Estimation of the Mathematical Model Parameters for a Multi-channel Electro-hydraulic Strength Test Bench

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***Abstract*—A feature of strength test benches is the presence of many channels of force loading interconnected through the design, which complicates the setting of the bench control system regulators. Synthesis of an efficient t est b ench control system and automatization of the controller parameters require a preliminary analysis of the mathematical model of the strength test bench. In this paper, we consider the problem of estimating the parameters of a mathematical model of a multichannel electrohydraulic stand for strength testing of aircraft structures. Identification o f t he m athematical m odel p arameters o f the stand is carried out by conducting a special experiment. This experiment is based on the applying a trial harmonic signal sequentially to each control channel and signals processing at the input and output of the stand. The results of such an experiment make it possible to evaluate the matrix of mutual influence of control channels. The paper presents the results of the experiments and estimation of the parameters of a multichannel test bench.**

Keywords—strength tests, aircraft tests, electrohydraulic drive, identification, harmonic analysis

I. Introduction

An important stage in the development of aerospace equipment is the performance of strength and fatigue tests [1]–[4]. During strength tests, the given cyclograms of force loading of structures are formed using electrohydraulic drives [5], [6]. At the same time, the quality of carrying out strength tests largely depends on the accuracy of the implementation of the given cyclogram of force loading [7], [8].

The complexity of the design, the mutual influence of channels of force loading, high requirements for the accuracy of force loading, backlash of actuators and the non-linearity of the characteristics of electro-hydraulic distributors complicate the procedure for setting up regulators of electro-hydraulic servo drives of benches [9]–[11].

At the same time, modern computer technology makes it possible to implement a wider range of algorithms and data processing methods through the use of large amounts of information with their real-time processing [12], [13].

In particular, the use of identification m ethods [14], [15] makes it possible to refine t he p arameters o f the mathematical model of the force loading bench, justify the choice of the controller structure, and also apply adaptive control algorithms based on the identification results, which ultimately will improve the accuracy implementation of given cyclograms of force loading of structures [16].

Increasing the efficiency of the force loading system requires refinement of the mathematical model of the multi-channel stand for strength testing of aircraft structures. Previous researches of this issue were devoted to the identification of the model and parameters of a single-channel strength test stand [17]. Existing test benches can contain several tens of force loading channels [1]–[4]. A feature of multi-channel test benches is the significant interrelationships between the processes of force loading between the channels of loading, which leads to a decrease in the accuracy of the implementation of cyclograms of force loading, complicates the processes of setting the regulators of channels of force loading and can lead to loss of stability of the multi-channel control system.

Thus, in order to ensure the required accuracy of the implementation of the given force loading cyclograms, it becomes necessary to evaluate the matrix that reflects the mutual influence of the bench force loading channels. Estimation of the parameters of this matrix can be used to refine and adapt the parameters of the electrohydraulic drive control algorithm, taking into account the relationship between the bench channels.

In this paper, we consider the issues of estimating the matrix of gain coefficients of the channels of force loading of a multichannel test bench based on the analysis of frequency characteristics.

II. Problem Statement

The studies discussed in this paper were carried out on the basis of the TU-154 half-wing strength test stand. This stand is designed to form a given cyclogram of force loading at the points of force application.

Fig. 1 shows a diagram of a strength test stand, consisting of several electro-hydraulic channels of force loading. Each force loading channel consists of an EHV electro-hydraulic servo drive, an FS force sensor and a load structure.

Ensuring the accuracy of reproduction of the cyclogram of force loading is achieved by the control system, where the implementation of control algorithms is carried out using the controller.

Since all channels load a single structure, there is an interference of channels of force loading on each other. The presence of mutual influence of channels leads to a decrease in the accuracy of the implementation of the cyclogram of force loading and complicates the procedure for setting the parameters of the controllers in the control channels.

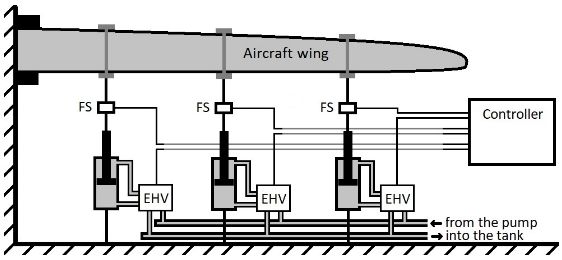

Fig. 1. Scheme of the strength test stand.

Therefore, there arises the problem of assessing the mutual influence of channels of force loading and the problem of constructing a mathematical model of the force loading system, which will clarify the method for choosing the structure and calculating the parameters of the controller to improve the accuracy of realizing the cyclogram of force loading.

III. Mathematical Model of the Strength Test Bench

In previous papers [17] a mathematical model of a force loading channel was considered, where the model of each channel was represented as an integrating link with a delay τ and a gain coefficiente g.

$$\dot{y}(t) = gu(t-\tau). \tag{1}$$

The influence of the unaccounted dynamics of a higher order in the model (1) is reflected in the form of a link of pure delay.

In this paper, a mathematical model of a multi-channel force loading test bench is considered in the following form:

$$\dot{Y}(t) = GU(t-\tau), \tag{2}$$

where Y is the vector of measured forces, $Y \in R^n$, U is the control vector, $U \in R^n$, G is a matrix reflecting the mutual influence of force loading channels and hydraulic drive gains, $G \in R^{n\times n}$.

The purpose of this work is to estimate the parameters of the G matrix based on the results of experiments carried out on the strength test bench for the TU-154 half-wing.

Estimating the parameters of the G matrix will further refine the method for choosing the parameters of control algorithms for the bench and, ultimately, improve the accuracy of generating the bench load cyclogram.

An integral property of experimental stands is the presence of nonlinearities in the channel of force loading. For example, due to backlash in the structure, the anisotropy of the properties of the load object, the nonlinearity of the processes in the hydraulic drive. These nonlinearities lead to the fact that in a closed system the signals u(t) and y(t) have a complex spectrum. Due to the nonlinearity of the characteristics of the test benches, harmonic analysis is used to estimate the parameters of the matrix G in the linearized model (2).

IV. Scheme of Experiment

The evaluation of the channel interference matrix is carried out by conducting a special experiment for each channel force loading. Since the delay τ is small value ($\tau \approx 50$ ms), therefore, the influence of the delay τ is not considered when solving the identification problem.

The first stage of the experiment consists in considering a system with a closed control loop for the first channel, where $u_1(t)$ is formed using a proportional-integral (PI) controller, to the input of which the control error signal for the first channel

$$e_1(t) = r_1(t) - y_1(t). \tag{3}$$

The driving force for the first channel is formed as a harmonic signal

$$r_1(t) = A_{r1}\sin(\omega t), \tag{4}$$

where

$$\omega = 2\pi/T, \tag{5}$$

T is the period of force impact. For other channels, the control action is set equal to zero

$$u_2(t) = u_3(t) = \cdots = u_n(t) = 0. \tag{6}$$

The results of the experiment are control signals $u_1(t)$ and signals from force sensors $y_1(t), y_2(t), \cdots, y_n(t)$. This experiment is repeated for each control channel.

Estimation of the each column for the matrix G is reduced to the analysis of the gain between the control signal of one channel and the signals from the force sensors of other channels.

The signals from the output of the controller and force sensors are decomposed into Fourier series.

$$\begin{gathered} u_1(t) = \frac{a_{0u_1}}{2} + \sum_{k=1}^{\infty}\left[a_{ku_1}\cos(k\omega t) + b_{ku_1}\sin(k\omega t)\right], \\ y_1(t) = \frac{a_{0y_1}}{2} + \sum_{k=1}^{\infty}\left[a_{ky_1}\cos(k\omega t) + b_{ky_1}\sin(k\omega t)\right], \\ y_2(t) = \frac{a_{0y_2}}{2} + \sum_{k=1}^{\infty}\left[a_{ky_2}\cos(k\omega t) + b_{ky_2}\sin(k\omega t)\right], \\ \cdots \\ y_n(t) = \frac{a_{0y_n}}{2} + \sum_{k=1}^{\infty}\left[a_{ky_n}\cos(k\omega t) + b_{ky_n}\sin(k\omega t)\right]. \end{gathered} \tag{7}$$

Based on the first harmonics, estimates of the amplitudes of the input and output harmonic signal of the bench are formed.

$$\begin{gathered} A_{1u_1}(t) = \sqrt{a_{1u_1}^2(t) + b_{1u_1}^2(t)}, \\ A_{1y_1}(t) = \sqrt{a_{1y_1}^2(t) + b_{1y_1}^2(t)}, \\ A_{1y_2}(t) = \sqrt{a_{1y_2}^2(t) + b_{1y_2}^2(t)}, \\ \cdots \\ A_{1y_n}(t) = \sqrt{a_{1y_n}^2(t) + b_{1y_n}^2(t)}. \end{gathered} \tag{8}$$

In accordance with the bench model (2), the ratio of the amplitudes of the first harmonics of the signals $u_1(t)$, $y_1(t)$, $y_2(t), \cdots, y_n(t)$ are related as follows:

$$\begin{gathered} A_{1y_1}(t)\omega \approx A_{1u_1}(t)|g_{11}(t)|, \\ A_{1y_2}(t)\omega \approx A_{1u_1}(t)|g_{21}(t)|, \\ \cdots \\ A_{1y_n}(t)\omega \approx A_{1u_1}(t)|g_{n1}(t)|, \end{gathered} \tag{9}$$

from which follow the expressions for estimating the coefficients of the first column of the G matrix in the mathematical model (2) of force loading channels:

$$\begin{aligned} |\hat{g}_{11}(t)| &= (A_{1y_1}(t)\omega)/A_{1u_1}(t), \\ |\hat{g}_{21}(t)| &= (A_{1y_2}(t)\omega)/A_{1u_1}(t), \\ &\cdots \\ |\hat{g}_{n1}(t)| &= (A_{1y_n}(t)\omega)/A_{1u_1}(t). \end{aligned} \tag{10}$$

Harmonic analysis makes it possible to obtain an estimate of the absolute value of the coefficient, but does not provide information about the sign. To estimate the sign of the coefficients of the G matrix, the following algorithm was used, where it follows from the results of the experiments carried out earlier that the own coefficient of the force loading channel is positive.

$$\begin{aligned} sign_{g_{11}} &= 1, \\ sign_{g_{21}} &= sign\left(y_1(t)y_2(t)\right), \\ &\cdots \\ sign_{g_{n1}} &= sign\left(y_1(t)y_n(t)\right), \end{aligned} \tag{11}$$

where $sign_{g_{11}}$ is the sign of the element g_{11} of the matrix G.

$$\begin{aligned} g_{11} &= sign_{g_{11}}|\hat{g}_{11}(t)|, \\ g_{21} &= sign_{g_{21}}|\hat{g}_{21}(t)|, \\ &\cdots \\ g_{n1} &= sign_{g_{n1}}|\hat{g}_{n1}(t)|. \end{aligned} \tag{12}$$

In the next section, the resulting relationships are used to identify model parameters based on experimental data.

V. Experimental Results

Below are the results of experiments for a three-channel stand.

The results of the experiment for the first channel are shown in Fig. 2 - Fig. 5. After carrying out experiments

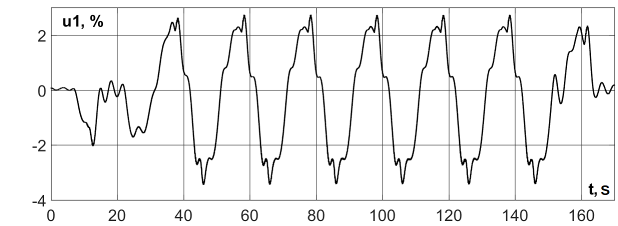

Fig. 2. Plot of control signal $u_1(t)$.

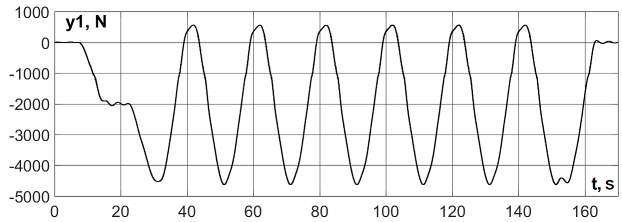

Fig. 3. Plot of force sensor signal $y_1(t)$.

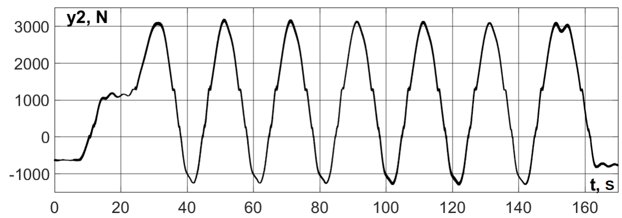

Fig. 4. Plot of force sensor signal $y_2(t)$.

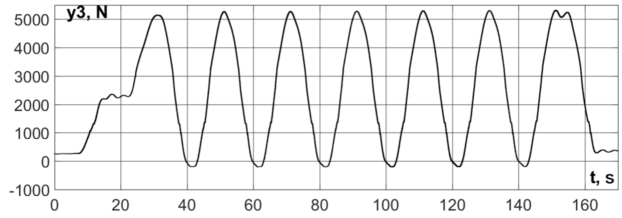

Fig. 5. Plot of force sensor signal $y_3(t)$.

The results of the experiment for the second channel are shown in Fig. 6 - Fig. 9.

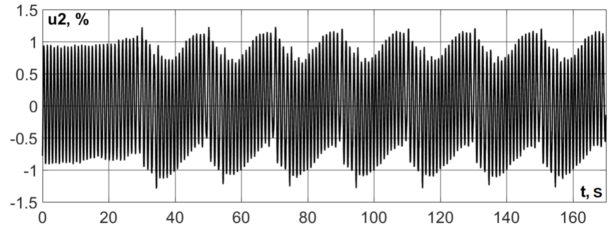

Fig. 6. Plot of control signal $u_2(t)$.

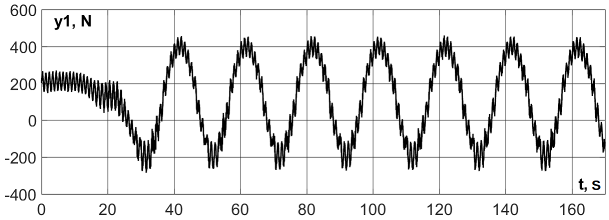

Fig. 7. Plot of force sensor signal $y_1(t)$.

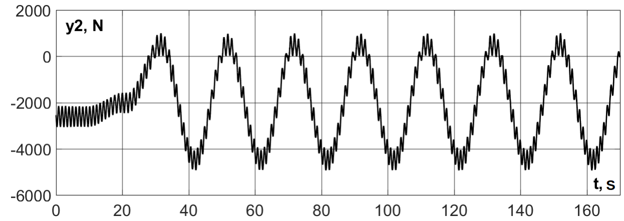

Fig. 8. Plot of force sensor signal $y_2(t)$.

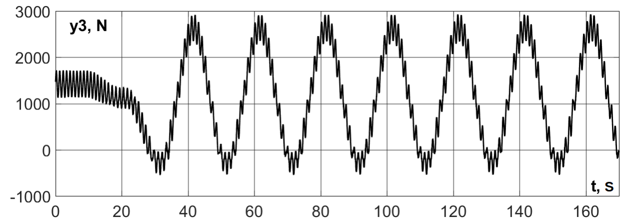

Fig. 9. Plot of force sensor signal $y_3(t)$.

The results of the experiment for the third channel are shown in Fig. 10 - Fig. 13.

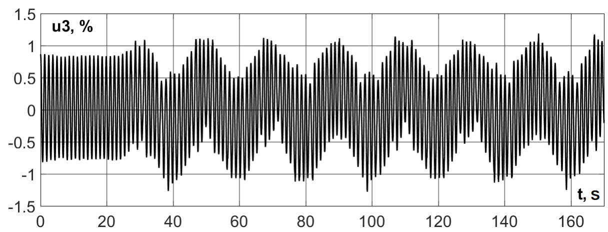

Fig. 10. Plot of control signal $u_3(t)$.

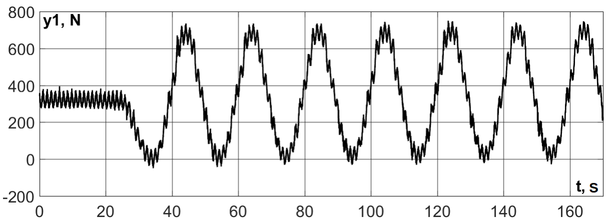

Fig. 11. Plot of force sensor signal $y_1(t)$.

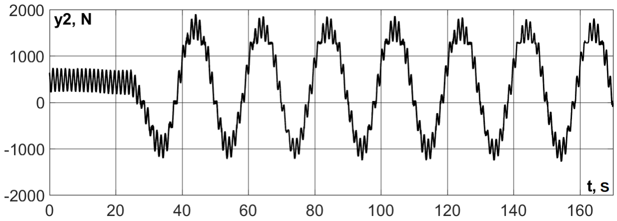

Fig. 12. Plot of force sensor signal $y_2(t)$.

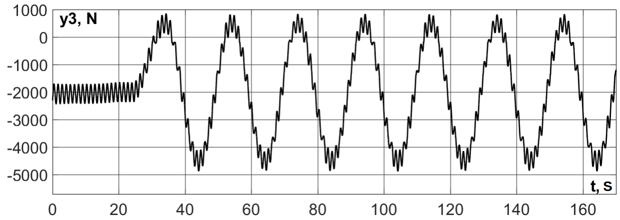

Fig. 13. Plot of force sensor signal $y_3(t)$.

for each channel and processing the received signals, an estimate for the matrix G of the three-channel control system of the bench for testing the strength of the half-wing of the TU-154 aircraft was obtained:

$$G = \begin{bmatrix} 1450 & -1350 & -1900 \\ -1200 & 9300 & -7150 \\ -1550 & -5200 & 13650 \end{bmatrix}. \qquad (13)$$

Estimating the parameters of the matrix G for the mathematical model (2) will further refine the method for choosing the parameters of control algorithms for the bench, taking into account the relationship of the channels of the bench.

VI. Conclusions

The paper proposes a technique for estimating the parameters of a model of a multichannel strength test stand, which is based on a harmonic analysis of the signals at the input and output of the stand. The proposed method for estimating the parameters of a multi-channel test bench was tested on an experimental test bench for the half-wing of the TU-154 aircraft. Based on the results of the experiments, an estimate of the mutual influence matrix for force loading channels was obtained. The propoused technique is planned to be used in the future for the calculation of regulators of stands for strength tests of aircraft structures.

Acknowledgment

This work was supported by the Ministry of Science and Higher Education of the Russian Federation (state registration no. 121042900050-6).

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