Verification of Space System Dynamics Using the MATLAB Identification Toolbox in Space Qualification Test

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Abstract**—**This article presents an approach with regards to the Functional Testing of Space System (SS) that could be a space vehicle (spacecraft-S/C) and/or its equipment and components – S/C subsystems. This test should finalize the Space Qualification Tests (SQT) campaign. It could be considered as a generic test and used for a wide class of SS that, from the point of view of System Dynamics and Control Theory, may be described by the ordinary differential equations. The suggested methodology is based on using semi-natural experiment laboratory stand that does not require complicated, precise and expensive technological control-verification equipment. However, it allows for testing totally assembled system during Assembling, Integration and Testing (AIT) activities at the final phase of SQT, involving system hardware (HW) and software (SW). The test physically activates system input (sensors) and output (actuators) and requires recording their outputs in real time. The data are then inserted in a laboratory computer, where it is post-experiment processed by the MATLAB/Simulink Identification Toolbox. It allows for estimating the system dynamics in the form of estimation of its differential equation coefficients through the verification experimental test and comparing them with expected mathematical model, prematurely verified by mathematical simulation during the design process. Mathematical simulation results presented in the article show that this approach could be applicable and helpful in SQT practice. Further semi-natural experiments should specify detail requirements for the test laboratory equipment and test-procedures.

Keywords**—**System dynamics, space system ground tests, space qualification, system dynamics identification, satellite attitude control, assembling integration and testing.

I. Introduction

THE problems with Ground Tests of SS first appeared together with the lunch of the first human made Earth orbiting satellites. In contrast to aircraft flying mainly at altitudes below 25 km, spacecraft fly at altitudes above 225 km, practically outside the Earth's atmosphere, almost in a vacuum, being affected by a high temperature gradient and the cosmic radiation. For the air vehicles, such as airplanes, environmental conditions at the time were already studied and well known, and ground test procedures existed and were almost conventional. But for the SS, they were completely new, and the same applies for the mechanical impacts from the launch rocket. These conditions had to be carefully studied and appropriate ground tests types, methodology and the procedures developed. Today, this is now widely performed and presented in several international and national standards and regulations. Following the studying of space environment and the increase in knowledge with regards to the launch and operation of SS, a new group of special ground tests was developed and presented in related standards and documents [1]-[4]. This group of tests generally includes the following test types: Thermo and Vacuum (TVAC), Vibration and Strength, Radio Communication and Electro Magnetic Compatibility (EMC), final refinement and verification of system AIT. These tests are finalized by the customer or authorized independent expert's conclusion of the launch readiness and named Space Qualification (SQ). Usually, SQ is carried out within facilities that are fully equipped for these purposes and is performed by trained personnel and highly qualified experts. For example, in Canada, SQ service is provided by the Canadian Space Agency (CSA) David Florida Laboratory [5].

It is important to mention that AIT activities should include a final functional test for SS Flight Model, which should demonstrate its capabilities to perform in space specified functions (at least to transition and stay in the Safety Mode). In this Functional Space Qualification Test (FSQT), SS is completely assembled and integrated, as well as refined (calibrated). In this test especially, SS HW and SW working jointly should be verified. This test should finalize the SQ procedures, preceding the release of the Space Qualification Report (SQR), and declaring readiness of SS for the launch and operation in space. Unfortunately, in common practice due to many various reasons, FSQT does not occupy the right place in a number of SQ tests. For many important spacecraft systems, for example, the Attitude Control System (ACS), this test often is restricted by checking the electric interface and ensuring the right direction of rotation of the reaction wheels ("polarity test"). Sometimes, such a superficial attitude to FSQT leads to stressful and even dramatic situations after the launch during SS operation in space. That is why many authors [6]-[8] and others often address this problem to SS developers and present some simulation tools and procedures to resolve the issue. The author's experience with Space Operation of Canadian satellites also shows that the results of such a "simplified" approach to FSQT can be quite onerous [9], resulting in the necessity to debug the satellite ACS that is already in space because of many anomalies in its functionality.

With regards to the Satellite Control System (SCS) and its

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components [10], [11] the main difficulty for FSQ is to model on-the-ground orbital flight with relevant gravitation and magnetic field, and orbital motion. For the purpose of testing the SCS of a modern small satellite some methods (hardware in closed control loop-HWL) were developed recently using sophisticated test-beds. These methods use three degrees of freedom air bearing rotated tables that allow to simulate on the ground absence of the friction in bearings, which prevent the free arbitrary rotation of a satellite in space [6].

This article presents a different approach that allows to identify SS (in particular, SCS) dynamics in open control loop using the common MATLAB/Simulink Identification Toolbox, available for engineers and scientists. Therefore, this does not require complex tests (control and verification) equipment. Essentially, only special laboratory emulators, activating SS sensors must be used in addition to conventional AIT SQ equipment (assembling stand, laboratory registration console for simulation radio link to satellite Tracing, Telemetry and Control System (TTCS), power supply, installation device and a mass properties determination machine).

II. Functional SQT as SS Dynamics Identification

Looking at the problem of SS FSQ from the point of view of System Dynamics, a common understanding is if a system has proper dynamics, previously verified with mathematical simulation (MSim), and it meets design requirements, and it (structure and parameters) is validated with semi-natural simulation (SNSim), then this system will be able to perform expected functions in space, at least in some mission essential operation modes. The evaluation process of system dynamics through experimentation is called System Identification process [12]. Currently, identification methods have been developed to be practically used in many engineer applications. The most known and commonly used engineering tool for identification purposes is the MATLAB/ Simulink Identification Toolbox (ITB) [13]. The latter is applicable for both cases; when system structure (mathematical model) is partly known and the only uncertainties are system parameters (mathematical model coefficients), referred to as "gray box" case and when a considered system is totally unknown, a "black box" case. For both of these cases, ITB allows to identify (estimate) system mathematical model. Only experimentally measured system input and output signals are used. The ITB adjusts the most suitable model's estimate to minimize the difference between the output measured experimentally and its estimation, provided by the estimated model.

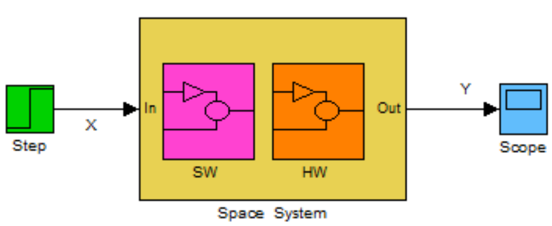

Fig. 1 SS unit

A brief presentation of the essential elements of this identification is presented below. Let us consider a SS as a unit consisting of the HW and the SW components, as presented in Fig. 1.

From the System Dynamics' point of view, this system can be characterized by its input $x(t)$, output $y(t)$ and some mathematical operation, $\Im$ determining system conversion from the output to the input

$$y(t) = \Im[y(t)] \tag{1}$$

At the first approximation, many aerospace device and systems' dynamic can be considered in the scope of Linear Time Invariant (LTI) dynamic system theory. In this case, (1) can be represented as:

$$y(t) = \int_0^t g(t-\tau)x(\tau)d\tau \tag{2}$$

where $g(t)$ is system's impulse characteristic - response to the Dirac's input impulse $x(t) = \delta(\tau)$. Using Laplace transformation to (2), it can be represented as

$$y(s) = G(s)x(s) \tag{3}$$

where $y(s) = L[y(t)],\ x(s) = L[x(t)]$ are Laplace transformations of output and input signals and $G(s) = L[g(t)]$ is Laplace transformation of system impulse function. In other words,

$$G(s) = \frac{y(s)}{x(s)} \tag{4}$$

is ratio of Laplace transformations of output to input signals.

In general case, LTI system transfer function can be expressed as the two polynomials ratio

$$G(s) = \frac{b_m s^m + b_{m-1}s^{m-1} + b_{m-2}s^{m-2} + \dots\dots + b_1 s + b_0}{a_m s^n + a_{n-1}s^{n-1} + a_{n-2}s^{n-2} + \dots\dots + a_1 s + a_0} \tag{5}$$

where b_i, a_j are constant polynomial coefficients, $m \le n$. Usually, (5) represents a stable system with the characteristic equation

$$a_m s^n + a_{n-1}s^{n-1} + a_{n-2}s^{n-2} + \dots\dots + a_1 s + a_0 = 0 \tag{6}$$

which roots $s_{k1,2} = \mathrm{Re}_k \pm j\,\mathrm{Im}_k$ satisfying the following condition

$$\mathrm{Re}_k \le 0 \tag{7}$$

Usually, for any designed SS assumable (before identification) transfer function $G(s)$ for system unit, presented in Fig. 1, is known from its design documentation.

Identification experiment provides measured input $X_m(t)$

and output $Y_m(t)$ data (Fig. 2) and the identification procedures used in ITB allows to estimate this function coefficients $\hat{a}_i$ and $\hat{b}_i$.

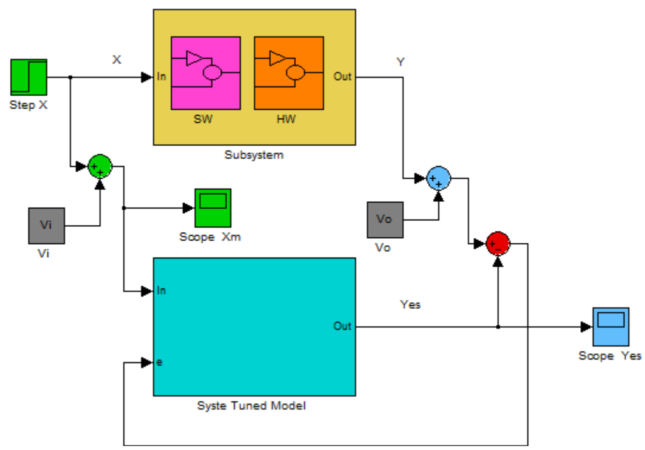

Fig. 2 System parameters identification experiment scheme

Idealistically, ratio between the input x and the output y of a LTI system $G(s)$ is (3). However, in fact, input x_m and output y_m signals are measured experimentally, with some added input V_i and output V_o errors

$$x_m = x + V_i \tag{8}$$

and

$$y_m = y + V_o \tag{9}$$

The difference between expected and experimental output signals is as follows

$$e = y_m - y = \hat{G}(s)x_m + V_o - G(s)x = \hat{G}(s)(x + V_i) + V_o - G(s)x = \\ = [\hat{G}(s) - G(s)]x + \hat{G}(s)V_i + V_o \tag{10}$$

where $\hat{G}(s)$ is estimate of system transfer function. This difference (10) is used in ITB to tune (adjust) model coefficients $\hat{a}_i$ and $\hat{b}_i$ to minimize it so that the outputs y_m and y_e would coincide as much as possible.

It can be mentioned that such identification does not require the simulating of system dynamic in closed feedback control loop configuration. In the considered case, identifying the open loop transfer function $G(s)$ is sufficient. Then the closed loop transfer function $W(s)$ can be recalculated with [14]:

$$W(s) = \frac{G(s)}{1 + G(s)} \tag{11}$$

where $W(s)$ is negative feedback control closed loop transfer function, $G(s)$ is transfer function of this loop in open state (assuming that feedback has unit transfer function $F(s) = 1$). This is important for SS, especially for SCS because it does not require unique complex equipment to simulate space flight and closed feedback control loop formed by the SCS in it.

Basic ideas of such a simulation for the identification of transfer function of open loop of SCS are presented in Fig. 3.

The flight model of SS is installed on laboratory AIT table and is electrically connected to the Laboratory Control-verification console.

SS expected transfer function $G(s)$ is known and should be verified with ITB, or should be identified within its experimental estimate $\hat{G}(s)$.

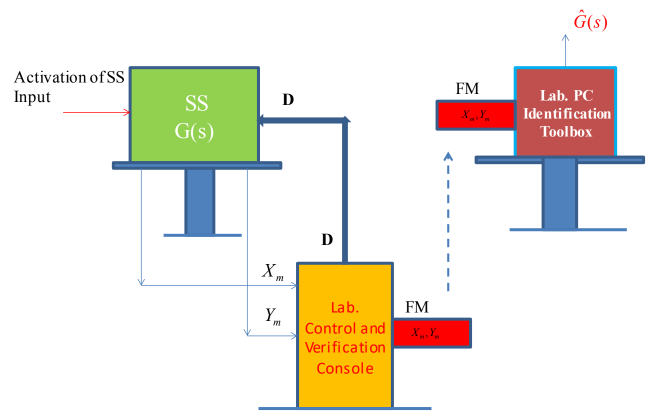

Fig. 3 Scheme of SS transfer function identification experiment

SS is switched on in special Ground Test Mode (GTM). Its power, reference and control data D are supplied via special data link from the laboratory Control and Verification Console (CVC).

It is important to note that in GTM SS should use special reference data about its state in SQ facility: Φ_0-latitude, Λ_0-longitude, h_0-altitude, $V_0 = 0$-velocity, B_0-magnetic induction vector. Its input is physically activated with a type of laboratory imitator (red arrow in Fig. 3). SS input and output data X_m and Y_m are recorded in real-time in the CVC. At the end of the experiment, these data are re-formatted in the form of mat. file and downloaded into the flash memory chip (FM in Fig. 3). Using regular USB interface is connected to laboratory PC for the data post-processing in ITB. This ITB carries out the estimate of SS transfer function $\hat{G}(s)$. If it is close to be expected due to the SS design function $G(s)$, then we can allege that $G(s)$ is verified by FSQT.

III. Examples of Identification of Basic Dynamic Units

To validate identification method for SS FSQ before performing semi-natural simulations, some typical liner time invariant (LTI) dynamic unit transfer functions were identified with mathematical (quasi-semi-natural) simulation. Some examples can be also found in [15]. The same methodology for this "quasi semi-natural simulation" was used. At first, the system was simulated without measured errors, idealistic ("clear" measurements) input X and output Y and its step response Y was received. After input $X_m = u$ and output Y_m

were distorted with superimposed Gaussian white noises, imitated measured errors and these signals were used for identification system dynamics (transfer function, step response, amplitude/phase frequency diagrams, characteristic polynomial roots).

Example 1. Simplest Aperiodic System, 1-st Order Unit

Given that the system is the first order dynamic unit that has the transfer function

$$G(s) = \frac{1}{Ts+1} \tag{12}$$

where $T = 10$ s is system time constant.

Characteristic equation $Ts+1=0$ root is $s_* = -\frac{1}{T} = -0.1$ s^{-1}.

Simulink block diagram of this system is presented in Fig. 4. This scheme allows for analyzing the step response of the system with and without measured noise.

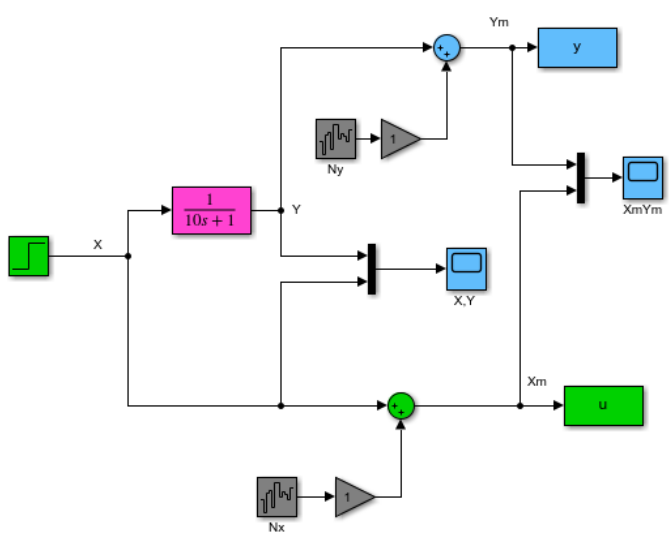

Fig. 4 Simulink block diagram of 1-st order unit

A. Mathematical Simulation

Step response of the system (12) without noise is shown in Fig. 5

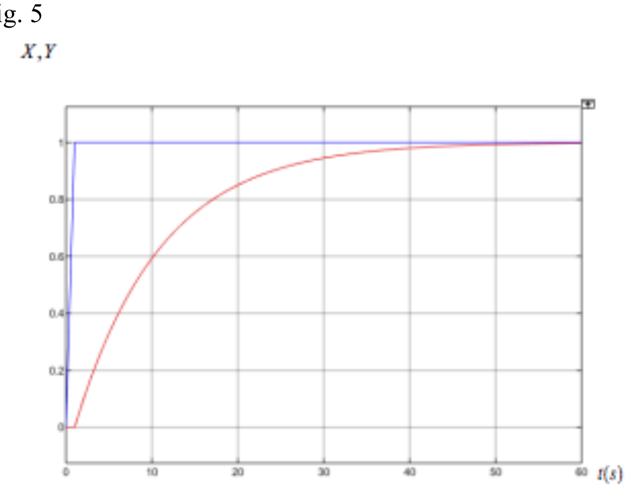

Fig. 5 Step response of the system (12) with or without noise. X is input-blue, Y is output-red

B. "Quasi Semi-Natural" Simulation

Step response of the system (12) with noise is shown in Fig. 6.

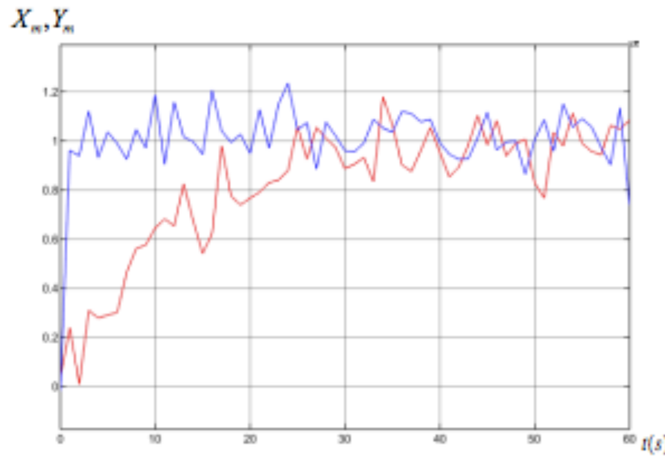

Fig. 6 Step response of the system (12) with noise in measurements. $X_m = u$ is input-blue, Y_m is output-red

C. Identification Results

System (12) identification results are presented Figs. 7-9.

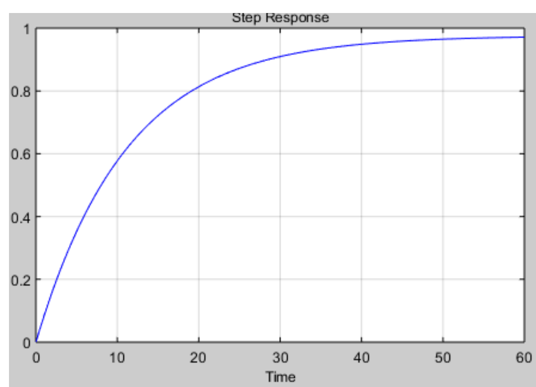

Fig. 7 Step response $h(t)$ of the identified system (12)

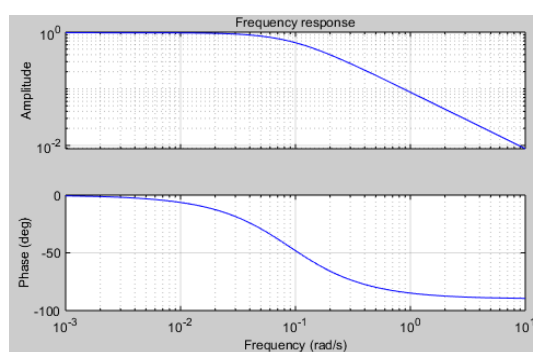

Fig. 8 Amplitude $A(\omega)$ and phase $\varphi(\omega)$ diagrams of the identified system (12)

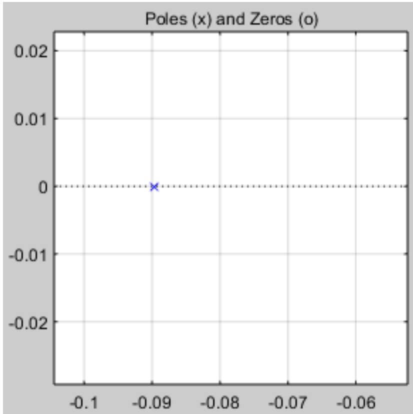

Fig. 9 Root of the characteristic equation of the identified system (12)

Estimated characteristic equation of the system (12) is $\hat{T}s+1=0$ with the root $s_*=-0.09$, estimated time constant is $\hat{T}=\frac{1}{s_*}=11.1$ s. Estimated transfer function of the system (12) is

$$G(s)=\frac{1}{\hat{T}s+1} \quad (13)$$

Example 2. Damped Oscillator, 2nd Order Unit

Given that system is 2nd order dynamic unit that has transfer function

$$G(s)=\frac{k}{T^2s^2+2dTs+1} \quad (14)$$

where $T=10$ s is system time constant, $d=0.707$ is specific damping coefficient, $k=5$ is static control gain.

System characteristic equation is $T^2s^2+2dTs+1=0$. Its roots are $s_{*1,2}$ = $-0.0707\pm0.0714j$. Simulink block diagram of this system is presented in Fig. 10. This scheme allows for analyzing the step response of the system with and without measured noise.

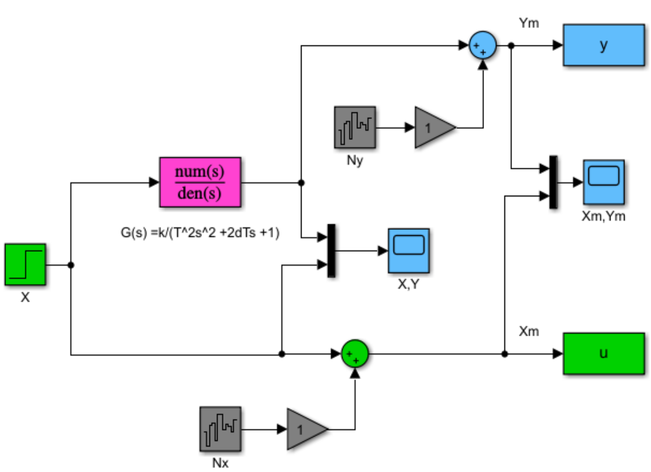

Fig. 10 Simulink block diagram of 2nd order unit

D. Mathematical Simulation

Step response of the system (14) without noise is shown in Fig. 11.

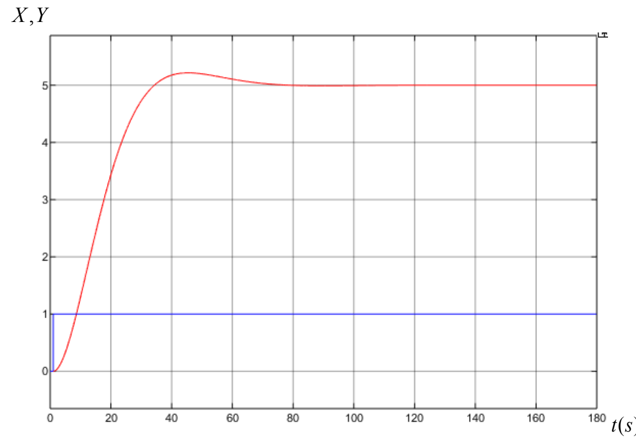

Fig. 11 Step response of the system (14) without noise. X is input-blue, Y is output-red

E. "Quasi Semi-Natural" Simulation

Step response of the system (14) with noise is shown in Fig. 12.

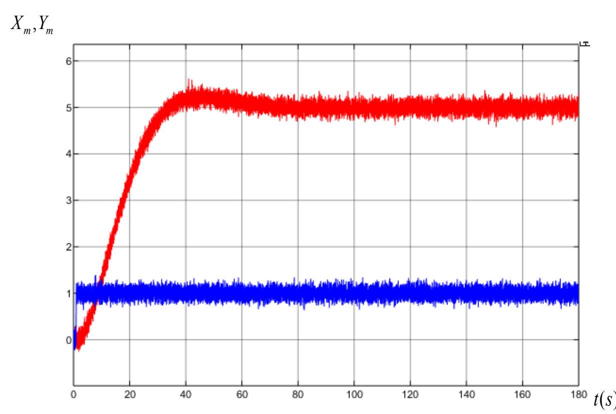

Fig. 12 Step response of the system (14) with noise in measurements. X_m is input-blue, Y_m is output-red

F. Identification Results

System (14) identification results are presented Figs. 13-15.

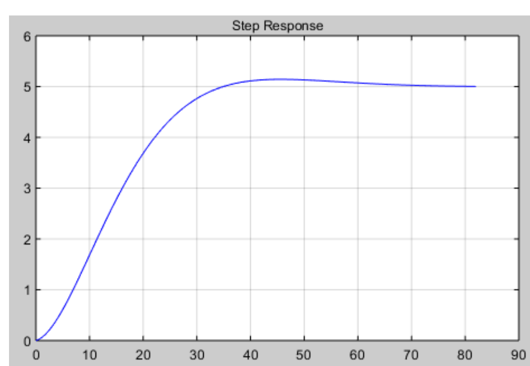

Fig. 13 Step response $h(t)$ of the identified system (14)

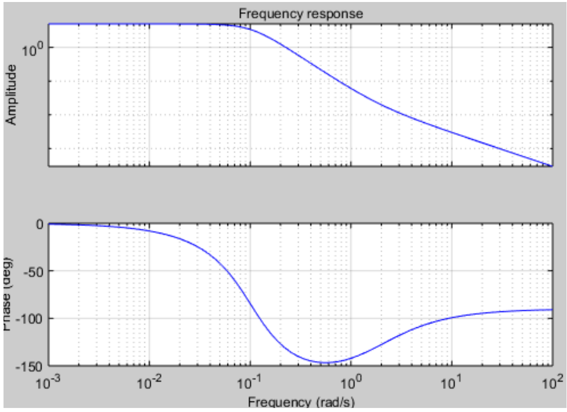

Fig. 14 Amplitude $A(\omega)$ and phase $\varphi(\omega)$ diagrams of the identified system (14)

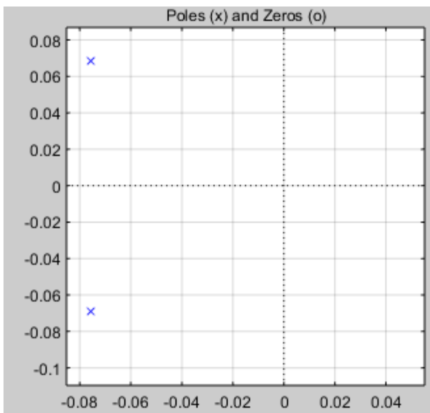

Fig. 15 Roots of the characteristic equation of the identified system (14)

Estimated characteristic equation of the system (14) is $\hat{T}^2 s^2 + 2\hat{d}\hat{T}s + 1 = 0$. It has two complex roots $s_{*1,2} = -0.0622 \pm 0.0688i$. Estimated transfer function of the system (14) is

$$G(s) = \frac{\hat{k}}{\hat{T}^2 s^2 + 2\hat{d}\hat{T}s + 1} \tag{15}$$

where estimated time constant is $\hat{T} = 10.78$ s, specific damping coefficient is $\hat{d} = 0.6707$, static control gain is $\hat{k} = 4.99$.

Example 3. PID Controller

Given that system is Proportional, Integral and Damping controller that has transfer function

$$G(s) = k_p + \frac{k_i}{s} + k_d s \tag{16}$$

where the control gains are as follows: k_p is positional gain, k_i is integral gain, k_d is damping gain.

Essentially, ideal differentiation assumed in (16) cannot be realized. Realistically, (16) has to be represented as

$$G_c(s) = k_p + \frac{k_i}{s} + \frac{k_d s}{\tau s + 1} \tag{17}$$

where τ is a small time constant. In other words, the differentiation with filtering takes place and $\omega_c = \frac{1}{\tau}$ is the cut frequency (bandwidth) of this differentiating filter. Let us say that $k_p = 0.1 Nm/rad$, $k_d = 0.03 Nm/rad/s$, $k_i = 0.05 Nm/rad \cdot s$, $\tau = 10s$ (assuming that the input of this controller is an angle in radians - rad and output is the control torque in Newton meters - Nm).

After algebraic transformation, (17) can be represented as:

$$G(s) = \frac{(k_p\tau + k_d)s^2 + (k_p + k_i\tau)s + k_i}{s(\tau s + 1)} \tag{18}$$

or in the numerical form

$$G(s) = \frac{1.03s^2 + 0.6s + 0.05}{s(10s + 1)} \tag{19}$$

Denominator of (19) $s(10s+1) = 0$ has following roots (poles): $s_{*1} = 0,\ s_{*2} = -0.1$ and the nominator $1.03s^2 + 0.6s + 0.05 = 0$ following (nulls) $s_1^* = -0.482,\ s_2^* = -0.101$.

Simulink block diagram of this PID controller is presented in Fig. 16.

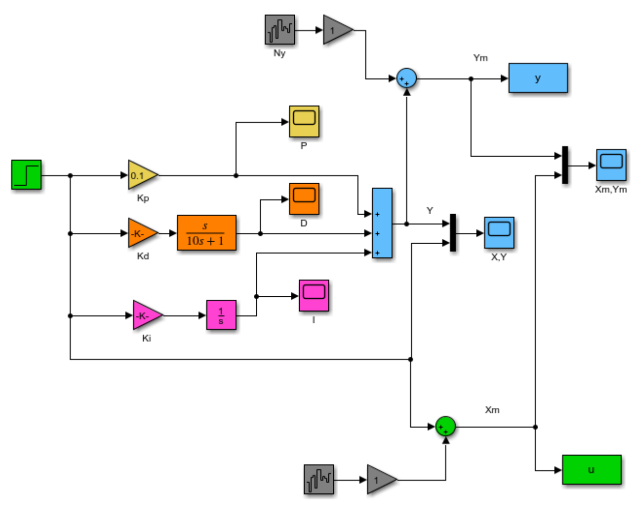

Fig. 16 Simulink block diagram of PID controller

G. *Mathematical Simulation*

Step response of the system (17) without noise is shown in Fig. 17.

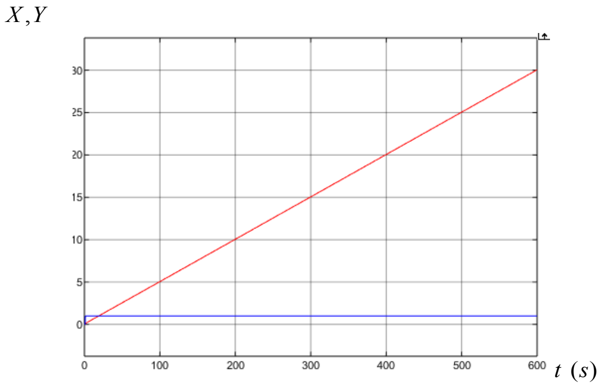

Fig. 17 Step response of the system (17) without noise. X is input-blue, Y is output-red

H. "Quasi Semi-Natural" Simulation

Step response of the system (17) with noise is shown in Fig. 18.

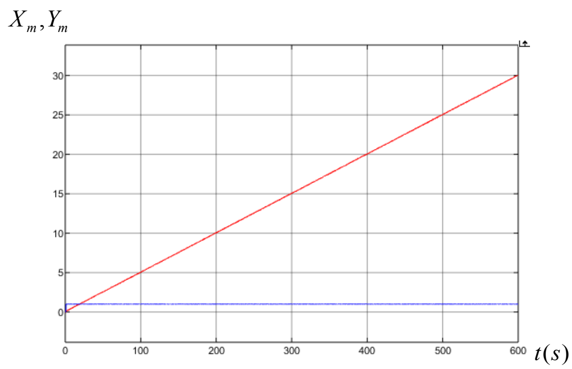

Fig. 18 Step response of the system (17) with noise. X_m Is input-blue, Y_m is output-red

I. Identification Results

Identification results of the system (17) are presented Figs. 19-21.

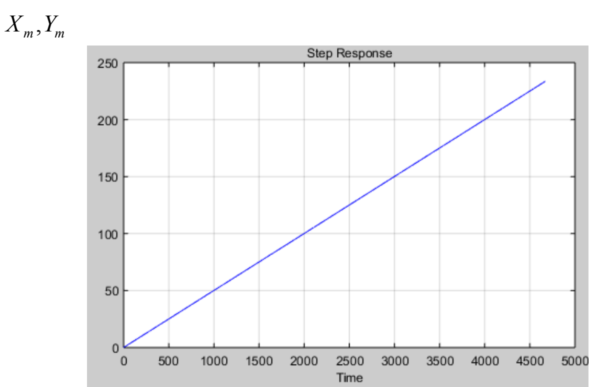

Fig. 19 Step response $h(t)$ of the identified system (17)

Estimated transfer function of the system (17) is

$$G(s) = \frac{1.034s^2 + 0.0618s + 0.004929}{s^2 + 0.0986s + 1.289 \cdot 10^{-16}} \qquad (20)$$

Formula (20) can be approximately represented as:

$$\hat{G}(s) \approx \frac{1.0487s^2 + 0.6103s + 0.05}{s(10.142s + 1)} \qquad (21)$$

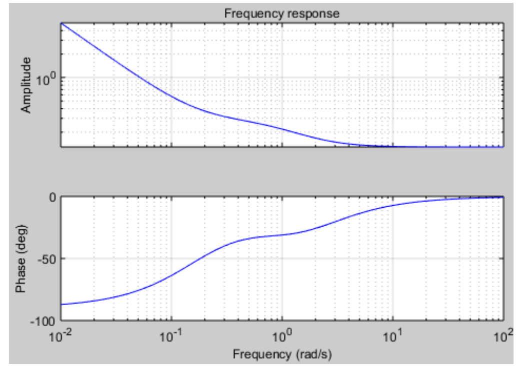

Fig. 20 Amplitude $A(\omega)$ and phase $\varphi(\omega)$ diagrams of the identified system

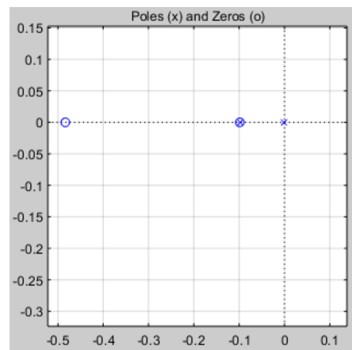

Fig. 21 Roots of the characteristic equation of the identified system (17)

Denominator of (21) $s(10.142s + 1) = 0$ has following roots (poles): $s_{*1} = 0,\ s_{*2} = -0.0986$ and the nominator $1.0487s^2 + 0.6103s + 0.05 = 0$ following (nulls) $s_1^* = -0.4818,\ s_2^* = -0.1008$.

Comparing coefficients (20) with (18) we can determine PID control gains and the time constant

$$k_p = 0.1033 Nm/rad,\ k_d = 0.025 Nm/rad/s,$$
$$k_i = 0.05 Nm/rad \cdot s,\quad \tau = 10.142s$$

Comparing identification results obtained with "quasi semi-natural" simulation with real mathematical model, we can notice that for all three examples considered above, both systems (identified and real) are very close, which demonstrates the effectiveness of application of ITB for this purpose.

IV. Conclusion

Mathematical simulation shows that the MATLAB Identification Toolbox can be successfully used for the identification of the dynamic characteristics for simple LTI units that can represent mathematical models of some class of the SS. Further studies with real physical experiments (semi-natural simulation), involving system HW, should verify, if this SS dynamics Identification Approach can be implemented in SS FSQT practice.

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