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INCREASE OF EFFECTIVENESS OF HARDWARE-IN-THE-LOOP TEST BENCH

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Abstract**—***Hardware-in-the-loop test bench for testing and verification navigational equipment structure is shown. Equation for determination hardware-in-the-loop test bench for testing and verification navigational equipment effectiveness is determined.*

Index Terms—Effectiveness; hardware-in-the-loop test bench.

I. INTRODUCTION

Hardware-in-the-loop (HIL) test bench for testing and verification of navigational equipment is designed to provide high-accuracy positioning, speed and accelerations during testing, development or production of inertial systems and their components in aviation, defense, aerospace and marine industries. Use of such HIL test benches for modeling of aircraft flight allow to decrease time and cost of testing. Such tests are characterized by high accuracy and reliability. However, significant disadvantage of HIL test benches for testing of navigational equipment is their price. The cost of HIL test benches presented by different manufacturers such as Acutronic, Ideal Aerosmith, is rather high. So the task is to develop HIL test bench with sufficiently high characteristics at minimal cost.

II. HARDWARE-IN-THE-LOOP TEST BENCHES FOR TESTING NAVIGATIONAL EQUIPMENT

Hardware-in-the-loop test benches for testing navigational equipment [1] designed to accurately reproduce the motion on axes of roll, pitch and yaw in the test lab.

They are developed in order to optimize and significantly reduce the complexity of the calibration process, inertial sensors, as well as to research and clarify the errors of micromechanical sensors and navigation systems based on them.

Their use reduces the time and reduces the cost spent on the development and production of navigation equipment. Often HIL test benches are used to calibrate inertial devices such as sensors of angular positions in production. Application of HIL test benches for seminatural testing of aerial vehicles reduces costs by reducing the number of field tests.

Test benches can also be used to confirm the quality of output products. According to the type of positioning of equipment under testing HIL test benches can be divided into the following types:

– turntables;
– 2-axis test benches;
– 3-axis test benches;
– 5-axis test benches;
– centrifuges;
– special systems.

Depending on the weight of equipment under test HIL test benches can be divided into:

– high load test benches;
– average load test benches;
– low load test benches.

By the presence of additional equipment are the following test benches:

– with additional equipment;
– without additional equipment.

Another important parameter is the accuracy of HIL test benches for testing of navigational equipment. According to this parameter are distinguished:

– high precision benches;
– medium accuracy test benches;
– standard accuracy test benches;
– rough test benches.

Triaxial HIL test benches of navigational equipment are used when there is requirement for simultaneously turning of the load on three axes.

Structural diagram of a triaxial test bench is shown in Fig. 1.

The test program for the test object is formed on the basis of selected methods for determination of errors of tested equipment and is entered into the computer with installed special software.

Data from the computer is received through the data input-output board by the motor control system. This data is processed by a microcontroller/FPGA and converted into PWM control signals for the actuators. Equipment under test is mounted on moveable platform driven by three actuators, for roll pitch and yaw. Resolvers and tachogenerators are also connected to axes of moveable platform to measure speed and angles of rotation of platform. Resolvers and tachogenerators transmit their data to corresponding ADC blocks, where data is transformed into digital form. After transformation this data comes back to the computer through data input-output board.

Use of microcontroller\FPGA in the system, reduces the load on the control program and allows to implement it in real time. This factor is one of the priority tasks of seminatural modeling, which makes it possible to increase the efficiency of the system as a whole.

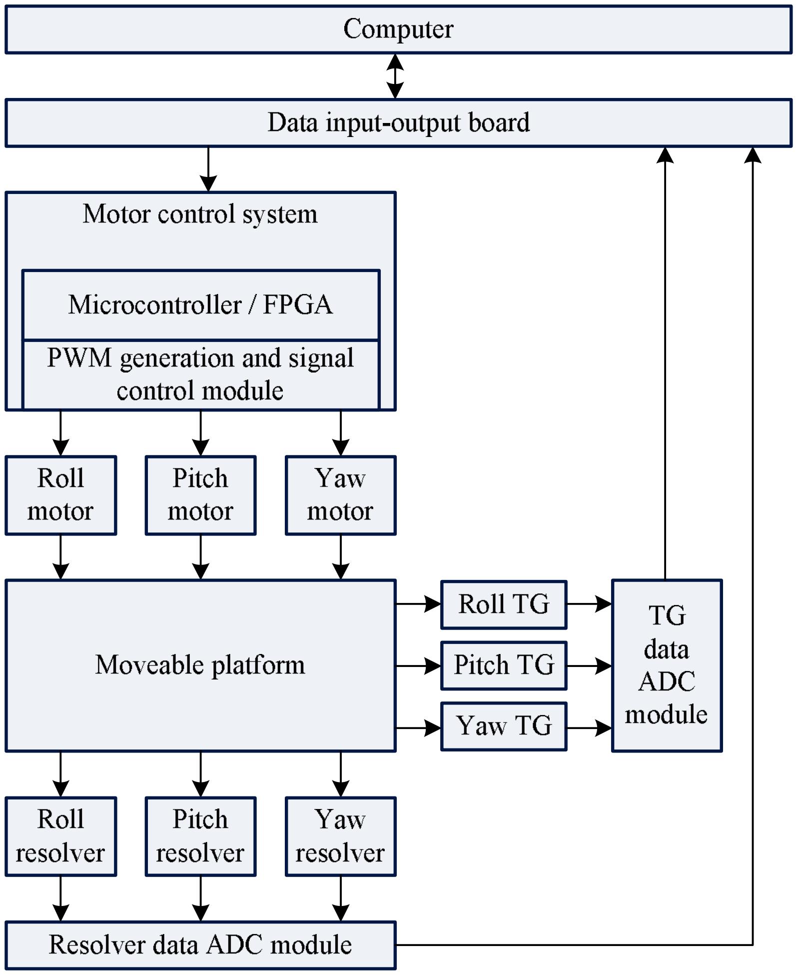

Fig. 1. Structural diagram of a triaxial test bench: FPGA is field programmable gate array; PWM is pulse width modulation; TG is tachometer generator; ADC is analog-to-digital conversion

III. Effectiveness of Hardware-in-the-Loop Test Bench Calculation

As can be seen from Fig. 1 HIL test bench for testing and verification of navigational equipment consists of three separate channels: for roll, pitch and yaw. Since channels have the same structure, lets consider them on example of one channel.

Effectiveness of HIL system for testing and verification of navigational equipment consists of set of different criteria [2]. Key criteria are:

– energy efficiency (η);
– dimensions and weight;
– positioning accuracy;
– rotation speed;
– price indices;
– reliability.

To determine effectiveness of the system (E_{syst}) it is proposed to summarize effectiveness criteria (E_{crit}) with definite weighting coefficient (b) over price index (Pr):

$$(E_{syst}) = \frac{\sum(b\,E_{crit})}{\text{Pr}}. \tag{1}$$

From the structure of the system it is possible to identify two main parts affecting the effectiveness criteria (Fig. 2):

– electronic part (motor control system);
– mechanical part (ensuring the mobility of the system).

In turn, the control system consists of:

– computing module (microcontroller / FPGA);
– motor control unit (thyristor bridge circuit).

Mechanical part consists of:

– motor;
– gear (wave gear);
– moveable platform.

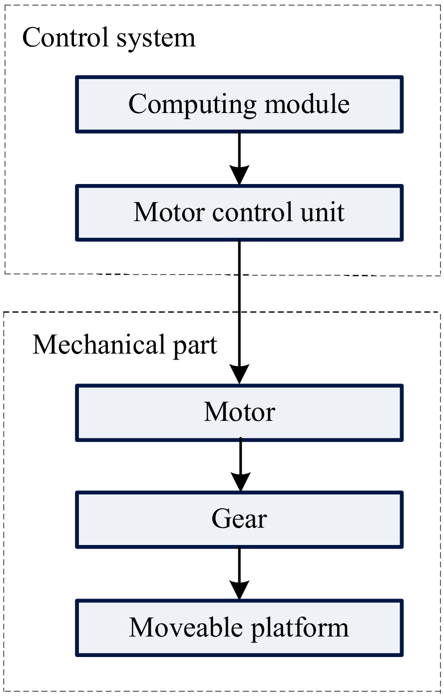

Fig. 2. Main elements of HIL system chanel

To calculate the *energy efficiency* of the system is necessary to multiply the energy efficiency of its components [3] – [5]:

$$\eta_{syst} = \prod \eta_{component}. \tag{2}$$

Energy efficiency of each system element is characterized by its efficiency.

Efficiency of DC motors [6], strongly depends on the load and can vary depending on it (40 % at idle to 90 % at full motor load).

In DC motors during work occurs a loss of energy, which is composed of three components. The first component is the iron loss due to hysteresis and eddy currents in the armature core. Upon rotation of the armature core continuously remagnetizes and spends the extra power, called hysteresis loss.

Simultaneously at rotation of the armature in a magnetic field in the core the eddy currents induced. Losses on hysteresis and eddy currents are called iron loses and are transformed into heat of the core of the armature.

Magnetic induction defines motor EMF or otherwise, voltage, and frequency of remagnetization depends on frequency of rotation of the armature. Therefore, at work of DC motor iron losses are constant, independent of the load if the voltage at the terminals of the armature and the frequency of rotation are constant. The second component includes energy losses due to the heating of wires of excitation windings and armature by currents passing over them. Losses in the armature winding and brush contacts depend on the current in the armature, i.e. are variable – they change with load changes. The third component – the friction losses which are the energy losses due to friction in the bearings, the friction of the rotating parts and air, friction of brushes and commutator. These losses depend on the frequency of rotation of the motor armature. So the mechanical losses are also constant, independent of the load. DC motor efficiency can be calculated as follows:

$$\eta_{motor} = \frac{UI - \left(P_{mat} + P_{wind} + P_{mech}\right)}{UI}, \tag{3}$$

where P_{mat} is iron losses; P_{wind} is heat losses; P_{mech} is friction losses; U is motor input voltage; I is current consumed by the motor.

Efficiency of the movable platform, with proper mechanical implementation, is close to 1 due to the rigid connection with the gear and the influence of platform backlashes can be neglected at turns on sufficiently large angles (during turn on small angles, the effect of backlash can be considered as part of the efficiency loses of the gear). It is also necessary to take into account the effect of backlash on the reliability and wear of mechanical parts.

It is known that wave transmission efficiency is calculated as well as the efficiency of the planetary gear [7], [8]. Power losses in gears, mainly consist of: meshed friction losses, hydraulic loses – on splashing the oil, losses in the bearings. Total gear efficiency is:

$$\eta_{gear} = 1 - \left(\psi_{fr} + \psi_h + \psi_b\right), \tag{4}$$

where ψ_{fr} is meshed friction losses; ψ_h is hydraulic loses; ψ_b is losses in the bearings.

Thyristor bridge efficiency slightly depends on the load current, and in any case is significantly greater than 90 %, and can be calculated by formula:

$$\eta_{thb} = 1 - \frac{\left(I_{in} - I_{out}\right)}{I_{in}}, \tag{5}$$

where $\frac{\left(I_{in} - I_{out}\right)}{I_{in}}$ are thyristor bridge heat loses; I_{in} is thyristor bridge input current; I_{out} is thyristor bridge output current.

Substituting (3) – (5) into (2) we will obtain formula for calculation of energy efficiency of HIL test bench:

$$\eta_{syst} = \left(\frac{UI - \left(P_{mat} + P_{wind} + P_{mech}\right)}{UI}\right) \times \left(1 - \left(\psi_{fr} + \psi_h + \psi_b\right)\right) \times \left(1 - \frac{\left(I_{in} - I_{out}\right)}{I_{in}}\right). \tag{6}$$

Weight and dimensional characteristics (*MS*) are the weight (*M*), the payload capacity (*L*), the physical size of the HIL test bench (*S*). Weight and dimensions are totally dependent on the structure of HIL test bench and cannot be changed without the introduction of new or replacement of old elements of the system. Payload capacity depends only on the specific model of selected motor. Weight and dimensional characteristics are determined by summing the respective characteristics of the equipment used.

As a measure of weight and dimensional characteristics it is proposed to use a weighted sum:

$$MS = k_1 M + k_2 L + k_3 S \quad k_1 + k_2 + k_3 = 1, \tag{7}$$

where $k_1 + k_2 + k_3$ are weight coefficients of weight, the payload capacity, the physical size of the HIL test bench correspondingly.

Price indices consist of three categories:

– cost of manufacturing $\left(\Pr_{prod}\right)$ (Depends on the cost of elements included in the hardware, cost of assembling elements in the finished product, designing product cost);

– cost of service $\left(\Pr_{serv}\right)$ (Costs for repair, maintenance, replacement of failed elements, etc.);

– cost of equipment testing $\left(\Pr_{testing}\right)$.

Price index is calculated as:

$$\Pr = \left(\Pr_{prod}\right) + \left(\Pr_{serv}\right) + \left(\Pr_{testing}\right). \tag{8}$$

Positioning accuracy (*a*) is determined by the ratio of positioning error and predetermined position signal $\left(d_{in}\right)$. It includes: mechanical parts manufacturing errors $\left(\varepsilon_{mech}\right)$ (static error), control error $\left(\varepsilon_{cs}\right)$, error caused by mechanical system nonlinearities $\left(\varepsilon_{nonl}\right)$, transformation errors $\left(\varepsilon_{conv}\right)$ (ADC, DAC errors), measurement errors $\left(\varepsilon_{meas}\right)$, random error caused by system noises $\left(\varepsilon_{noise}\right)$:

$$a = \frac{d_{in} - d_{out}}{d_{in}} = \frac{d_{in} - \left(d_{in} - \varepsilon_{mech} - \varepsilon_{cs} - \varepsilon_{conv} - \varepsilon_{nonl} - \varepsilon_{noise} - \varepsilon_{meas}\right)}{d_{in}}. \tag{9}$$

Positioning accuracy is one of most important criteria of HIL test bench for testing and verification navigational equipment.

Rotation speed $\left(V_{syst}\right)$ of HIL test bench platform is also one of key parameters characterizing effectiveness of system. Rotation speed of HIL test bench platform is tightly connected with characteristics of control system, motors, gear. For calculation of measure of rotation speed of platform it is proposed to use:

$$V_{syst} = V_{cs} V_m u_{gear}, \tag{10}$$

where V_{cs} is control system performance; V_m is motor rotation speed; u_{gear} is gear ratio.

Motor speed is primarily dependent on the type of motor used in the system. For the DC motor rotation speed is defined as:

$$V_m = 2\pi \frac{U_m - I_{anch} \sum R}{C_e \Phi},$$

where U_m is motor voltage; I_{anch} is anchor current; $\sum R$ is the total resistance of the armature winding; C_e is constant coefficient determined by the design of motor; Φ is magnetic flux.

Positioning accuracy and speed of HIL test bench platform rotation are tightly connected: the higher the accuracy of positioning is the lower rotational speed of the platform will be.

The main *reliability index* is the probability of failure-free operation [2], [9]. Probability of failure-free operation – the probability that within a given predetermined operating time interval no equipment failure occurs. Probability of failure-free operation is defined by statistical estimate:

$$P(t) = \frac{N_0 - n(t)}{N_0},$$

where N_0 is initial quantity of workable nodes; $n(t)$ is quantity of failed nodes during time *t*.

In case of complex system like HIL test bench, shown in Fig. 1, probability of node failure-free operation probability P_{syst} will be determined as:

$$P_{syst} = P_{comp} P_{pio} P_{cs} \Big(P\big(P_{m1}\left(P_{tg1} + P_{r1}\right) + P_{m2}\left(P_{tg2} + P_{r2}\right) + P_{m3}\left(P_{tg3} + P_{r3}\right)\big) + P_{adcr}\big(P_{m1}\left(P_{tg1} + P_{r1}\right) + P_{m2}\left(P_{tg2} + P_{r2}\right) + P_{m3}\left(P_{tg3} + P_{r3}\right)\big)\Big), \tag{11}$$

where P_{comp} is probability of computer failure-free operation; P_{pio} is probability of data input/output board failure-free operation; P_{cs} is probability of control system failure-free operation; P_{adctg} is probability of tachometer generators ADC unit failure-free operation; P_{adcr} is probability of resolver

ADC unit failure-free operation; P_m is probability of corresponding motors failure-free operation; P_{tg} is probability of tachometer generators failure-free operation; P_r is probability of resolver failure-free operation.

Probability of failure-free operation of node is determined as:

$$P_{node} = 1 - i_{node},$$

where i_{node} is probability of node failure.

As a result substituting (2) – (11) in (1):

$$E_{syst} = \frac{b_1\eta_{syst} + b_2V_{syst} + b_3a + b_4P_{syst} + b_5MS}{\Pr},$$

where are $b_1 + b_2 + b_3 + b_4 + b_5 = 1$.

IV. Increasing the effectiveness of HIL test bench

Effectiveness of HIL test bench can be increased by increasing motors effectiveness.

Most of the parameters affecting the efficiency of electric motors are the same and depend on the properties of specific models of electric motors. So, in order to improve these parameters is necessary to use more effective models of motors. Motor load is an essential parameter that affects the efficiency of electric motors. The higher load (but not more than 95 % of its maximum power, since risk of motor failure increases significantly after this threshold is exceeded), the higher the efficiency of the motor is.

We must obtain output position signal of HIL test bench same as input one in result of execution of control actions. But control system parameters affect not only effectiveness of system, but also correctness of its work. Reliability of system can be increased through increasing critical units redundancy and introduction of protective circuits.

Effectiveness can be improved by applying the following improvements:

– use of more efficient motors;
– increase of electric motors load;
– use of more efficient gears;
– use of high-quality lubricants in order to reduce the losses of gears;
– more precise selection control actions;
– backup of critical components;
– use of gears with different gear ratio.

Another way to increase effectiveness of HIL test bench during testing of navigational equipment is to increase its functionality by adding special equipment, for example temperature chambers, simulating external environment.

V. Conclusions

Effectiveness of HIL test bench is determined by set of different parameters, and can be increased by methods described above. Use of thyristor bridge circuit in system don't affect total system effectiveness a lot due to their high efficiency, but is necessary to provide motors rotation in both directions. Also it should be mentioned that to improve the reliability and maintainability of the whole system it is necessary to provide a modular structure with redundant critical components.

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В. М. Синєглазов, Б. В. Роман. Підвищення ефективності випробувального стенду навігаційного обладнання

Наведено структуру автоматизованої системи випробувань навігаційного обладнання. Визначено формулу для знаходження ефективності автоматизованої системи випробувань навігаційного обладнання.

Ключові слова: ефективність; випробувальний стенд навігаційного обладнання.

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В. М. Синєглазов, Б.В. Роман. Повышение эффективности испытательного стенда навигационного оборудования

Приведена структура автоматизированной системы испытаний навигационного оборудования. Определена формула для нахождения эффективности автоматизированной системы испытаний навигационного оборудования.

Ключевые слова: эффективность; испытательный стенд навигационного оборудования.

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