begin{aligned} F_2 &= F_2^0 + \varepsilon F_2 = -k_2 d_{22}\varepsilon\varphi_2 - d_{22}c_2\varepsilon\dot{\varphi}_2 \,, \\ F_3 &= F_3^0 + \varepsilon F_3 = -k_3 d_{33}\varepsilon\varphi_3 - d_{33}c_3\varepsilon\dot{\varphi}_3 \,, \\ F_4 &= F_4^0 + \varepsilon F_4 = -k_4 d_{44}\varepsilon\varphi_4 - d_{44}c_4\varepsilon\dot{\varphi}_4 \,. \end{aligned}$$

Coefficients of the equations of both the motions depend on the geometrical characteristics and displacements of the excavator masses; they are also functions of the principal motion coordinates(3).

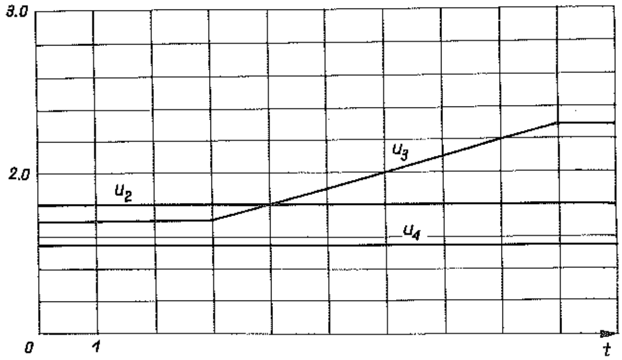

FIG. 10. Input signals in the excavation experiment.

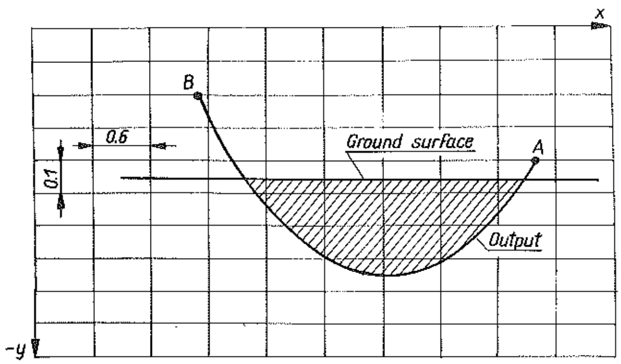

FIG. 11. Bucket tip trajectory during excavation.

In the experiment of soil excavation in the model equations the input signals $u_2(t), u_3(t)$ and $u_4(t)$, Fig.10, are given. This results in the arm and bucket displacement from point A to B, Fig.11. As a result of this displacement, soil is excavated, and the forces $P_1^*(t), P_2^*(t)$ which act on the bucket are measured (Fig.12).

The method of fixing of the excavator on the simulation stand (Fig.13) is such that displacements of its elements are possible only within the range

(3)The coefficients in explicit form and numerical values of the parameters are given in paper [4].

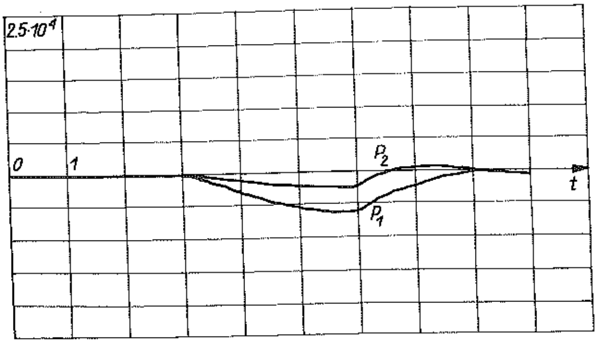

FIG. 12. Soil reaction forces (reference signals).

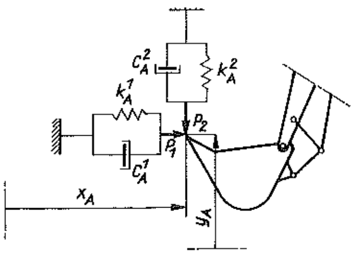

FIG. 13. Excavator model on the test stand (fixed bucket).

of the perturbation motion, while the principal motion coordinates remain constant. The mathematical model of the excavator is conceived in a slightly different manner: the input signals are the forces F_2, F_3 and F_4 exerted by cylinder actuators, whereas the output signals are the forces P_1, P_2 acting on the bucket tip (Fig.14). The equations of the mathematical model which describe vibrations of the excavator on the stand are written in the form

$$
\begin{aligned}
\varepsilon\ddot{\varphi}_1 a_{11} &= -c_0\dot{\varphi}_1 - \kappa\varphi_1 + P_1 d_{11} + P_2 d_{12}\,,\\
\varepsilon\ddot{\varphi}_2 a_{22} &= -\left[c_{22} + c_2 d_{22}^2\right]\varepsilon\dot{\varphi}_2 - \left[b_{22} + k_2 d_{22}^2\right]\varepsilon\varphi_2 - F_2 d_2^2\,,\\
\varepsilon\ddot{\varphi}_3 a_{33} &= -\left[c_{33} + c_3 d_{33}^2\right]\varepsilon\dot{\varphi}_3 - \left[b_{33} + k_3 d_{33}^2\right]\varepsilon\varphi_3 - F_3 d_3^2\,,\\
\varepsilon\ddot{\varphi}_4 a_{44} &= -c_4 d_{44}^2\varepsilon\dot{\varphi}_4 - \left[b_{44} + k_4 d_{44}^2\right]\varepsilon\varphi_4 - F_4 d_4^2\,,\\
\varepsilon\ddot{x}_0 a_{55} &= -c_{0x}\varepsilon\dot{x}_0 - k_{0x}\varepsilon x_0 + P_1\,,\\
\varepsilon\ddot{y}_0 a_{66} &= -c_{0y}\varepsilon\dot{y}_0 - k_{0y}\varepsilon y_0 + P_2\,,
\end{aligned}
\tag{5.12}
$$

and

$$
\begin{aligned}
P_1 &= -k_A^1\varepsilon x_A - c_A^1\varepsilon\dot{x}_A\,,\\
P_2 &= k_A^2\varepsilon y_A + c_A^2\varepsilon\dot{y}_A\,,
\end{aligned}
\tag{5.13}
$$

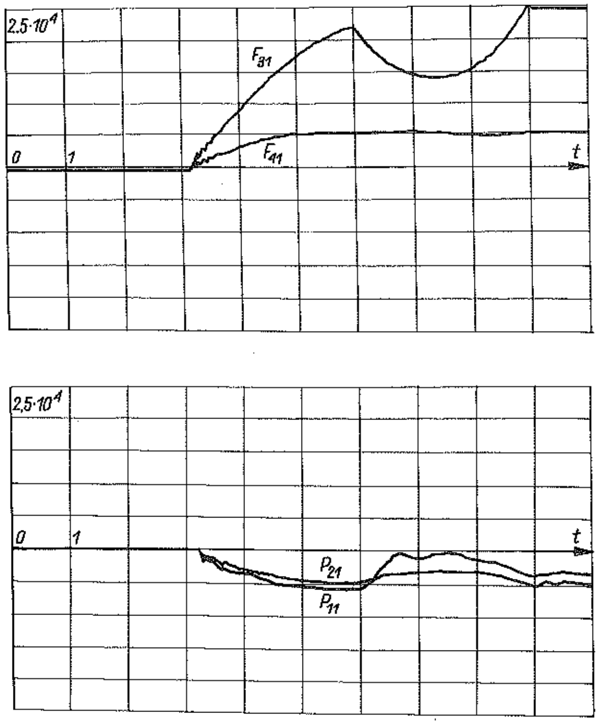

FIG. 14. Signals in the identification experiment (Experiment 1).

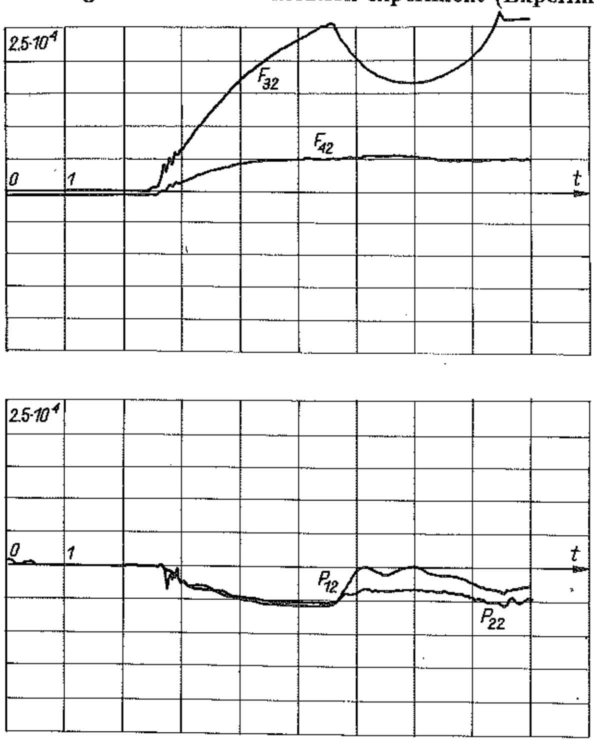

FIG. 15. Signals in the identification experiment (Experiment 2).

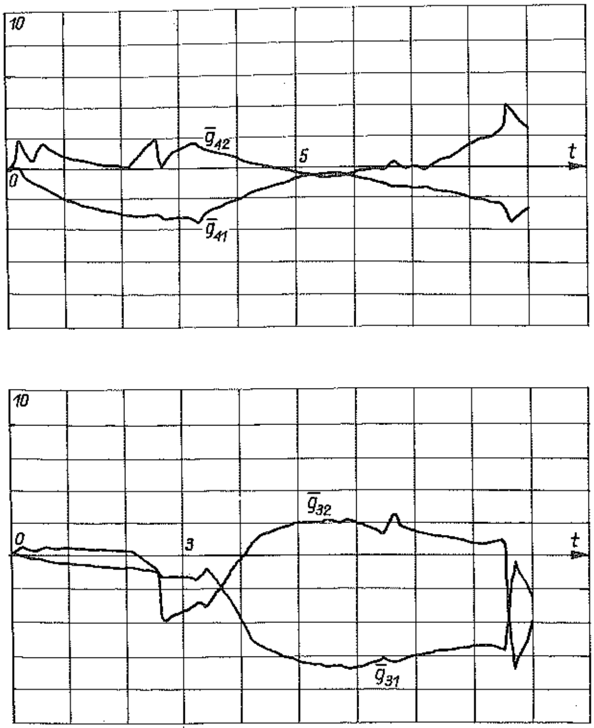

FIG. 16. Transfer function $\bar{g}_{ik}(t)$ obtained by identification.

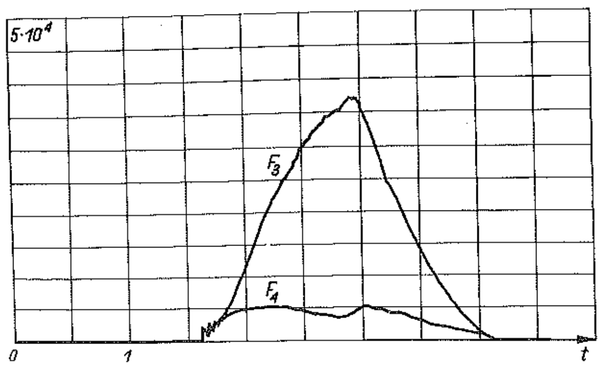

FIG. 17. Input signals obtained by synthesis.

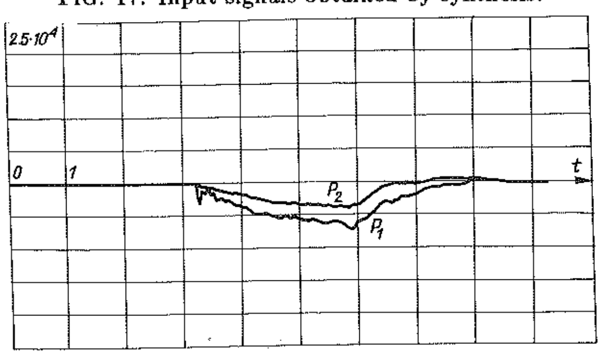

FIG. 18. Forces acting on the bucket in the verification experiment.

where the displacements of the bucket tip are

$$
(5.14)\quad
\begin{aligned}
\varepsilon x_A &= x_0 - \left[\left(x_2^1 \sin \varphi_2^0\right)\right] \varepsilon\varphi_2 \\
&\quad - \left[x_3^1 \sin\left(\varphi_2^0 + \varphi_3^0\right)\right] \varepsilon\varphi_3 - \left[x_4^1 \sin\left(\varphi_2^0 + \varphi_3^0 + \varphi_4^0\right)\right] \varepsilon\varphi_4 , \\
\varepsilon y_A &= y_0 + x_A^1 \varepsilon\varphi_1 + \left[x_2^1 \cos \varphi_2^0\right] \varepsilon\varphi_2 \\
&\quad + \left[x_3^1 \cos\left(\varphi_2^0 + \varphi_3^0\right)\right] \varepsilon\varphi_3 + \left[x_4^1 \cos\left(\varphi_2^0 + \varphi_3^0 + \varphi_4^0\right)\right] \varepsilon\varphi_4 ,
\end{aligned}
$$

The experiment on the stand is replaced by solution of the equations of the

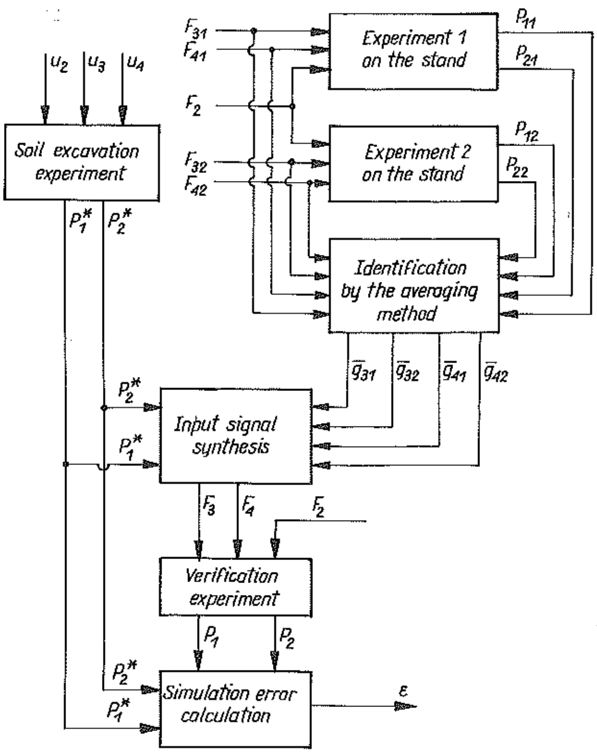

FIG. 19. Input signals generation in the simulation tests.

mathematical model. To make this model conform with the model (5.1) and (5.2), the signal $F_2(t)$ is treated as a disturbing signal, and its shape is the same as that in the experiments. After making two experiments for different input signals (Figs.14, 15), two transfer functions (5.3) were found, Fig.16. These transfer functions served for the synthesis of forcing signals (5.5) which yield the minimum simulation errors (Fig.17). To estimate the simulation error, a verifying experiment has been carried out. For the assessed input signals (Fig.17) the equations of the mathematical model have been solved for the corresponding forces (Fig.18) acting on the bucket on the test stand. The simulation error calculated according to Eq.(5.6) equals 12.3%. This error has been obtained for the input signals which resulted from the forming process (Fig.19), in which the iteration procedures have not been applied.

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Streszczenie

O PEWNEJ METODZIE IDENTYFIKACJI W STANOWISKOWYCH BADANIACH SYMULACYJNYCH

W pracy przedstawiono metodę identyfikacji (zwaną metodą uśredniania), w której informację o badanym obiekcie dostarczają wyniki szeregu eksperymentów przeprowadzanych w podobnych warunkach. Wskazano na możliwość zastosowania tej metody w stanowiskowych badaniach symulacyjnych, gdzie występują warunki dla wykonania wymaganych eksperymentów. Przedstawiono także odpowiednią dla tej metody identyfikacji metodę syntezy sygnałów wymuszających w badaniach symulacyjnych oraz przykład kształtowania sygnałów wymuszających dla badań koparki jednonaczyniowej, w którym eksperymenty rzeczywiste zastąpiono eksperymentami komputerowymi.

Резюме

О НЕКОТОРОМ МЕТОДЕ ИДЕНТИФИКАЦИИ В УСТАНОВКАХ ИМИТАЦИОННЫХ ИССЛЕДОВАНИЙ

В работе представлен метод идентификации (называемый методом усреднения), в котором информацию об исследуемом объекте дают результаты ряда экспериментов, проведенных в аналогичных условиях. Указана возможность применения этого метода в установках имитационных исследовани й, где выступают условия для проведения требуемых экспериментов. Представлен также, соответствующий этому методу идентификации, метод синтеза вынуждающих сигналов в имитационных исследованиях, а также пример формирования вынуждающих сигналов для исследовани й одноковшового экскаватора, в котором действительные эксперименты заменены компьютерными экспериментами.

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