

DIFFERENT MODELING TECHNOLOGIES OF HYDRAULIC LOAD SIMULATOR FOR THRUST VECTOR CONTROL ACTUATOR

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Original scientific paper

Hydraulic simulators are extremely important in the flight control actuator system's verification process. Flexible nozzle has a number of specifics, comparing to other flight controls, because the load cannot be described, classically, by the hinge moment. Additionally, classical hydraulic simulator, in which the cylinder simulates the load, is not sufficient for performing a complete simulation of the real load. Building a mechanical pendulum, to which a hydraulic cylinder acts, and that rests on two elastic supports, enables simulation of additional phenomena that exist in flexible nozzle, but not in other control surfaces. Force from impulse that exists in reality, and which is impossible to be generated by standard hydraulic simulator, can be realized through the pendulum. This paper demonstrates that a simulator can be designed through modelling of the elastic load using bond graph, without a precise elaboration of direction of forces in elastic structure, just by observing, on energy level, the input of force in flexible structure over the point in which actuator force acts. Simulator with hydraulic cylinder is convenient to be used when there is a need for considering the risk of self-oscillation of flexible joint and nozzle, i.e. for defining the so-called notch filter. Then, the hydraulic cylinder of load simulator can generate the oscillation, frequency and amplitude that match this dynamic case of flexible nozzle actuator's load that is being reduced to its piston rod, without a risk of damaging the flexible structure that exists in the construction of a simulator with pendulum.

Keywords: *bond graph modelling; electro-hydraulic actuator; flexible nozzle; load simulator; servo-distributor*

Različite tehnologije modeliranja hidrauličkog simulatora opterećenja aktuatora za upravljanje vektorom potiska

Izvorni znanstveni članak

Hidraulički simulatori su posebice važni u procesu verifikacije aktucijskog sustava za kontrolu leta. Fleksibilni mlaznik ima niz specifičnosti u odnosu na druge komande leta, jer se opterećenje ne može opisati na klasičan način preko zglobnog momenta. Pored toga, klasičan hidraulički simulator, na bazi cilindra koji simulira opterećenje, nije dovoljan za potpunu simulaciju realnog opterećenja. Potrebno je napraviti mehaničko njihalo na koje deluje hidraulički cilindar i koje se oslanja na dva elastična oslonca kako bi se mogle simulirati i dopunske pojave koje postoje kod fleksibilnog mlaznika, a koji ne postoje kod drugih upravljačkih površina. Preko njihala se može zadati impulsna sila koja postoji u realnosti, a koju nije moguće generirati standardnim hidrauličkim simulatorom. U članku se pokazuje da se modeliranjem elastičnog opterećenja preko bond grafova simulator može projektirati bez preciznog razmatranja smjerova i pravaca sila u elastičnoj strukturi, već se samo energetski promatra unošenje sile u fleksibilnu strukturu preko mjesta djelovanja aktucijske sile. Simulator s hidrauličkim cilindrom je pogodan u slučaju kad treba razmotriti rizik od vlastitih vibracija fleksibilne veze i mlaznika, to jest definirati takozvani notch filter. Tada hidraulički cilindar simulatora opterećenja može generirati oscilatorno gibanje, frekvenciju i amplitudu koje odgovaraju ovom dinamičkom slučaju opterećenja aktuatora fleksibilnog mlaznika koje je svedeno na njegovu klipnjaču, a da ne postoji rizik oštećenja fleksibilne strukture koja postoji u konstrukciji simulatora s njihalom.

Ključne riječi: *bond-graf modeliranje; elektro-hidraulički aktuator; fleksibilni mlaznik; servo-distributor; simulator opterećenja*

1 Introduction

Thrust vector control (TVC) can be realized in several ways and usage of this technology of control is linked to the beginnings of the rocket techniques development. For many years, basically until 1998, only hydraulic actuators had been used for TVC, when the development of electro-mechanical actuator system began, as an alternative to electro-hydraulic actuator systems. What remained as the challenge in design, even nowadays, was the modelling of flexible nozzle behaviour, which still requires experiment to determine some of the important parameters, such as the stiffness of elastic bond. It is far more difficult to determine the stiffness in real objects, structures of rocket and engine with flexible nozzle and actuator, and to determine the stiffness in simulator with pendulum [1]. Flexible nozzle has other characteristics, the moments of ignition and shutdown of rocket engine, when pressure pulsation is such that can take actuation system and flexible nozzle into resonance. At that moment, very powerful forces are being generated that put extra load on the actuator system. Previously stated adds an argument in favour of the need for the wide-ranging approach in design of a load simulation technology. Besides, the latest solutions on the structure of control algorithm [2] are based on small loop control or inner loop control technologies. In this case, we

have an algorithm structure that has, within itself, an outer loop control per position and an inner loop control per force. Inner loop control ensures that hydraulic cylinder, in the role of an actuator, is a controlled force generator based on the real loads.

That is the basic reason why it is necessary to design a load simulator, since only then a flexible and wide zone for load simulation is ensured, and hence excellent conditions are being created for quality check of inner loop control in the control algorithm.

Electro-hydraulic actuator systems are characterized by severe non-linear nature. Non-linearity can originate from the electro-hydraulic system's configuration and the load [3, 4]. In practice, a significant part of electro-hydraulic actuator system's non-linear nature can be compensated by making a good choice of components of electro-hydraulic system. Among these components the most important are: servo-distributor with zero lap, work of actuator system with no saturation on control and no saturation on hydraulic cylinder stroke and selection of cylinder with two-sided piston rod. By doing so, what is left to be dealt with is a non-linearity of flow characteristic, as a function of real drop in pressure in the actuator. It is more difficult to solve the problem of non-linear nature of real actuator system's load. In practice, significant simplifications are used, that can be verified on the example of a flexible nozzle, such as: load mass is

perceived to be concentrated, loosely tied to an end of a piston rod. In reality, load mass is almost never loosely tied to the piston rod. Usually, there is at least one other link to the environment. This imposes a question of determining the so-called reduced or equivalent mass, as well as taking into account elastic forces between concentrated masses. These forces primarily influence own frequency of closed electro-hydraulic actuator system, frequency that is usually calculated, solely based on concentrated mass. Sometimes, in this problem, a load is presented with several concentrated masses with appropriate elastic joints between them [5]. However, actuator's own frequency is important initial input in the control system synthesis process. Based on this information, bandwidth of an actuator system can be immediately evaluated, as well as the applicability of a simple P regulator. A general rule is that for the half of a bandwidth, P regulator should achieve satisfactory results (sinusoid change of actuator's target position value), which is proven to be adequate criterion for testing an actuator system with a load simulator. Besides, external friction for almost all loads is significantly bigger from the friction in hydraulic cylinder, where it is reduced to minimum by using new constructions and sealing systems [6 ÷ 8]. This means that the dominant friction is external and as a load, it has both positive and negative effects. Positively, it increases the level of the actuator system's damp, while negatively, it can be a cause of instability. Nature of external friction is also non-linear. In flexible nozzle, dominant is the viscous friction that can significantly change over time, which gives an actuator system a non-stationary character. Previously stated confirms that, when a direct mathematical modelling cannot result in a precise model, a different type of analysis should be applied [9]. One of the technologies for obtaining missing information on actuator system, i.e. its load, is identification [10 ÷ 12]. Identification is performed on already built model of completely realistic load, complete nozzle construction and rocket engine chamber (HILS Hardware in Loop Simulation). Before the identification of dynamic parameters, as an inter-phase in electro-hydraulic actuator systems design, suggestion is to design a load simulator that can realistically simulate intensity of actuator's load, by generating adequate force in time [6, 13 ÷ 18]. This means that load intensity can be realistically simulated, while character of change in intensity cannot be precisely determined, because it depends on real elastic forces and friction forces that change with temperature, which changes in time. Still, much unfavourable character of change in load, from the envisioned, can be defined. By doing so, advantage over the real load (real flexible nozzle) is created, and load simulation can be performed with certain reserve on the character of the change in load. Generating load intensity that is greater than expected in reality can compensate for not knowing the character of the change in load. Previously described testing technology for actuator system is presented in this paper, on the example of the design of electro-hydraulic actuator for rocket engine flexible nozzle's TVC. Flexible nozzle is an extremely complex load to be mathematically modelled, primarily due to its non-linear nature.

2 Flexible nozzle actuator's load

Flexible nozzle construction is shown in Fig. 1. In mechanical sense, this is relatively simple, meaning also a cheap construction, but at the same time, a very complex one for mathematical modelling as a hydraulic cylinder load. Flexible joint is characterized by high hysteresis that changes in time depending on temperature. Group of authors, in paper [19], suggested the initial modelling of flexible nozzle's dynamic behaviour by using certain functions in Matlab together with experimental data from stress-deformation diagram.

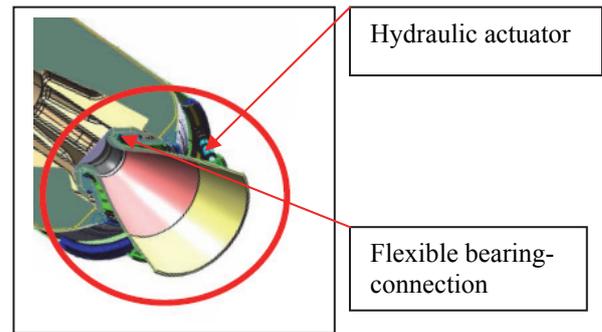


Figure 1 Schematic view of flexible nozzle construction [2]

Fig. 2 shows flexible joint characteristic - the character force-angle after modelling. In general, this type of a load can be defined as a non-ideal spring [20]. Mathematical description of this spring is not simple. Since maximal forces can be determined from experimental data for flexible joint, a spectrum of forces can be created to load electro-hydraulic actuator. Fig. 3 shows functional scheme of electro-hydraulic simulator of flexible nozzle's dynamic behaviour.

It can be observed, in the functional scheme, that the basic idea was to have servo-distributor and actuator distributor, control the cylinder that simulates load. Separate pumps are used to power servo-distributor. Basic actuator system is being observed as positional, but the change in force is being observed when the piston rod speed changes in load cylinder.

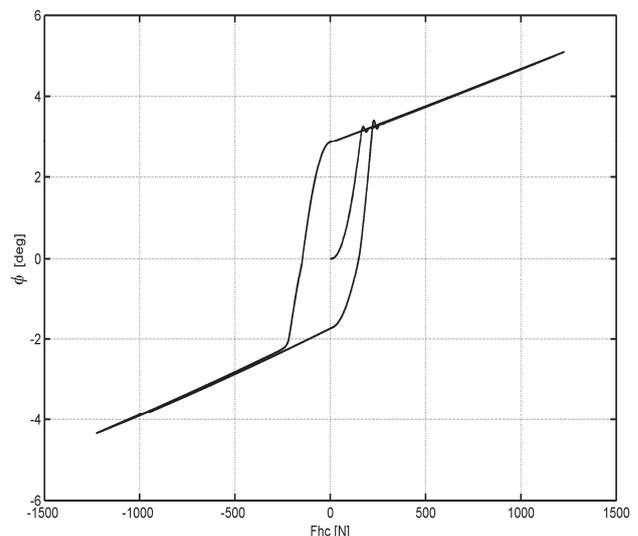


Figure 2 Static load characteristic after modelling

On electro-hydraulic actuator, load is simulated via cylinder that is connected to actuator cylinder [21]. Having this set up, there is a possibility to load an actuator cylinder with adequate forces (variable load) at given speed of actuator system. Fig. 4 shows the position of force transducer that enables measuring real losses, primarily due to the friction in cylinders when simulating a force. An alternative to this concept would be a load simulator with pendulum. Its advantage is that certain elastic joints can be defined in structure, using data from [19], and inserted in the functions from Fig. 2. In one load simulation configuration, it is not possible to provide both a wide range of options for change in load intensity and adequate simulation of elastic forces. Hence, this paper separately discusses hydraulic force simulator and force simulator with pendulum for flexible nozzle's electro-hydraulic actuator.

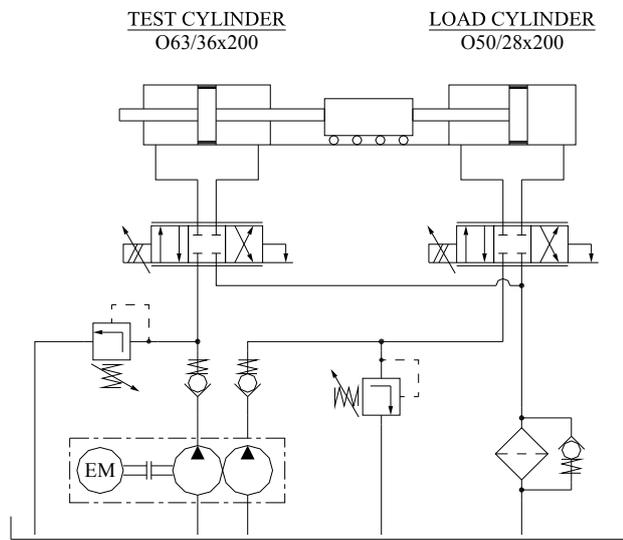


Figure 3 Functional scheme of electro-hydraulic simulator

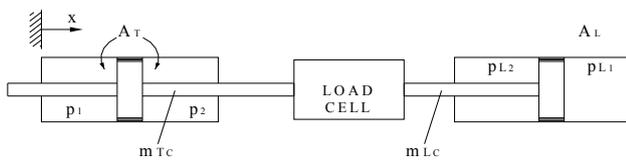


Figure 4 Build-in force transducer

3 The importance of force simulator construction

Construction of a force simulator is very important when actuator load is of a flexible nozzle type. First, the very identification process has a couple of shortcomings. If a non-linear identification is applied, it is performed based on one input signal, which is a big limitation, when expecting significant change in some of the load parameters. Second, if a linear identification is applied, several different transfer functions will be obtained for different amplitudes of input signal, i.e. nominal values of variables around which the linearization was performed. Third, it is irrational to conduct a large number of real experiments with flexible nozzle, because it requires a running rocket engine. In this case, a hydraulic simulator enables: force simulation up to the desired intensity, and also the simulation of load force change in character, in much wider scope than it happens (on average) in reality, on flexible nozzle. The term average is being used since

the nature of the object is such that a significant repetitiveness cannot be achieved. When that is the case, force simulator enables, relatively easy, the coverage of the entire scope of assumed changes in load and even broadening the scope to provide with guarantee for actuator robustness and control algorithm. When control synthesis results are confirmed, certain influences of load structure, such as real build-in (i.e. joint stiffness and influence of real inertial load (reduced mass)), are being verified on the very model. It should be pointed out that hydraulic simulator enables loading actuator with force oscillations that originate from pulsing operations of rocket engine, and are being transferred from the chamber to flexible joint and nozzle.

4 Mathematical model of an actuator and system for simulation of hydraulic cylinder load

A mathematical model is proposed for the simulation validation of force simulator construction, i.e. flexible nozzle's dynamic behaviour. As an input for mathematical modelling, bond graph models of servo-distributor and actuator cylinder were used [22]. Bond graph allows describing energetic changes in the system on conceptual level [23]. On mathematical level, those changes can be presented in analytical form, or in the form of simulation model using linear and non-linear descriptions. Fig. 5 shows bond graph models of servo-distributor. Fig. 6 represents energetic process at cylinder. Servo-distributor is being described by 4 throttle valves connected in Wheatstone bridge. In the bond graph, throttle valves are presented by modulated, non-linear, dissipative elements. Modulation is being performed by changing the flow orifice at throttle valves with the piston moves, where the condition of symmetry of flow orifice is fulfilled. By using storage mechanisms $C : V_i / \beta_e$ stiffness of hydraulic fluid in cylinder's chamber, i.e. potential energy accumulated in the storage, is being modelled. At the piston, hydraulic energy is being converted into: translational kinetic energy ($I : m$), losses caused by the friction ($R : R_f$) and energy used on external load, ($S_e : F_L$).

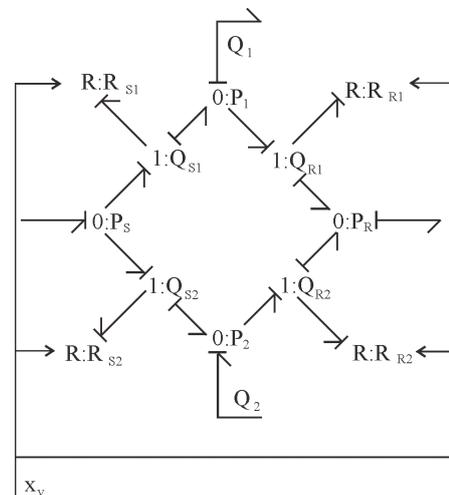


Figure 5 Bond graph of servo-distributor 4/3

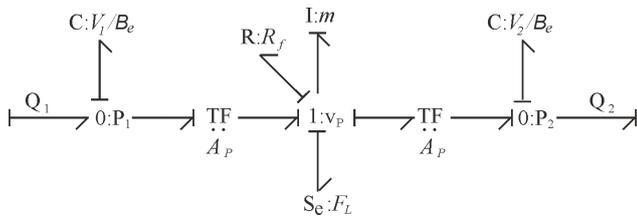


Figure 6 Bond graph of a cylinder

Now, we can obtain mathematical model of load simulator for an actuator based on classical linear description [4, 5]:

$$(m_{Tc} + m_{Lc})\ddot{x} = p_1 A_T - p_L A_L - F_{FT} - F_{FL} \Rightarrow$$

$$F_{FT} - F_{FL} = p_1 A_T - p_L A_L - (m_{Tc} + m_{Lc})\ddot{x} \quad (1)$$

$$F_L = p_L A + F_{FL} \Rightarrow F_{FL} = F_L - p_L A_L \quad (2)$$

From (1) and (2), the equation for force is obtained:

$$F_{FT} + (F_L - p_L A_L) = p_1 A_T - p_L A_L - (m_{Tc} + m_{Lc})\ddot{x} \Rightarrow$$

$$F_{FT} = p_1 A_T - (m_{Tc} + m_{Lc})\ddot{x} - F_L \quad (3)$$

Actuator, equation for flow:

$$Q_1 - Q_{l1} = \frac{dV_{Tc1}}{dt} + \frac{V_{Tc1}}{\beta} \frac{dp_1}{dt}, V_{Tc1} = V_{Tc10} + A_T x \quad (4)$$

$$Q_2 - Q_{l2} = \frac{dV_{Tc2}}{dt} + \frac{V_{Tc2}}{\beta} \frac{dp_2}{dt}, V_{Tc2} = V_{Tc20} - A_T x$$

Previous Eqs. (1) ÷ (4) can be simplified, under the assumption that internal leaks in cylinder (Q_{l1}, Q_{l2}) do not exist, as well as that the constant volume, inside a cylinder, is significantly bigger than variable

$V_{Tc1(2)} \gg A_T x$, so that for mathematical simulation the following equations are obtained in the form of:

$$\dot{p}_1 = \frac{\beta}{V_{Tc10}} (Q_1 - A_T \dot{x}) \quad (5)$$

$$\dot{p}_2 = \frac{\beta}{V_{Tc02}} (A_T \dot{x} - Q_2)$$

By modelling load cylinder the same way as the actuator cylinder was modelled, the following equation in final form is obtained (6):

$$\dot{p}_{L1} = \frac{\beta}{V_{Lc10}} (Q_{L1} - A_{L1} \dot{x}) \quad (6)$$

$$\dot{p}_{L2} = \frac{\beta}{V_{Lc02}} (A_{L2} \dot{x} - Q_{L2})$$

Actuator cylinder (test cylinder) and load cylinder motion equation, based on which a complete block diagram in Fig. 6 is developed is:

$$m_{eq} \ddot{x} = p_1 A_T + p_{L2} A_{L2} - p_2 A_T - p_{L1} A_{L1} - F_F \text{sign}(\dot{x}) \quad (7)$$

In global approach, it has been established that when an actuator system acts on the load, the fastest is the change in force, then the change in speed and position. In that case load cylinder is expected to have a greater bandwidth for the force than the actuator cylinder, in order to enable generation of forces that correspond to the real load. These facts need to be taken into consideration when choosing the load cylinder dimensions and servodistributors, since those are the most important factors for provision of the greatest possible force bandwidth.

On the basis of mathematical model (1) ÷ (6) simulation model is depicted in Fig. 7 (Simulink).

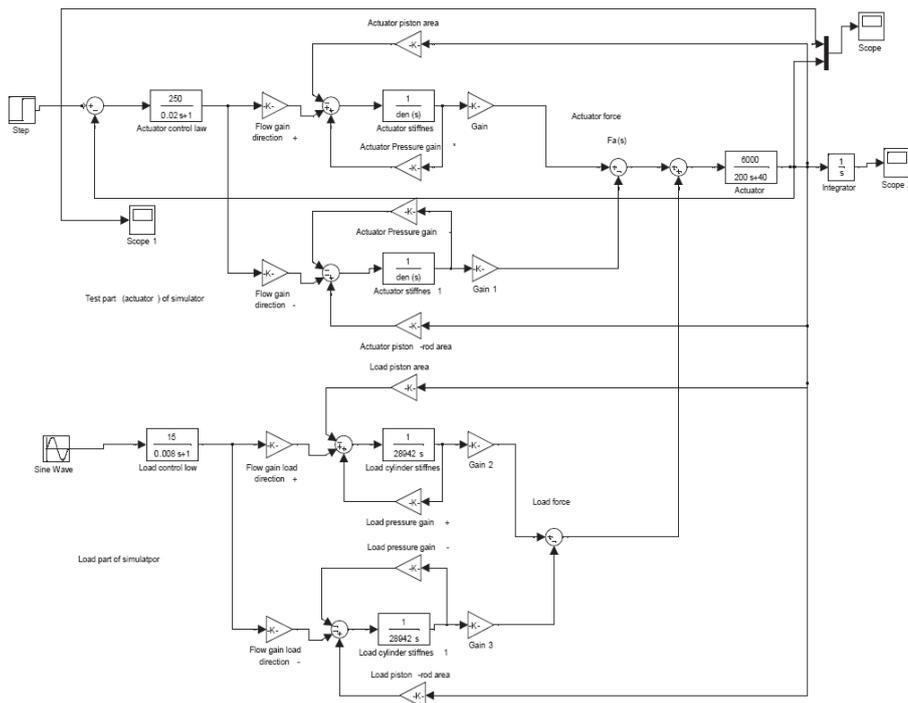


Figure 7 Block diagram of simulator's mathematical model with load defined via cylinder

The main purpose of the simulator presented in Fig. 3 is testing the robustness of electro-hydraulic control system under the external disturbances. Load-cylinder enables quick changes in disturbing force to be made, which amplitude can be altered in a desired manner. Fig. 8 shows the change in actuator's speed caused by stepping change of referent signal in the oscillatory change mode of external force. It is hard to use previously described simulator for simulation of each non-linearity that occurs in a TVC system. Therefore, further in this paper, a simulator with mechanical pendulum load will be discussed (Fig. 9). Mechanical pendulum represents a hardware model of flexible nozzle.

5 Mathematical model of an actuator and system for simulation of mechanical pendulum load

Fig. 8 depicts another version of load simulator. Nozzle is represented by a pendulum supported by elastic support structure. F_{HC} marks the force through which a cylinder acts on the nozzle. F_{HCX} and F_{HCY} are the corresponding projections. Inertial characteristics of nozzle are being simulated through concentrated masses m . In this model, inertial load component can be easily changed by changing the mass and/or changing the distance l_C . Flexible joint between nozzle and rocket engine chamber is simulated through the spring of stiffness k . Simulator's dynamics is shown in Fig. 10.

Bond 1 represents energy originating from horizontal projection of cylinder force (F_{HCX}). Bonds 6 and 7 transfer part of that energy to the pendulum's rotary motion. Transitional kinetic energy of the movement along the axis x comes through the bond 2. Bonds 4 and 5 establish connection between rotational kinetic energy and translational kinetic energy (for movements along the axis x).

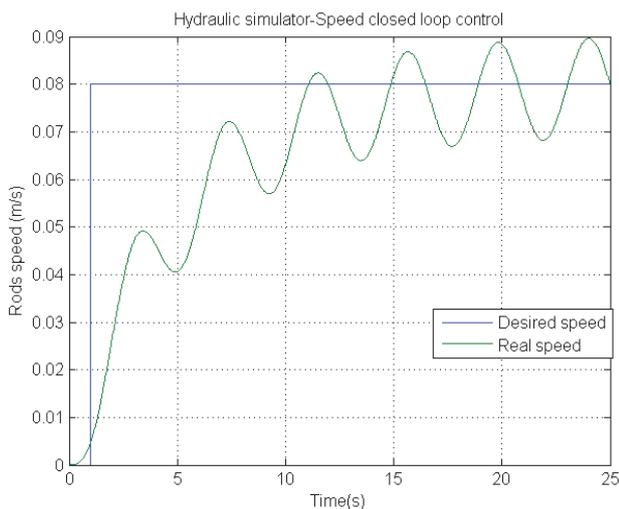


Figure 8 Test cylinder's speed change for oscillating change in pressure

Bond 17 represents the energy that originates from vertical projection of cylinder's force (F_{HCY}). Bonds 16 and 9 transfer part of that energy to rotary motion of the pendulum.

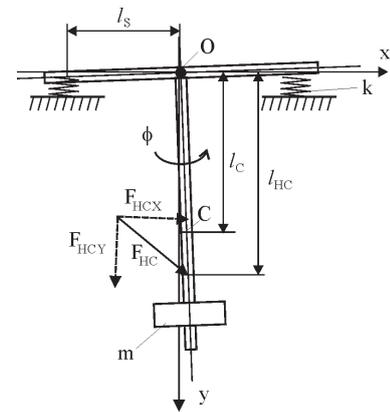


Figure 9 Schematic view of pendulum type load simulator

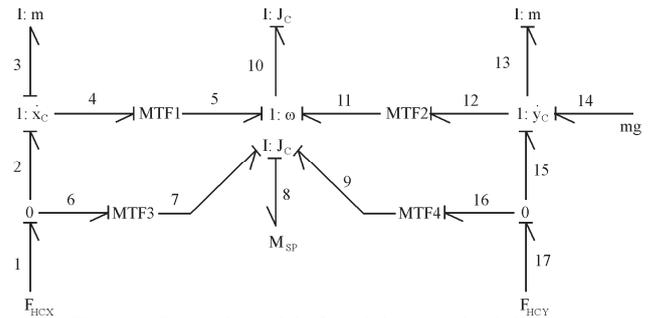


Figure 10 Dynamic model of pendulum type load simulator

Kinetic energy due to translation along the y axis, comes through bond 15. Bonds 12 and 11 establish connection between rotational kinetic energy and translational kinetic energy (for movements along the y axis). Below are presented the constitutive relations of bond graph presented in Fig. 10.

$$\begin{aligned}
 e_1 &= e_2 = e_6 \\
 f_1 &= f_2 + f_6 \\
 f_2 &= f_3 = f_4 \\
 e_2 &= e_3 + e_4 \\
 m\ddot{x}_C &= e_3 \\
 e_5 &= l_C \cos(\phi) e_4 \\
 f_4 &= l_C \cos(\phi) f_5 \\
 e_7 &= \Delta l \cos(\phi) e_6 \\
 f_6 &= \Delta l \cos(\phi) f_7 \\
 \Delta l &= l_{HC} - l_C \\
 f_{10} &= f_5 = f_{11} = f_7 = f_8 = f_9 \\
 e_5 + e_7 - e_8 - e_9 + e_{11} - e_{10} &= 0 \\
 \omega &= \frac{1}{J_C} \int e_{10} dt \\
 e_{11} &= -l_C \sin(\phi) e_{12} \\
 f_{12} &= -l_C \sin(\phi) f_{e_{11}} \\
 e_9 &= \Delta l \sin(\phi) e_{16} \\
 f_{16} &= \Delta l \sin(\phi) f_9 \\
 f_{15} &= f_{16} + f_{17} \\
 e_{15} &= e_{16} + e_{17} \\
 f_{12} &= f_{13} = f_{14} = f_{15} \\
 e_{15} + e_{14} &= e_{26} + e_{13}
 \end{aligned}$$

$$m\ddot{y}_C = e_{13}$$

e_i and f_i , $i = 1, \dots, 17$ represent effort and flow variables of corresponding bonds.

Bond graph library developed in Simscape language [24, 25] is being used for the simulation of dynamic model (Fig. 10, Fig. 11, and Fig. 12).

For spring load modelling, Simscape [2, 6, 7] model of Translational Hard-Stop [19, 24, 25] as presented in Fig. 12 is being used.

One of the basic requirements in load simulation by intensity is to provide with constant common speed (of $\pm 20\%$ of predetermined speed) of piston rods (closed loop control) of load cylinder and actuator. The model of hydraulic simulator has very high non-linear nature and fine-tuning is necessary.

Change in pressure in a load cylinder can be given in many forms. Fig. 13, 14, 15 and 16 show the simulation results of controlled actuator: when a flexible nozzle, as a load, was modelled by equivalent pendulum and when a character of spring load changes as an ideal spring (Fig. 13); when there is a dead zone (Fig. 14); when there is a saturation in static characteristic (Fig. 15) and with the change in viscous friction component (Fig. 16). (All depict open loop control for different desired angle of nozzle.)

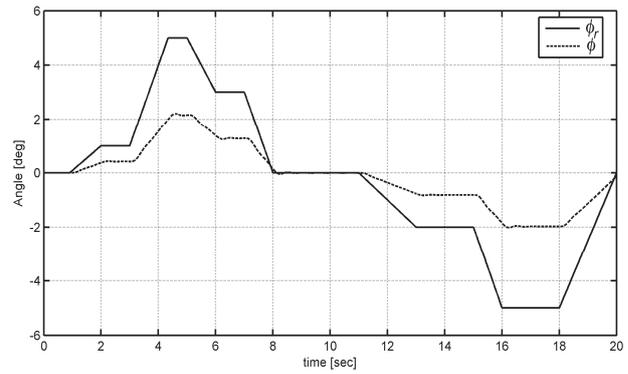


Figure 13 Change in referent angle (ϕ_r) and angle (ϕ) when an ideal spring is observed

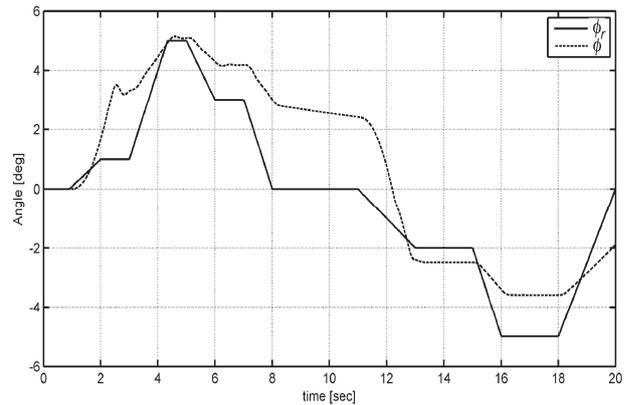


Figure 14 Response in the case of the insensitivity zone existence

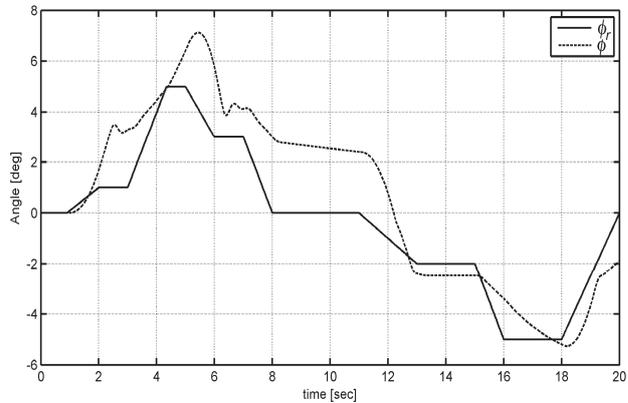


Figure 15 Response in the case of saturation of spring static characteristic

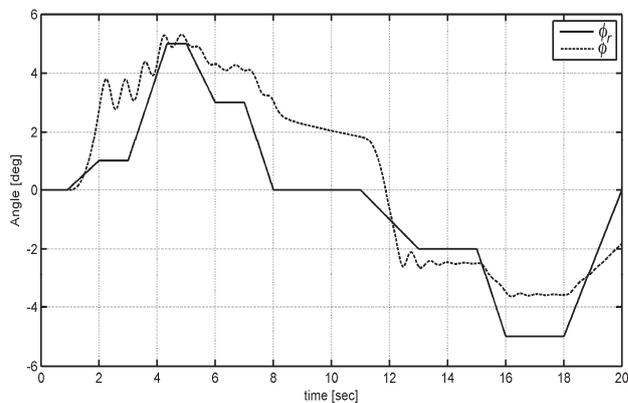


Figure 16 Change in response when viscous damp in spring is reduced

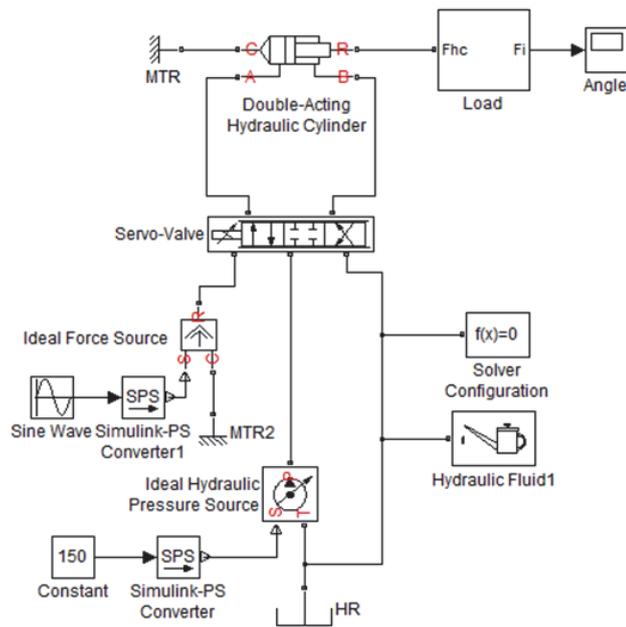


Figure 11 Simulation Model

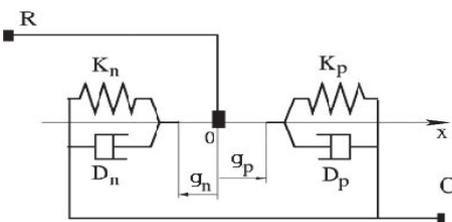


Figure 12 Model for non-ideal spring behaviour description [27]

6 Conclusions

This paper presents the justification of steps of experimental load simulation of an actuator system, through providing adequate arguments and mathematical simulations results. It is clear that only one type of load simulator – a hydraulic cylinder, could not simulate the entire load dynamics, but only the change in force (Fig. 6 and Fig. 7).

However, together with pendulum-type load simulator, dynamic behaviour of an actuator with a flexible nozzle load type, can be completely modelled with all elements of non-ideal spring type load. When inertial loads are to be modelled at minimal movements, which is specific case of controlling flexible nozzle in TVC, absolute advantage is being given to pendulum-type load simulator. This is because it can replicate, by adequate weights, the inertial load, which is not possible with hydraulic load simulator with hydraulic cylinder. It is evident that these two load simulation techniques can, mutually, ensure the complete test preparation of hydraulic actuator prior to firing test, i.e. prior simulation of the load that will be generated in the firing test.

Previously described construction of a load simulator, for the actuator within flexible nozzle of TVC, can handle one real interaction of the rocket (motor) with actuator, i.e. occurrence of vibrations that are close to resonant frequencies at the ignition and shut down of a motor. What cannot be realized through the actuator load simulation is the other important interaction - the first two modes of vertical rocket bending and their influence on actuator. Currently, finite elements calculation method is being used in this case, so the additional forces (foremost at connection points between motor chambers and nozzle) that put load on actuator are arithmetically being added. So far, this interaction can be considered an un-modelled actuator's load dynamics within the basic model.

Notice

Short version of this paper has been presented and published in "Proceedings of 2nd International Conference on Manufacturing Engineering & Management 2012" [26].

Acknowledgement

The research was supported by the Ministry of Education and Science of Serbia (project No. TR 35044).

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