Proceedings of the International Conference on Manufacturing Systems – ICMaS
Vol. 4, 2009, ISSN 1842-3183
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RESEARCHES CONCERNING THE USE OF ELECTROHYDRAULIC SERVOSYSTEMS TO COLDWORKING MACHINES

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Abstract: *This paper present some researches concerning the stability in use of cold-working machines driven with electro-hydraulic servo-systems such as hydraulic linear amplifiers. In this work, a complex synthesis of electro-hydraulic servo-systems used in driving machines and industrial robots is also presented. The researches conducted upon a particular system, reveal the optimum design elements for obtaining a good behaviour in use, subsequently a good stability in use.*

Key words: *electro-hydraulic, servo-systems, analysis, dynamic stability.*

1. GENERAL CONSIDERATIONS REGARDING SYSTEM BEHAVIOUR

It is known that in the representation of reality, the system concept emphasises primarily the interaction, correlation and the relations between the elements of the whole, in other words its organisation and in a certain sense, the notion of system is the opposite of chaos.

From this perspective, the objects, the phenomens and the processes, regardless of their nature, can be considered as systems that possess a certain structure to the extent in which they represent a unit whose elements are in logical relationships, determined one towards the other and thus possess properties that can be reduced to elements or to relations.

The system's elements are on their turn subsystems, in which the laws of the whole are not identical with those of the integrated elements.

The system's structure indicates the manner in which interactions are organized, the main relationships between the system's elements which determine its functionality. In this way the structure represent a way to organize the system and also its relatively stable and invariable contents, which determines its entire behavior.

The structure is characteristic to all systems, from the most simple ones to the most complex ones, any system being built from elements and possessing a structure. The elements are constitutive parts belonging to the system.

Another important feature of the system as an assembly of elements (to which we will refer in this paper) is its maintainance in a proper working state so that its goal can be achieved. Each element can work between some admissible limits. If these limits are surpassed, it can no longer function according to the requirements set, the system does not maintain its normal equilibrium state, its functionality deviates from the intended goal and often this kind of disturbances can lead to the system's destruction.

The structure's stability is not absolute, but relative, and therefore these aspects will be adressed in the following research [6].

2. ELECTROHYDRAULIC SERVOSYSTEMS

It is a well known fact that the utilisation of hydraulic actuation systems in the building of machine-tools leads to the simplification of the structure of their kinematic chains.

An important contribution in this direction is constituted by the appearance and quick expansion of the electro-hydraulic servo-systems used in systems of actuation for machine-tools.

Depending on the type of the electric control element, we distinguish analogous and discreet electrohydraulic servo-systems, and depending on the hydraulic engine used, we distinguish servo-systems with translational, rotational and oscillatory motion.

The specifics of these electro-hydraulic servo-systems consist in the fact that they harmonise the low-power electrical control with the hydraulic actuation at very large powers.

The mentioned servo-actuators are powered by small electric motors. Due to their force, rapidity, simplicity and precision, these actuators are recommended especially where an increase of the power capacity can’t be made with conventional actuators.

The small electric input powers will be transformed with the hydraulic energy in final big output powers, providing well determined kinematic, static or dynamic ratios between the input and output parameters. These are obtained through one or more internal or external feedback links [1].

Electro-hydraulic servo-systems is used especially as a discrete positioning devices to machine tools with NC.

3. THE IMPLEMENTATION OF THE ELECTROHYDRAULIC SERVOSYSTEM IN THE ACTUATION OF METAL FORMING MACHINES

The electro-hydraulic servo-systems of hydraulic amplifiers type can be used also in the case of forming machines, as shown in Fig. 1[4].

Here the authors adopted the solution with a symmetrical linear hydraulic engine, due to the simplicity of the construction.

The turning of the control screw and reaction 1 displaces axial distribution drawer 2, opening the access path of the pressurised oil in the hydraulic engine chamber 3, realising a motion in the opposite direction to the distribution drawer's motion. At the stop of the electric engine pilot 4, the motion of the hydraulic engine continues until the drawer is brought back in the initial position, closing the liquid access path, stopping the motion.

The simultaneous movement of the two cylinders 3 is done with the help of a rigid, mechanic coupling, by the mobile sleeper 9 of the machine. The screw is driven by a low-power pilot micro-engine 4, using the belts 6. The guidance columns 7 are embedded in structure 8 at the base of the machine and the fixed beam 9.

4. RESEARCHES CONCERNING THE ANALYSIS AND SYNTHESIS OF THE SERVO-SYSTEM

The study solves, even from the design phase, the way in which the functional performances of the electro-hydraulic servo-system employed in the structure of metal forming machines can be improved.

The linear models are described by transfer functions, and using them allows the researcher to determine the answer to the frequency, which is a relatively complete test on the behaviour of the system, without being necessary to solve the differential equation. The block diagram of the system from Fig, 1 is presented in Fig. 2, where *EE* is the execution element (the motor-distribution group), θ is the input value, D_1 / D_2 the belt gear, p_s pitch of the command screw, *Z* output parameter, *a* actuation parameter [2].

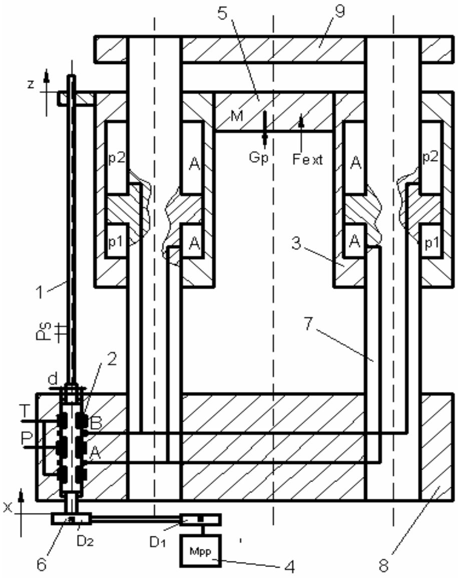

Fig. 1. The considered servo-system for forming machines.

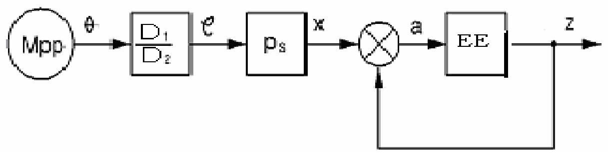

Fig. 2. The block diagram of the system from Fig. 1.

The feedback loop is unitary and it is realised from the exit (the translation movement of the piston's core bar) towards the parameter "a". The transfer function of the execution element will be presented in the following.

5. DETERMINING THE LEVEL OF STABILITY OF THE SERVO-SYSTEM

It is well known that in order to determine the transfer function of a servo-system, there need to be taken into account the physical relations for the functioning of the servo-system. Thus, the flow through the distributor, Q, is:

$$Q = C_d \cdot S_C \cdot \sqrt{\frac{2}{p}(p_0 - p_1)} \ , \tag{1}$$

where: $S_c = \pi \cdot d \cdot a$, d being the diameter of the distributor drawer:

$$d = \begin{pmatrix} 0.5 \\ 1 \\ 1.5 \\ 2.5 \\ 3 \end{pmatrix},$$

or, by linearising: $Q = A_Q \cdot a$,

$$A_Q = C_d \cdot \pi \cdot d \cdot \sqrt{\frac{2}{\rho}} \cdot p_0 - \text{ flow amplification,}$$

$$Q = A\frac{dz}{dt} + K_2 \cdot (p_1 - p_2) + \frac{V_M}{2E} \cdot \frac{d(p_1 - p_2)}{dt} \ , \tag{2}$$

which is the engine flow equation, where: $\Delta p = p_1 - p_2$ and the medium volume is $V_M / 2$.

The pump's flow should assure the piston's movement speed, compensate the liquid losses from the engine and compensate for the liquid volume's compressibility.

- The equilibrium condition of the forces in the engine is:

$$A \cdot \Delta p = M\frac{d^2 z}{dt^2} + K_1\frac{dz}{dt} + F_R = M \cdot \ddot{z} + K_1 \cdot \dot{z} + F_R , \tag{3}$$

$$\Delta p = \frac{M}{A} \cdot \ddot{z} + \frac{K_1}{A} \cdot \dot{z} + \frac{F_R}{A} . \tag{4}$$

By derivating, we obtain:

$$\Delta \dot{p} = \frac{M}{A} \cdot \dddot{z} + A \cdot \ddot{z} , \tag{5}$$

after substituting Δp and $\Delta \dot{p}$ we obtain equation (6):

$$A_Q \cdot a = \frac{V_M}{2\cdot E}\cdot\frac{M}{A}\cdot\dddot{z} + \left(K_2\cdot\frac{M}{A}+\frac{K_1}{A}\cdot\frac{V_M}{2\cdot E}\right)\cdot\ddot{z} + \left(A+\frac{K_1}{A}\cdot K_2\right)\cdot\dot{z}\ . \qquad (6)$$

- After applying the Laplace transformation, the transfer function of the direct circuit is:

$$T_d(s) = \frac{z(s)}{a(s)}\ . \qquad (7)$$

The transfer function of the feedback circuit is:

$$T_{r(s)} = \frac{r(s)}{z(s)} = 1 \qquad (8)$$

and the transfer function of the closed circuit is:

$$T_0(s) = \frac{T_d(s)}{1+\mathrm{T_d}(s)\cdot\mathrm{T_r}(s)}\ . \qquad (9)$$

- The transfer function of the execution element:

TEE(s) ≡ Td(s), (10)

$$\frac{z(s)}{a(s)} = \frac{A_Q}{\frac{V_M}{2\cdot E}\cdot\frac{M}{A}\cdot s^3 + \left(K_2\cdot\frac{M}{A}+\frac{K_1}{A}\cdot\frac{V_M}{2\cdot E}\right)\cdot s^2 + \left(A+\frac{K_1}{A}\cdot K_2\right)\cdot s} \qquad (11)$$

where:

$$B_1 = \frac{K_1\cdot K_2}{A} + A\ ,$$

$$B_2 = K_2\cdot\frac{M}{A} + \frac{K_1}{A}\cdot\frac{V_M}{2\cdot E}\ ,$$

$$B_3 = \frac{V_M}{2\cdot E}\cdot\frac{M}{A}\ .$$

This leads to:

$$T_{d(s)} \equiv T_{EE(s)} = \frac{A_Q}{B_3\cdot s^3 + B_2\cdot s^2 + B_1\cdot s}\ . \qquad (12)$$

- The transfer function of the open circuit

TD(s) = Td(s)· Tr(s) = TEE(s) , Tr(s) =1. (13)

- The transfer function of the closed circuit:

$$T_0(s) = \frac{z(s)}{\theta(s)} = \frac{A_Q\,\frac{D_1}{D_2}\cdot p_s}{B_3\cdot s^3 + B_2\cdot s^2 + B_1\cdot s + A_Q}\ , \qquad (14)$$

$$\frac{D_1}{D_2} = 1\ ,$$

where $C_d = 0.6$ – distributor constant;

$d = 0.5 \ldots 3$ cm – distributor drawer diameter;

$p_0 = 15$ daN/cm^2 – pressure of the agent provided by the pump;

$p_s = 1$ cm – command screw pitch;

ρ = 0.86 × 10^{-6} daN s^3/cm – density of the hydraulic agent;

$A = 32$ cm^2 – piston area;

$K_1 = 1.2$ daN·s/cm – viscous friction coefficient;

$K_2 = 1.4$ cm^3/daN·s^2 – volume losses coefficient;

$M = 0.03$ daN·s^2/cm – inertial mass to be moved;

$VM = A$ × stroke (20–80 cm) – linear hydraulic motor volume = 1600 cm^3;

E = 1500 daN/cm^2 – elasticity modulus of the hydraulic agent.

In the following part, various criteria are applied to verify the stability of the studied system.

5.1. Determining the stability of the servo-system considering the drawer diameter as variable.

Using the MathCAD program, we calculate the coefficients of the transfer function.

The five values of the drawer diameter vector are:

$$d = \begin{pmatrix} 0.5 \\ 1 \\ 1.5 \\ 2.5 \\ 3 \end{pmatrix}.$$

With the above-mentioned value, the transfer function's coefficients are (B_1, B_2, B_3):

$B_1 = 32.0525$; $B_2 = 2.1313 \times 10^{-2}$; $B_3 = 5 \times 10^{-4}$;

$$A_Q = C_d\cdot\pi\cdot d\cdot\sqrt{\frac{2\cdot p_0}{\rho}}\ , \qquad (15)$$

$$A_Q = \begin{pmatrix} 556.6504 \\ 1113.3008 \\ 1669.9512 \\ 2783.2520 \\ 3339.9024 \end{pmatrix}.$$

The Hurwitz Criteria (MathCAD) (closed ystem). The characteristic equation of the closed system is:

$$B_3\cdot s^3 + B_2\cdot s^2 + B_1\cdot s + A_q = 0. \qquad (16)$$

The stability condition according to the Hurwitz criterion is that all the determinants until $D_{n-1} > 0$, $n = 3$, $D_1 = B_2 > 0$

$$D_1 = 0.0213,\ D_2 = B_2\cdot B_1 - B_3\cdot A_Q\ ,$$

$$D_2 = \begin{pmatrix} 0.4048 \\ 0.1265 \\ -0.1519 \\ -0.7085 \\ -0.9868 \end{pmatrix} \begin{matrix} \text{- positive, stable} \\ \\ \\ \\ \text{- negative, unstable} \end{matrix}\ .$$

The first two values are positive, so the system is stable, while the last three are negative, so the system is unstable.

Conclusion*: When the drawer diameter increases, the stability decreases.*

5.2. BODE characteristics

It is known that in the analysis and design of automated systems, the logarithmic frequency characteristics have a large utilisation, the most important for the open system being:

a) amplitude-frequency characteristic,

b) phase-frequency characteristic, which are known also as BODE characteristics.

The BODE characteristics give us information about the relative stability of the open system through the module reserve and the phase reserve. It can be noticed that for the drawer diameter values of 0.5 and 1.00, the module reserve is positive, so the system is stable. For all other values of the drawer diameter: 1.5, 2.5 and 3, the system is unstable. The phase reserve is also positive for the values of 0.5 and 1.00 of the drawer diameter.

5.3. Nyquist Criterion

The Nyquist criterion analyses the transfer locus of the open system TD (jω). According to this criterion, a linear automated system is stable if the transfer locus of the open circuit TD (jω) for values from $\omega = -\infty$ to $\omega = +\infty$, is inside the domain bordered by the critical point (–1, j0).

Thus, it can be noticed that for the drawer diameter values of 0.5 and 1.00, the Nyquist transfer locus is located within the domain bordered by the critical point (–1, j0), so the system is stable for these values, but for all other values of the drawer diameter: 1.5, 2.5 and 3, the system is unstable.

Considering the facts shown above, it can be concluded that starting with the value 1.5 of the drawer diameter, the system becomes unstable. This means that the Nyquist transfer locus surrounds the critical point (–1, 0) for the values of the drawer diameter of 1.5, 2.5 and 3 [daN·s^2/cm] [5].

5.4. The Root Locus

The roots of the polynomial expression from the denominator must be calculated and placed in the complex system, for several values of the drawer diameter (Fig. 5).

The system is completely stable if all of the transfer function's poles are placed on the left side in the plane (s). The poles of complex character (with a negative real part) will determine the system's dampened oscillatory aspect $x_e(t)$, as shown in Fig. 5.

If the location of the poles is on the left side of the roots diagram, the system described by means of this transfer function will be a stable one. In addition, the method shows that the farther from the imagined axis the poles will be situated, the smaller the system's inertia will be and also its resulting time constants.

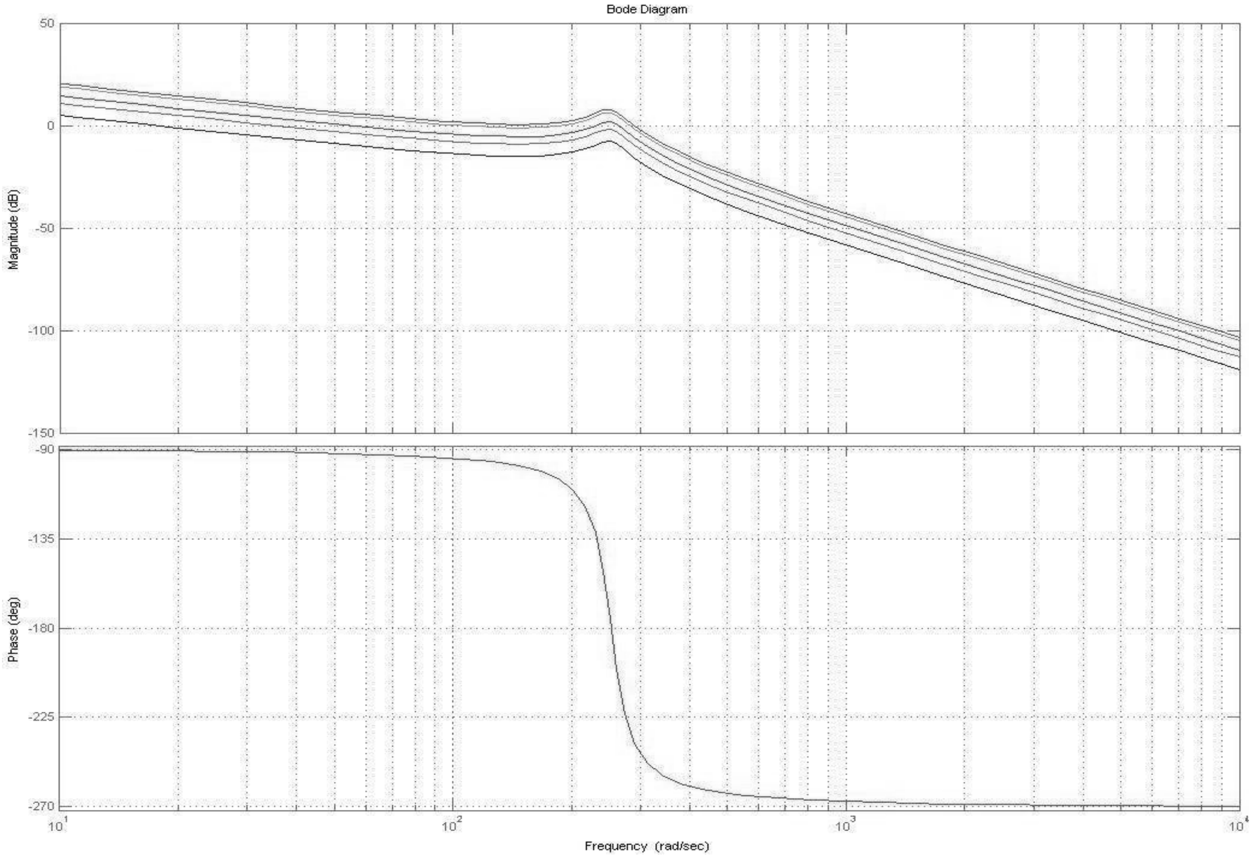

Fig. 3. Bode characteristics.

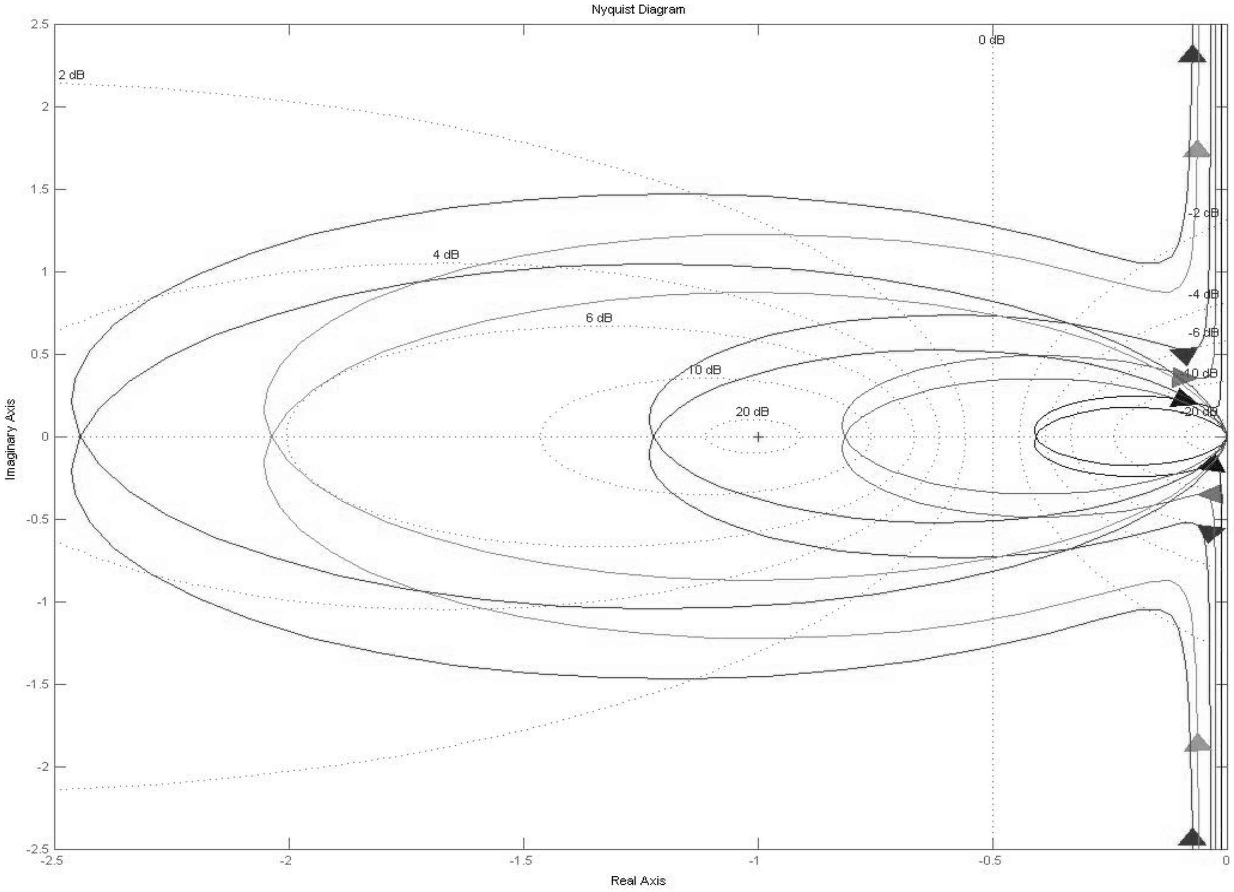

Fig. 4. Nyquist transfer locus.

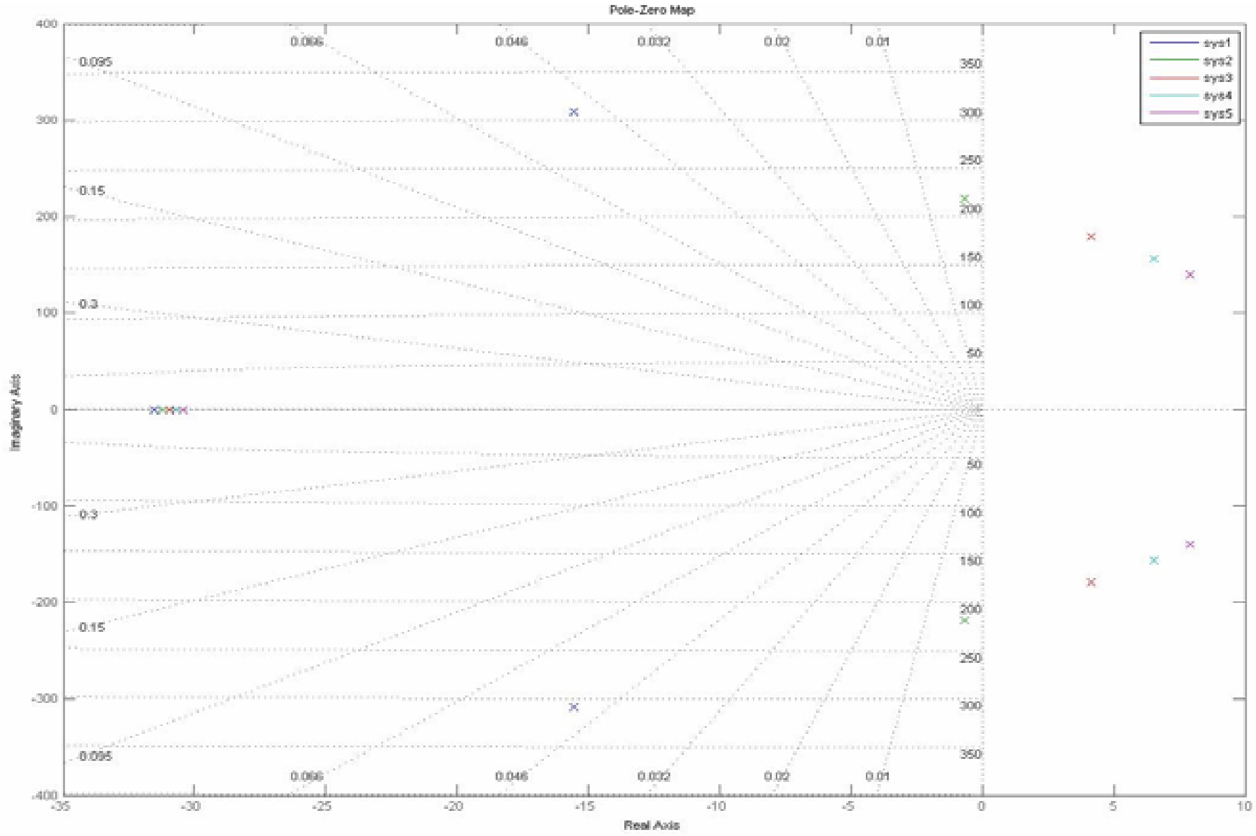

Fig. 5. The root locus.

The transitory character duration of service is not the only condition imposed for obtaining a satisfactory answer. The transitory regime has to present an acceptable over-adjustment and therefore a proper dampening behaviour. The conjugated complex poles that give the oscillatory aspect of the transitory regime have to be limited. The limitation of the imaginary part of the complex conjugated poles is done starting with the origin of the plane s under angle θ. This limitation corresponds to a limitation of the amortisation factor ξ of the oscillations answer written as $\cos\theta = \xi$.

6. CONCLUSIONS

1. The paper researched the behaviour of an electro-hydraulic servo-system used in the actuation of forming machines.

The behaviour has been analysed from the point of view of the stability, through the presented methods.

The following steps were followed:

- drawing the block diagram according to the constructive sketch of the system;
- linearising and obtaining the transfer function by applying the Laplace transformation;
- analysing the stability of the servo-system by modifying a parameter in the presented situation, the drawer diameter;
- using the algebraic Hurwitz criteria and root locus, as well as frequency methods - Nyquist and Bode diagrams.

From the analysis of the stability of the presented servo-system, the same stability condition was concluded; the drawer diameter must be less than 1.5 cm.

The present analysis refers strictly to this parameter.

2. For drawer diameter values over 1.5 [cm], the system becomes unstable.

3. The comparative dynamic analysis of the kinematic feed chain through the four presented methods leads us to the same conclusion mentioned at the first point.

4. These analysis methods are beneficial in the design phase. In this case it is possible to establish the variation field of the drawer diameter in order to achieve a stable functioning of this system.

5. Expecially in the roots diagram, we can notice that already at a drawer diameter value of 1.5 cm, the system's functionality is at the stability limit, the transfer function poles being in the right semiplane.

6. We can notice that the stability depends on the elements and the conditions in which the system works and functions, that is why this research is important even from the design phase.

7. These discreet systems compared with analog systems, has the following advantages: they are cheaper, there is residual strain of elastic elements and are compatible with computer controlled.

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