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Design Criterion to Select Adequate Control Algorithm for Electro-Hydraulic Actuator Applied to Rocket Engine Flexible Nozzle Thrust Vector Control Under Specific Load

The paper presents the challenge of finding the best criterion in selecting adequate control algorithm for electro-hydraulic atuator with a defined load. The ideal control algorithm that adapts to the actual configuration of electro-hydraulic actuator and defined load is used as an initial assumption. Atipical flexible load that is viscose-elastic, with a significant level of hysteresis that also depends on time and temperature is considered as well. Two types of load modeling approahes are proposed, acompanied by presentation on how load modelling options affect the actual response of an actuator system. The main disturbance, in this case, is considered to be external force generated by thrust force real oscillations.

Keywords: *flexible nozzle, thrust vector control, control algorithm, electro-hydraulic actuator*

1. INTRODUCTION

The paper describes the process of defining the appropriate criteria to select an adequate electro-hydraulic actuator control algorithm that is used for the rocket engine with a flexible jet nozzle thrust vector control. The term 'adequate' is used instead of the terms 'ideal' or 'optimal' for enabling more comprehensive approach to the selection of control algorithm.

Rocket engine thrust vector control cannot be observed separately from the general object that is controlled, in this case, the rocket. In the initial approach, electro-hydraulic actuator control can be identified as a problem to be solved in the later stages of rocket design. The adequate approach implies that the problem of control should be addressed simultaneously with defining flying and tactical characteristics of a rocket in order to avoid, in the later stages of the design, situation that the shape and dimensions of a rocket are such that it cannot be accurately controlled, i.e. poor monitoring of rocket trajectory. Rocket control, regardless of the physical realization, has three segments: control of the centre of gravity, stabilization of rocket movement around its centre of gravity and balancing rocket movements.

It is very difficult to define typical requirements for control of a rocket due to the existence of a large number of different rocket designs for different purposes, but generally, the basis of dynamic requests can be defined as [1]: deflection of control organs, dmax=30°; maximum speed of deflection of control organs, d/dt(dmax) =300°/s; static error of angular position of control organs, e=1°; Hinge momentum on control organ, Ms=5-25 daNm; Phase delay at 10 Hz, Df<=20. The maximal dynamic capacity of an actuator system is significant before a motor thrust cut off, when rocket speed is at maximum (6000-7000 m/s). At that moment any delay in actuation may cause a problem for the key rocket performance. In accordance with this criterion, the actuator performances are defined as a bandwidth frequency of the range from 1 to 20 Hz. [2]

In order to perform the selection of control algorithms, once the basis of dynamic requests is set, it is necessary to determine the criteria for the selection of control algorithm for electro-hydraulic actuator control. Initial criteria are set to be: the character of desired value, the expected bandwidth of the actuator system, the type of external load, the changeability of the system parameters and external disturbances. [3-7].

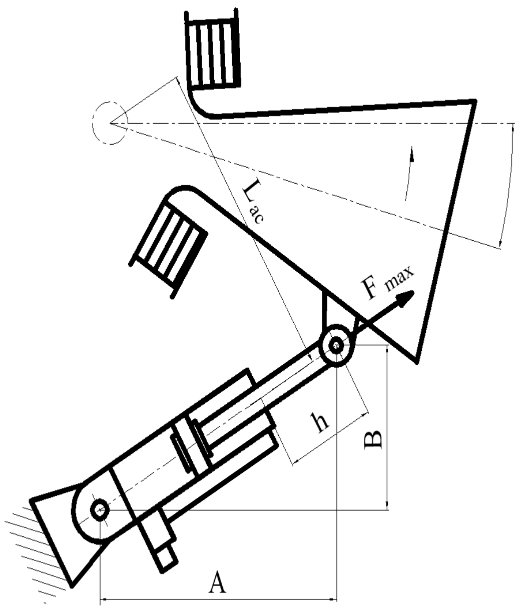

Figure 1. Basic schematic view of a flexible nozzle construction

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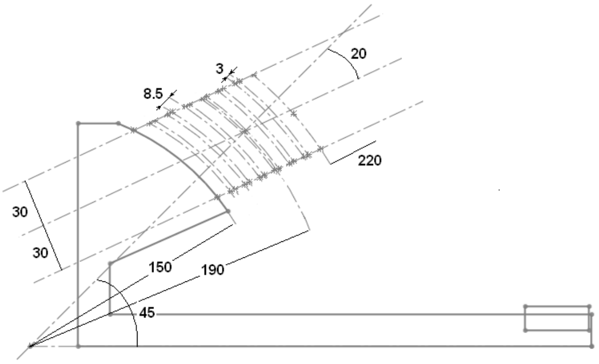

Figure 2. Detailed schematic view of flexible joint construction

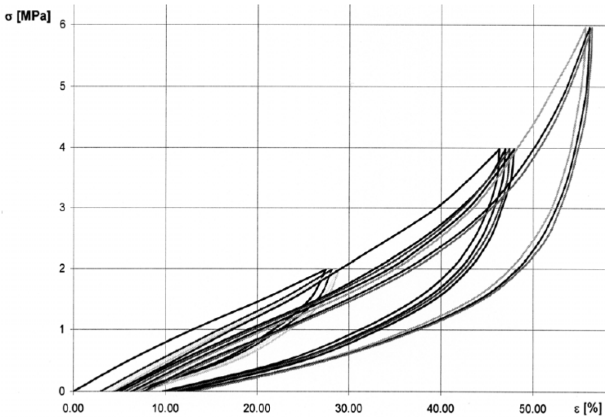

Figure 3. Experimental data for flexible joint modelling

2. FLEXIBLE NOZZLE

Fig. 1 shows a schematic layout of a flexible nozzle design. Flexible nozzle is characterized by an elastic – flexible joint between the nozzle and the rocket engine chamber. Thus, the thrust vector control is performed by rotating the nozzle within the elastic joint flexibility. Flexible joint is realized (in structure) using moulded rubber that is reinforced with metal plates.

The main characteristic of this flexible joint is a huge hysteresis of rubber, which is particularly increasing with the change in temperature. This represents the most complex part of the load that needs to be modeled and related to the well-known options of mathematical models, an electro-hydraulic distributor valve-cylinder in non-linear or linear model of a different order. [8] Flexible nozzle represents a good structural solution for the thrust vector control because there are no losses in thrust, the weight of the actuator system is relatively low and own frequencies of control sections are much higher than own frequencies of the actuator section, cylinder and servo valve. Thus, high dynamic characteristics of electro-hydraulic actuator systems can be used without any limitation.

In addition, for the deflection of control angles of up to 10 degrees, there is a linear change of the normal force that creates the control momentum for rocket movement. A real disturbance, in this case, is the external periodical force acting on the flexible joint between the nozzle and the rocket engine chamber as the axial force. A periodical force is the force which is generated by the thrust force oscillation in real engine operating regime. This force is characterized by the amplitude of around 2% of the maximal thrust with a frequency range of up to 100 Hz.

The second source of oscillation, in practice, can be real internal friction. This friction, without a control signal, causes the nozzle not to be in a neutral position. But these frequencies are several times smaller than in the case of oscillations coming from the first source, the thrust force. This is why this paper considers only oscillations of the thrust force.

3. PRE-SELECTION OF THRUST VECTOR CONTROL ALGORITHM FOR FLEXIBLE NOZZLE WITH ELECTRO-HYDRAULIC ACTUATOR

The selection of control algorithm or control system synthesis is not possible without a mathematical model of complete actuator structure. Mathematical models can be used in the process of implementation of control algorithms (Control based on the mathematical model) or in simulation – robust control algorithms check-up, which implementation does not require familiarity with mathematical model. When selecting a control algorithm, one of the first criteria is whether the management would require that the control ensures system's achievement of desired discrete values of position or force (set point mode), or it will have to ensure that the actual value of the output reflects the change of the desired input value. It is obvious that, when it comes to the rocket movement, the electro-hydraulic system is required to have good tracking features, because the desired value is continuously changing over time.

Based on previously stated, it is clear that classical PID control algorithms cannot be implemented without certain extensions and additions. Besides, the so-called tracking control algorithms [9] are also available, which, by definition, provide with the tracking procedure.

However, their drawback is that they are very sensitive to the changes in parameters that, when it comes to controlling a rocket, are not small. Also, there are options provided by state space: from classical state regulator, over combination with observers and adaptive control. But, the main problem, here, is how to provide information about the desired values of acceleration, thrust loads and similar values adopted as state values. Based on previously said, it is evident that one a "hybrid" option of the control algorithm should be chosen. By merging several algorithms, a more adequate control algorithm for the considered case of implementation of the actuator system will be obtained. Table T1, [10] presents an overview of the development of algorithmic solutions for electro-hydraulic systems.

Apart from the problem control algorithm selection, in the actuator system design process, as previously mentioned, special significance is give to the mathematical model. Every mathematical model is followed by a permanent dilemma of whether the actuator system is entirely identified (what is left in the, so-called, non-modelled dynamics) and, in the system configuration, which nonlinearities are significant and which are less significant. [11]

Table T1. Control algorithm – selection list

Control technique	Remarks
Classic feedback control	For greater bandwidths and higher orders of mathematical model, the input-output space is not sufficient for defining control actions
State feedback control	By definition, fully describes the system but there is a problem of determining the desired values of the size of some state.
Feed forward control	Correct algorithmic approach but without additions is insufficient for standard quality control.
Adaptive control	Open platform for defining required number of adjustable parameters to assure the quality of control but reference model order and algorithm of adaptation always remain an open issue of actual algorithms. [9]
Variable structure control	Integrated behaviour of the actuator, i.e. the inability of determining the nominal coordinate values of the system for nominal controls represent limitation to efficient implementation. When a mathematical models of order higher than order 3 is used, it is very complex to implement.
Natural Tracking Control Algorithm With High Gain	Very good properties of tracking of the actual actuator output according to the required value, but significant sensitivity to the change in parameters. Reason is high gain.
Feedback linearization (Input output linearization)	Based on the results from available literature review, this represents the most universal control algorithm for electro-hydraulic actuators. This algorithm is a well-known option for compensation of non-linearity part of the actuator's nature without direct linearization.
Fuzzy control	Robust algorithm that should be specially examined in for actual load of the actuator system. This algorithm requires a lot of test experiments, which is very expensive in this case. [12]
Neuron-control	Robust algorithm that should be specially examined for the actual load of the actuator system.
Bilinear control	A relatively simple nonlinear control without special verification in practice.

This paper focuses on the load modelling, i.e. flexible joint between the nozzle and rocket engine chamber. The question of non-modelled dynamics is a complex one. In practice, the main recommendation is that the best choice in solving non-modelled dynamics problems is application of adaptive control algorithms with certain number of adjustable parameters, by definition. At the same time, the order of reference model remains an open question of actual algorithms. At one point, it seemed that self-adjusted control algorithms represent the best solution for non-modelled dynamics, but practical experience identified not such small restrictions in their application.

Regarding the choice of control algorithm, during the last 15-20 years, the idea of feedback linearization has been gaining advantage. [13]

In general, a simple approach transforms a nonlinear system into an adequate linear system without addressing direct issues related to the linearization of nonlinear models. In this paper, due to the specific nature of load, a variation of this approach was applied, with the internal force-feedback control and external position-feedback control.

The hysteresis of flexible joint, as shown in Fig. 3, implies the need to, at any given time, have an assured value of the desired force for control, while the position remains within certain limits, because due to hysteresis the same force is realized at different positions of the actuator system.

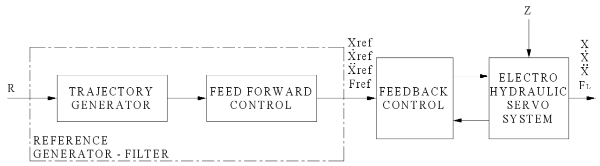

Figure 4. Structural schematic view of actuator control configuration [10]

4. SELECTION OF THRUST VECTOR CONTROL ALGORITHM FOR FLEXIBLE NOZZLE WITH ELECTRO-HYDRAULIC ACTUATOR

From the engineering point of view, the question is whether an ideal or optimal control algorithm, for the considered case, can be defined and whether, by reducing this ideal solution to the real conditions of project mission, we could obtain the appropriate control algorithm.

In literature [14] the ideal control algorithm for electro-hydraulic actuator systems, is defined as: a feed forward compensation loop, good feedback and highly dynamic control.

It is intuitively clear that the previous definition is simple and completely rationally defined. Feed forward compensation, by definition, compensates for the disturbance that introduces change in input value into the actuator operations.

Feedback, one or more, provides with conditions to generate control signal and thus compensate the influence of immeasurable disturbance. This is based on the difference between actual and desired output value or state value. Highly dynamic control element fulfils the condition that its reaction can be sufficiently quick as a respond to all control disturbances.

The above mentioned fact that adaptive algorithms represent the best solution when there is a risk of a significant non-modelled dynamics within a system, explains the preference that some adaptive algorithms also receive the attribute "optimal" since a large number of adjustable parameters can compensate all of that. In the literature, there is no qualitative answer to this dilemma, but the authors of this paper believe that for adaptive control algorithms the order of reference model represents a great limitation.

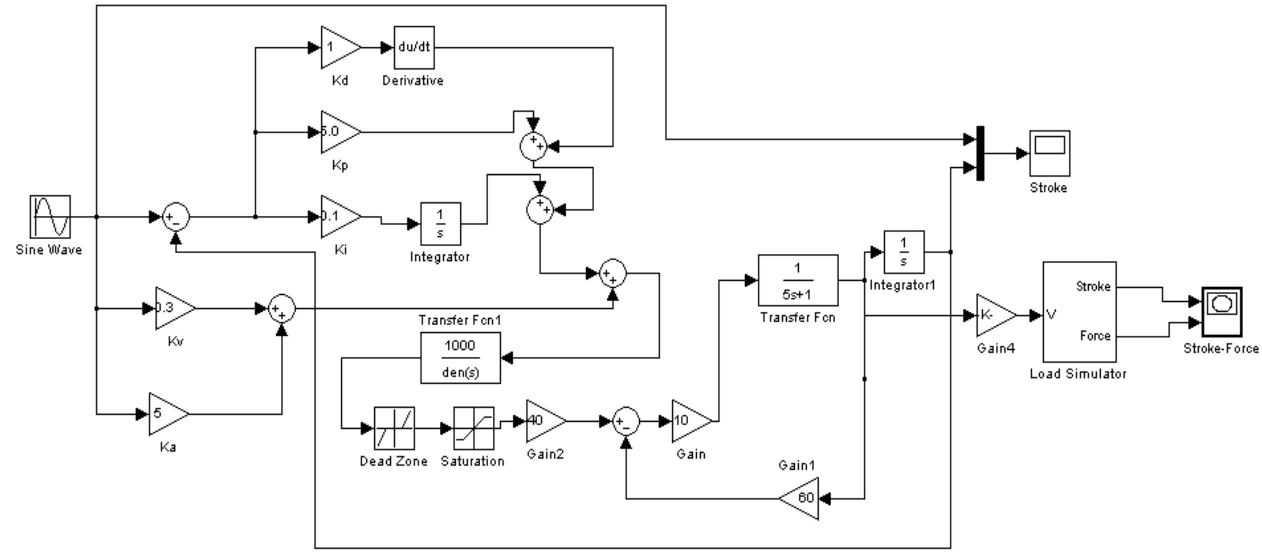

Figure 5. Block diagram of actuator control system with flexible load

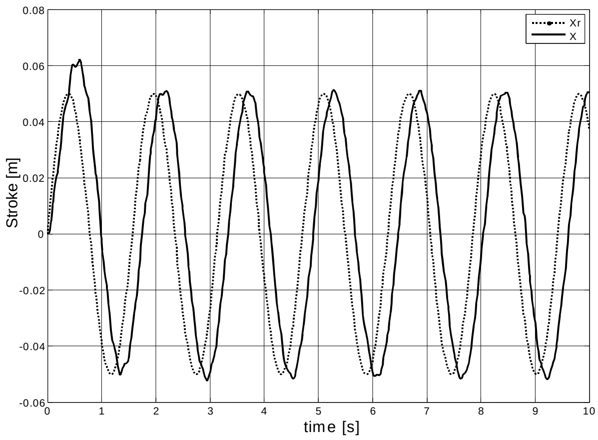

Figure 6. Stroke time response under control and real load simulation

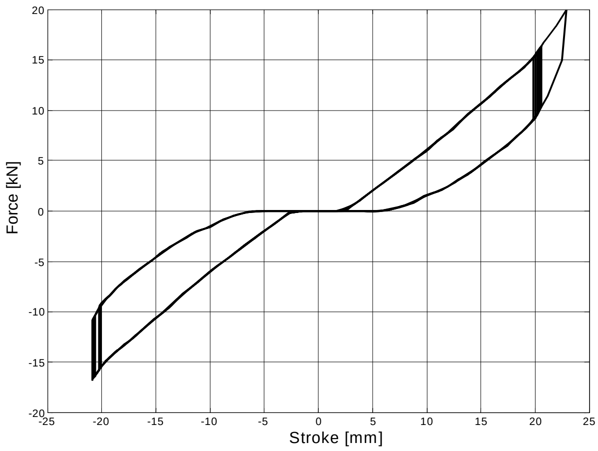

Figure 7. Force stroke characteristic based on experimental data defined in Fig. 3

From the Table T1, it can be concluded that for rocket engine flexible nozzle thrust vector control a classical approach in the actuator design, where the actuator is perceived as a positioning system, needs to be replaced by the approach where the actuator is perceived as a generator of force that can produce all forces required by external flexible load. Fig. 4 shows results of simulation of the initial steps in control algorithm synthesis using PID and feed forward as the actuator input, but without inverse dynamics. The algorithm is based on static models (static gains, K_a and K_v). In this case, a flexible model based on the experimental data form Fig. 3 is used. In the framework of the lookup modelling function, according to experimental data, in Fig. 8 a block diagram of load simulator is presented. The complete actuator control system block diagram is presented in Figure 5.

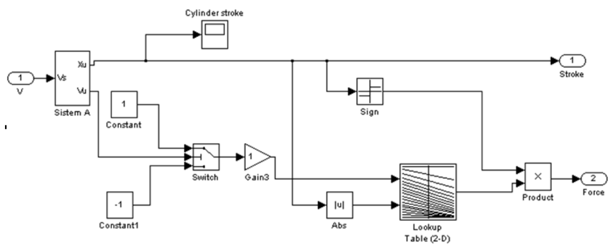

Figure 8. Block diagram of load simulator

Today, new technologies of control mechanisms are explored, to provide alternatives to the hydraulic thrust vector control (TVC) actuator system.

These are realistic trends, yet limits exist in maximal forces and dynamic requirements for high bandwidth frequencies.

The main advantage of electro-mechanical design is little maintenance, but this advantage is useful when smaller forces and low dynamic performances are required.

This difference is a value, which is the main information to be used in calculating additional control value. So, the nonlinear nature of the load force can be compensateed and the actuator system can be controlled as a linear system. This is a particular form of control algorithm based on feedback linearization, defined in [10]. The cascade FL control consists of two loops.

The inner loop, controlling the actuator pressure-difference F_L within the input-output linearization, is not influenced by load position. In this case the actuator is in the function of force generator.

The task of the outer loop control is to stabilize control of the loaded actuator motion

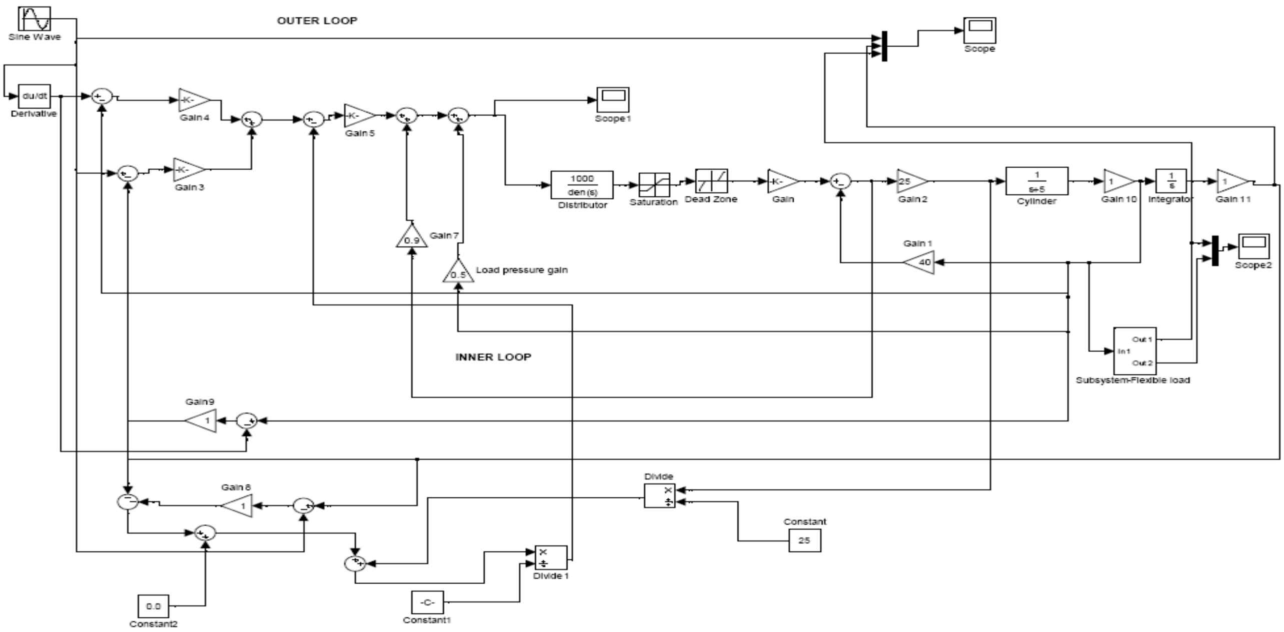

Figure 9. A simple control idea for realization of feedback linearization

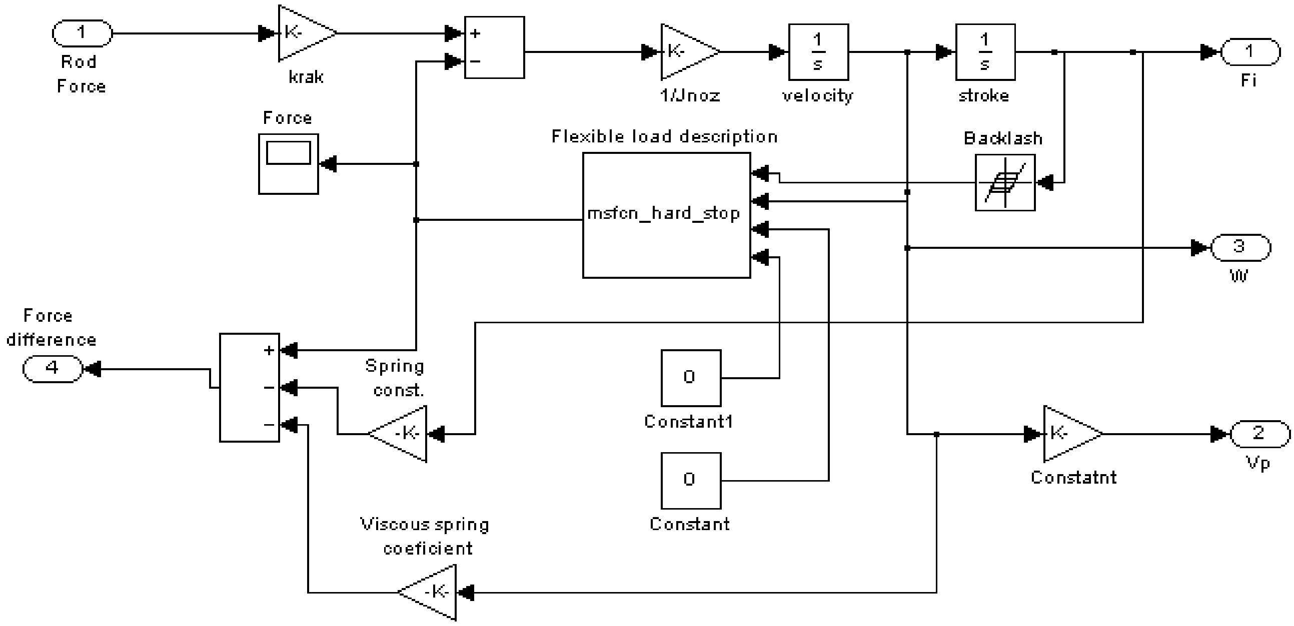

Figure 10. The structure of mathematical model for load simulation

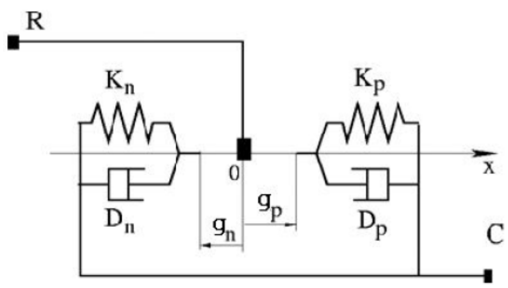

Figure 11. Mathematical structure model of non-ideal spring according to the general viscous-elastic model in Mat Lab. [15]

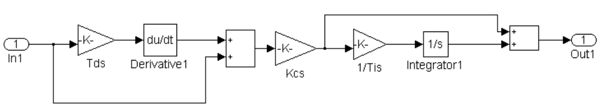

Figure 12. Block diagram of PID regulator for system modelsin Figure 10 and Figure 11

5. FLEXIBLE LOAD MODELLING

Two methods were used for flexible load modelling. In the first method the load on the actuator is presented in such a way that, at the same time, one spring is stretched, while the other is compressed. This corresponds to the actual structure, which can be seen in Fig. 1.

Another method is modelling the behaviour of rubber as a flexible load over the hysteresis curve. In Fig. 7 a block diagram of flexible load modelling, via the general viscous-elastic model of flexible connection is shown [15]. In Fig. 4 a flexible load modelling is shown, based on experimental data presented in the diagram in Fig. 3. Flexible load modelling using the finite element method is alternative the alternative to above mentioned methods. In this case, the flexible joint is simply treated as a distributed spring.

Using this modelling technique, a lag between the load and the velocity, and a lag between the load and the displacement can be found. These results can play an important role in flexible nozzle structure design. For the control design, these results are not as important as for the nozzle structure design.

In real environment, the information about the swing angle does not include the change in the condition of applied control force only, but also the velocity and accelerations, where the control force is applied. Besides the deformation of nozzle results from the control force, there is additional deformation from temperature influence, in practice, as well. In this paper, this influence is not modelled.

The first modelling method using experimental result is very important because a few excitation signals as control forces can be simulated. The second modelling method cannot take directly into account many excitation signals in rubber behaviour (flexible joint) description.

6. SIMULATION RESULTS

Simulation of the actuator system with a flexible load, modelled by block diagrams in Fig. 5 and 8, was performed. The load was connected to the classical, well-known model of hydraulic actuators and PID algorithm with feed forward compensation.

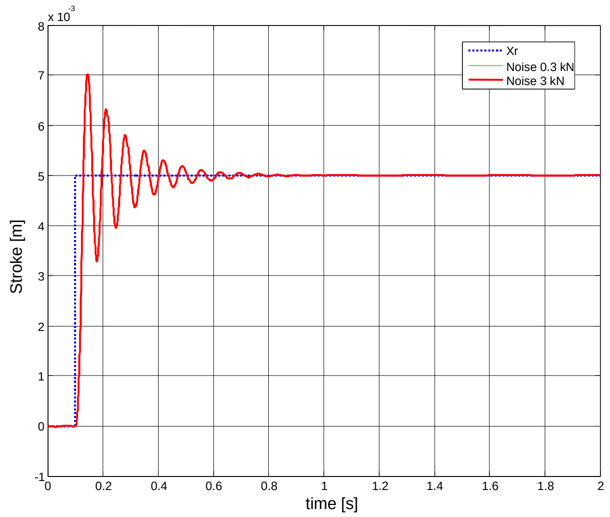

Figure 13. Position response for noise frequency 20 rad/s

Fig. 6 and 8 present different level of thrust force oscillations. Electro-hydraulic system, as the test system for experimental verification of robustness of electro-hydraulic actuator of thrust vector control for rocket engine with flexible nozzle, is the alternative technology for mathematical simulation process. A load model is used in simulation technology in order to define control that hydraulically generates load equivalent to the flexible load, Fig. 18.

The test system consists of the test cylinder, proportional directional control valve, pressure relief proportional valves and inertia load. The task of Poppet type valves, 2/2 is to simulate change in load with maximal gradient. Practically, it is an option for the fault operating situation simulation. Data analysis for the series of tests configured according to Fig. 16 will be used to update actuator system mathematical model. Tests include the step response, sine inputs and frequency sweep response. These tests determined the actuator performance parameters for the comparison against actuator design parameters. All design parameters must be verified with the exception of piston rate under maximal load.

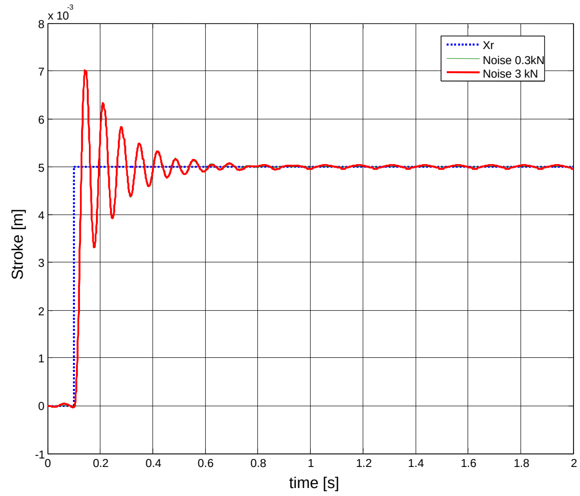

Figure 14. Position response for noise frequency 50 rad/s

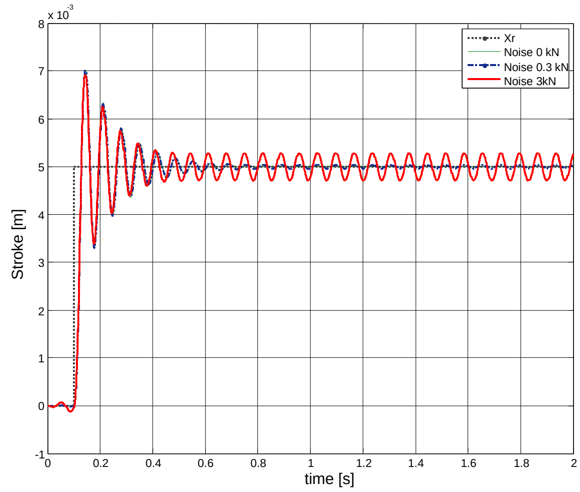

Figure 15. Position response for noise frequency 90 rad/s

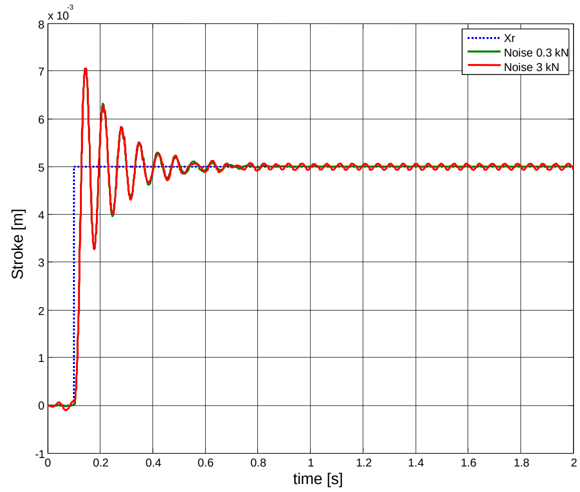

Figure 16. Position response for noise frequency 130 rad/s

Fig. 17 shows amplitude characteristic of the actuators closed system. This characteristic is very important and it shows real limits of the actuator design in the case of periodical disturbances generated by thrust force. In case of a small difference between operating and maximal frequencies, implied is that the design is under high risk for mechanical and control instability.

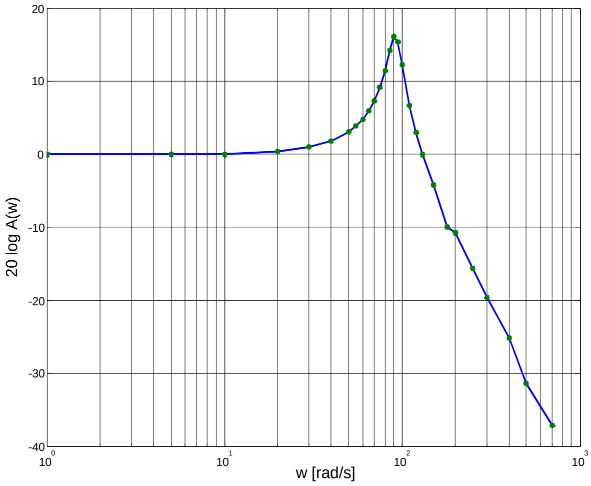

Figure 17. Amplitude characteristic of actuators closed loop system

7. CONCLUSION

This paper shows that the procedure of selecting the control algorithm for electro-hydraulic actuator under very specific load conditions can be clearly defined. The first selection is performed by a simple analysis of possible solutions based on known limitations, as defined in Table T1. Mathematical modelling and computer simulations are necessary to be employed in final selection of control algorithm for electro-hydraulic actuator.

The classic problems of developing a mathematical model structure, by partial introduction of nonlinearities and examining how the nonlinearities affect the mathematical model, are replaced by a new approach, where all nonlinear effects are considered simultaneously, which only allows approach known in the theory of automatic control as feedback linearization. In this way, the answer to the question how to deal with the problem of non-modelled dynamics is being proposed by the authors of this paper.

This paper is comprehensive in the consideration of actuator design. This is a very complex process, and the paper presents only one part of the actuator design technology. In general, the actuator system consists of a linear double acting hydraulic cylinder controlled by an electro-hydraulic flow control servo valve.

To improve the system performance, a few modifications are possible. In this case a very important conclusion is that disturbance from thrust force oscillations can be compensated with control algorithms which are presented in this paper. The influence of force amplitude is much smaller than the influence of frequency of thrust force oscillations. This fact of the conclusion must be the subject of final experimental verification.

Comparisons of performances must always be conducted between different modifications of hydraulic actuator also applicable to TVC [16,17]. At the same time, performance comparisons are possible between EMA (Electro Mechanical Actuator) and comparable-performance hydraulic actuator applicable to same TVC structure. The same studies have shown that hydraulic systems cost the space program many valuable hours spent on tests, maintenance and repairs. Fig. 11 shows expected results for closed loop frequency response using a mathematical model. With pre-selected control algorithm, the following dynamic tests must be within a standard test program: [9,18]

- Piston velocity test against no load and against varying loads up to near stall conditions.
- Frequency response test with an inertia load simulation. These tests will be performed at varying amplitudes such that phase and gain response is determined.
- Step response with an inertial load applied. These tests will be performed with input commands of varying magnitudes such that overshoot conditions and stability are determined.

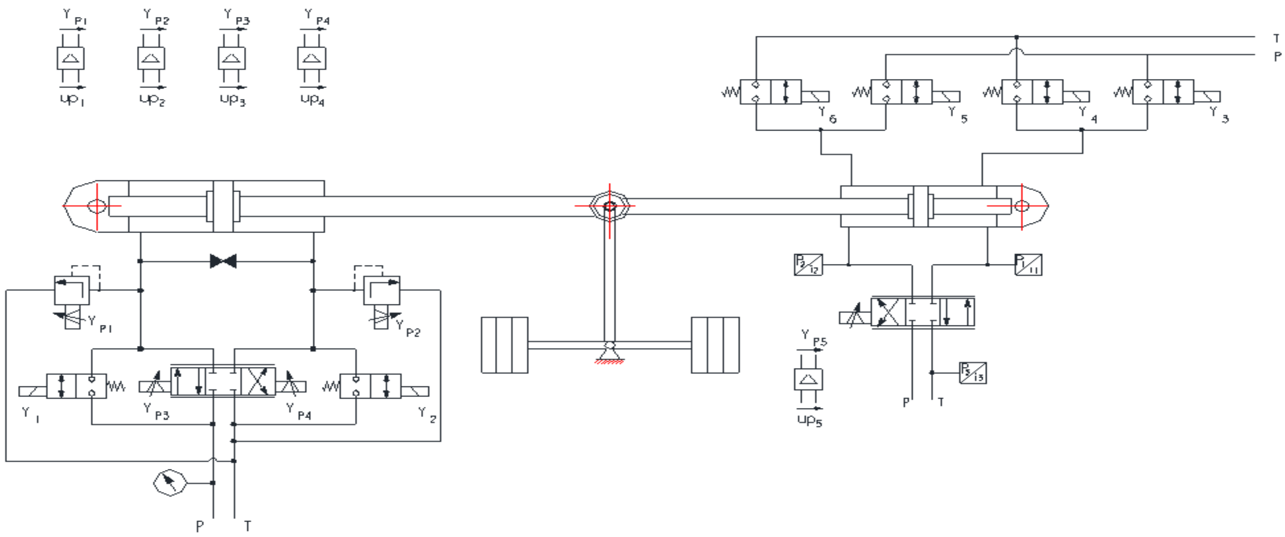

Figure 18 Functional schematic view of test system for electro-hydraulic actuator with flexible load

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КРИТЕРИЈУМИ ЗА ИЗБОР ОДГОВАРАЈУЋЕГ АЛГОРИТМА УПРАВЉАЊА ЕЛЕКТРО-ХИДРАУЛИЧНОГ АКТУАТОРА ПРИМЕЊЕНОГ НА РАКЕТНОМ МОТОРУ СА ПОКРЕТНИМ МЛАЗНИКОМ И ПОД СПЕЦИФИЧНИМ ОПТЕРЕЋЕЊЕМ

Драган Наупарац, Драган Прсић, Марко Милош, Марија Самарџић, Јован Исаковић

Рад разматра проблематику како на најбољи начин изабрати алгоритам управљања за електро-хидраулични актуатор са дефинисаним оптерећењем. Полази се од претпоставке идеалног алгоритма управљања који се прилагођава стварној конфигурацији електрохидрауличног актуатора и дефинисаном оптерећењу. Разматра се нетипично флексибилно оптерећење, вискозоеластично, са знатним хистерезисом који додатно зависи од времена односно температуре. Предлажу се два начина моделовања оптерећења и приказује се колико опције моделовања оптерећења утичу на стварни одзив актуаторског система. У разматраном случају главни поремећај је спољна сила проузрокована реалним осцилацијама силе потиска.