ENERGY SAVING SYSTEM FOR HEAVY DUTY ELECTROHYDRAULIC SERVOMECHANISMS - THEORY AND EXPERIMENT

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The paper presents the dynamic analysis of the modern electrohydraulic control systems used for driving very heavy equipment like linear and rotary hydraulic gates, double heavy cranes etc. The classical control systems dynamics and their power performances are compared with the ones of the new generation of high power electrohydraulic servosystems combinations. The numerical simulations results are then compared with the experimental ones, performed by the authors in the biggest two stages water gate sited on the Danube. Both motion control results, and stress distribution simulated and measured in real time are found in good agreement.

Keywords: Energy saving, heavy duty and high accuracy electrohydraulic servomechanisms, stress analysis, theory and experiment comparison

1. Problem formulation

Many technical systems include heavy or wide metal structures driven by two or more hydraulic cylinders. Typical examples from these categories can be found in the field of the water gates and the floodgates of the hydropower stations. Many other technical systems like complex cranes, rolling mill etc. demand the synchronous control of two or more hydraulic motors. Usually, the driving forces are supplied by hydraulic cylinders, which are working in heavy environmental, cinematic and random dynamic conditions. Under these situations, the position control accuracy needs a high-speed response flow control system. This performance can be achieved by high-speed industrial servovalves or by high-speed industrial servopumps. This paper is mainly devoted to the dynamic study of the hydraulic control systems of the water gates included in the sluice of the IRON GATE I hydropower station. This important component of the hydropower system has two basins, which divide in two the head of about 33 m by the aid of a

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two-section water gate of 900,000 kg (Fig. 1). Two heavy hydraulic cylinders move vertically the two sections of the gate, covering important friction random forces, which can tilt and lock the metal sections wide of 33 m and each weighting 450,000 kg. The main condition, which has to be accomplished by the driving system, is to move horizontally the sections, in order to respect the narrow gaps between the guiding railway system and the concrete walls of the motion space. Two cylinders with pistons of 600 mm and rods of 220 mm are supplied by two electrohydraulic servopumps of maximum 355 l/min at the nominal pressure of 35 MPa. The stroke of the cylinders is 16 m under a nominal load of 450,000 kg.

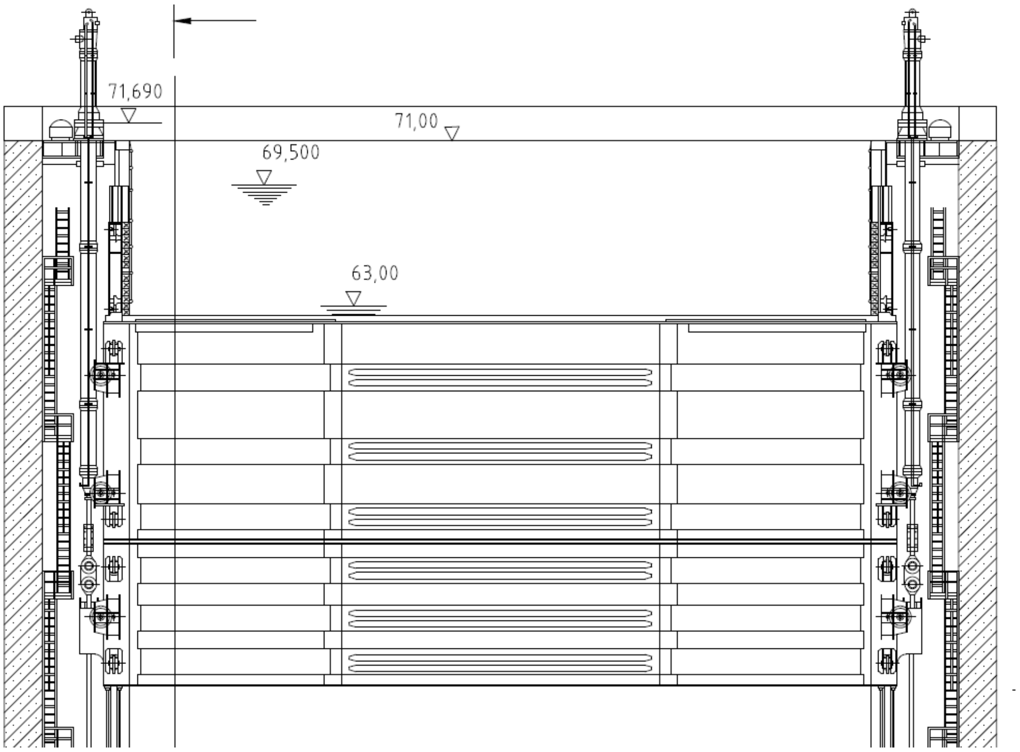


Fig. 1. Upper section of the water gate from the intermediate section of the two-stage lock of IRON GATES I HYDROPOWER STATION.

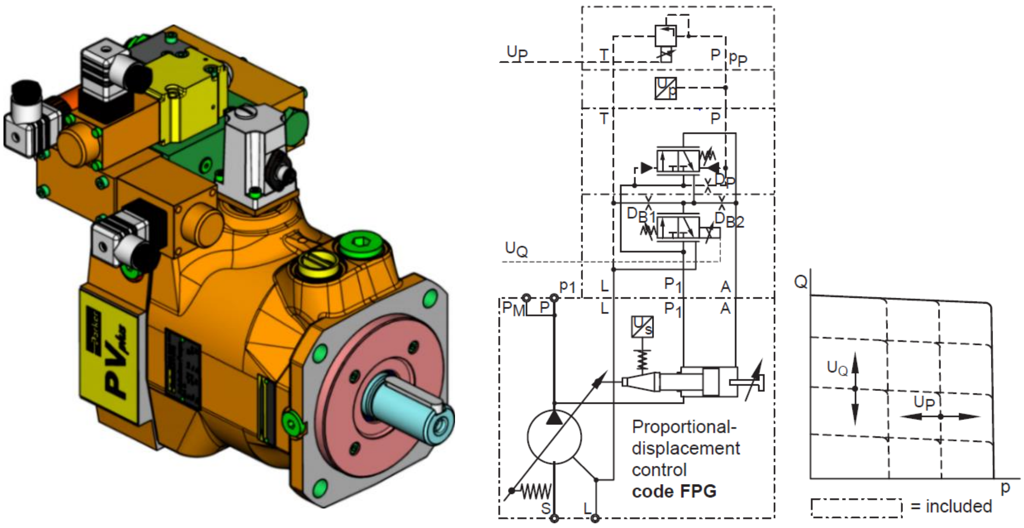
Independent circuits supply the two hydraulic cylinders. The cylinder rods are synchronized by different methods, according the flow needed to move the gate. The small cylinders can be controlled by industrial servovalves. The high diameters and strokes need the control by servo pumps. Both systems are studied in this section, in order to match the cinematic demands and limiting the energy consumptions. The cylinders include redundant position transducers (analog or digital), connected to industrial controllers which can be loaded with different control lows. The hydraulic supply circuits include pressure relief valves and security systems controlled by the synchronization error. The mechanical integrity of the gates is also preserved by a stress monitoring system included in a complex SCADA system. Such a system was implemented in 2000 by the authors in the IRON GATE I water gate sited between the two stages of the Romanian sluice. All the computation was performed by ANSYS, and the hardware & software implementation of the stress sensors was guided by the theoretical results. This successful application led to the conclusion that the driving system design has to be performed by numerical simulation in order to find the best control low of the motion process, and to know the main hydraulic, mechanic and electric process parameters.

Another study target is to find the effect of different failure events on the system components, and to supply the strength computation programs with realistic data about the stress introduced by the failure of the driving system. All the numerical simulations were performed by AMESIM. The numerical application was performed for the plain gate of intermediate head of the IRON GATES I lock (Fig. 2), which is a critical equipment.

Fig. 2. Hydraulic servomotor of the intermediate gate of a lock (IRON GATES I Hydropower and Navigation System)

2. Dynamics of the synchronization systems with industrial servopumps

The response time of the modern industrial swash plate pumps (Fig. 3) is small enough for efficiently reacting in the case of the common errors occuring in driving system supplied with well filtered oil, and sited in the common temperature range. The hydraulic scheme of the servopump includes a swash plate pump (Fig. 3), an electrohydraulic proportional servovalve, a hydromechanical pressure compensator piloted by an electrohydraulic proportional pressure valve, a differential hydraulic cylinder, an LVDT measuring the piston displacement, and a pressure transducer. The three control systems allow the precise tuning of the pump operation parameters and the automatic limiting of the pump power consumption by the aid of a special P-Q digital servo controller, compatible with any common industrial controller.



a) b)

Fig. 3. Electrohydraulic industrial servopump: a) SOLIDWORKS view of a PARKER PV Plus 46; b) complete hydraulic scheme and P/Q diagram.

The simplest mathematical model of the synchronizing system with servopumps (Fig. 4) includes two hydraulic cylinders loaded by half of the gate weight, and by disturbing forces generated by different factors like frictions, guiding roller jam etc. The gate motion direction is controlled by two high flow synchronized proportional valves. Two position transducers from the new generation dedicated to high rod diameters are sending information to the error stage of the overall controller [2-5]. This one sends the reference signals to the servo pumps in order to eliminate the error. The servo pumps pressure is limited by two proportional two stage pressure proportional relief valves.

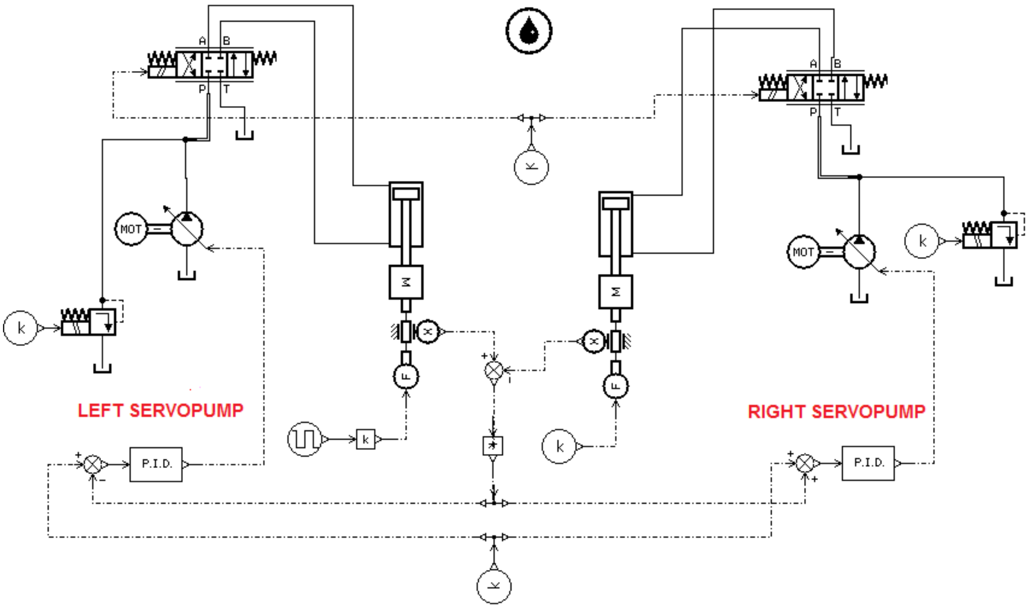


Fig. 4. Simulation network for the synchronizing system with servopumps.

Taking into account the nominal load of one hydraulic cylinder (4,500,000 N), the dynamic performance of the control system can be studied by loading one of the cylinders with a sudden external periodical force of 500,000 N (Fig. 5).

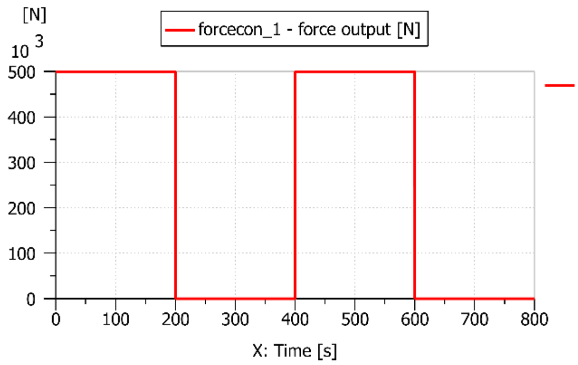


Fig. 5. External periodical force applied to the left cylinder.

The dynamic behavior of the synchronization system can be assessed from examination of the cylinders rods path (as in Fig. 6), the rod velocities (as in Fig. 7), the pressure variations into the cylinders chambers (Figs. 8 and 9). However, for such a long stroke cylinder (16 m) the best information is supplied by the synchronization error offered by the system controller (Fig. 10).

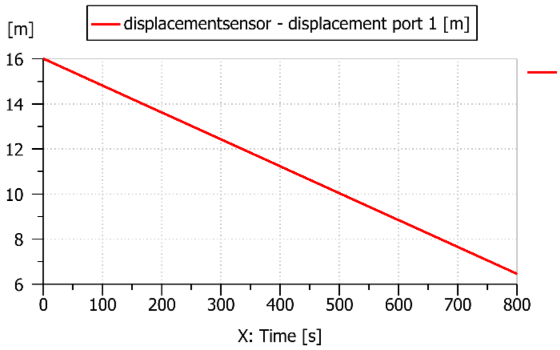


Fig. 6. Left cylinder rod displacement in the first 800 s of a motion cycle.

The cylinder rods velocity have small enough variations around the expected average value, as presented in Fig. 7 for the left cylinder rod.

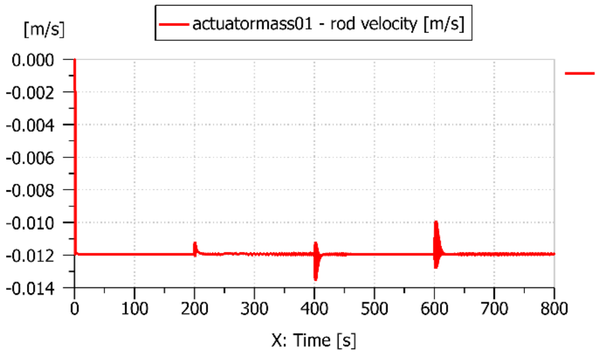


Fig. 7. Variation of the left cylinder rod velocity in the first 800 s of a motion cycle.

The highest operating pressure in the cylinder chambers (Figs. 7 and 8) is lower than the one recommended for the servopumps (20 MPa).

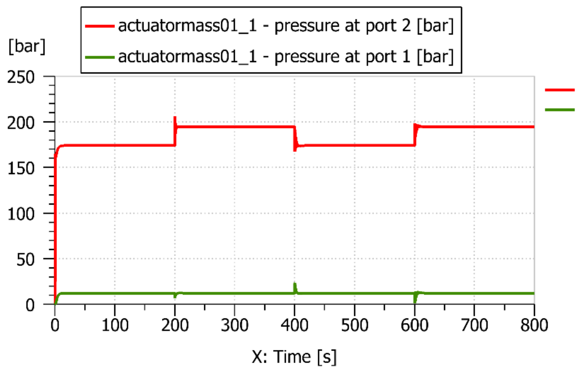


Fig. 8. Pressure variations in the chambers of the left cylinder.

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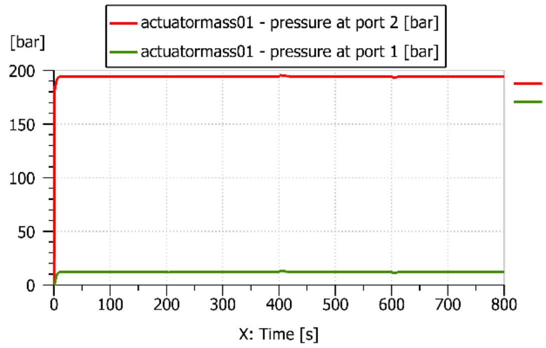

Fig. 9. Pressure variations in the chambers of the right cylinder.

The synchronization error is small enough from the point of view of the sliding sealing elements of the gate (Fig. 10).

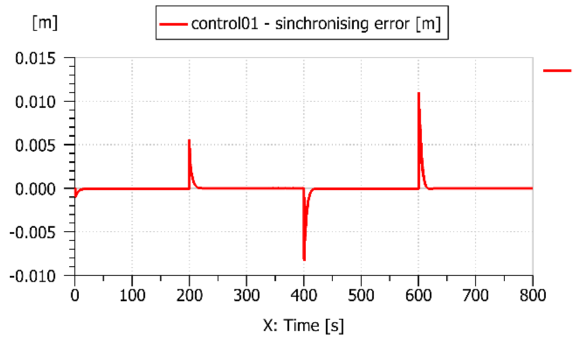

Fig. 10. Variation of the synchronization error between the two cylinders.

The outputs of the two PID compensators have small opposite variations around the ideal value (0.06 versus 0.50), as shown in Fig. 11.

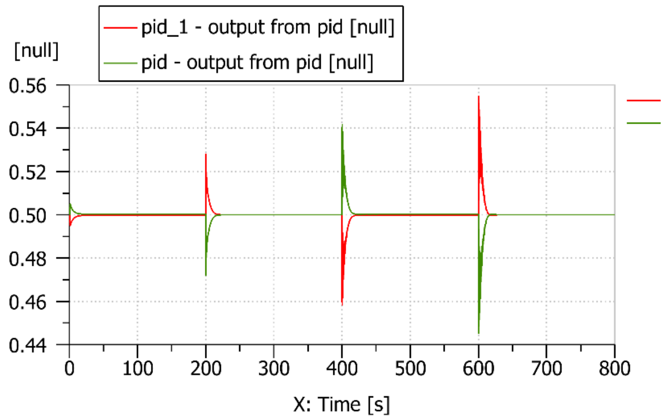

Fig. 11. Comparison between the outputs of the two PID error compensators.

Fig. 12 offers a useful image of the servopump operation cycles. One delivery pressure is constant, and the other presents sudden changes with a 200 s period. Such a regime keeps the overall efficiency of the two servopumps at a good level of about 90%, according the performances stated by a good hydraulic pumps supplier [1], [2].

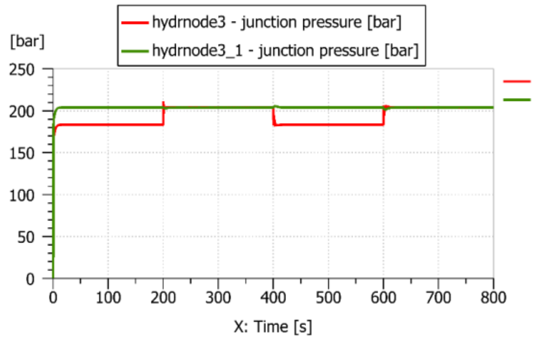

Fig. 12. Variations of the servo pumps output pressures during the gate motion with periodical brakes.

3. Dynamics of the synchronization systems with industrial servovalves

The synchronizing of the common hydraulic cylinders can be obtained directly, by the aid of two industrial servo valves. The price of this version is smaller than the previous one, but a large amount of energy is lost by heating all the flow through the narrow control windows of the servo valves. This kind of hydraulic scheme is used in many industrial or civil systems by assembling the cylinder, the servo valve, and the position transducer in one entity called “servo cylinder” (Fig. 13). The controller task becomes simpler by changing information by a CAN (PROFIBUS, ETHERCAT etc). The simulation network from the Fig. 14 is similar with the previous one.

Fig. 13. Electrohydraulic servo cylinder for water gates (*Source: REXROTH*). [2]

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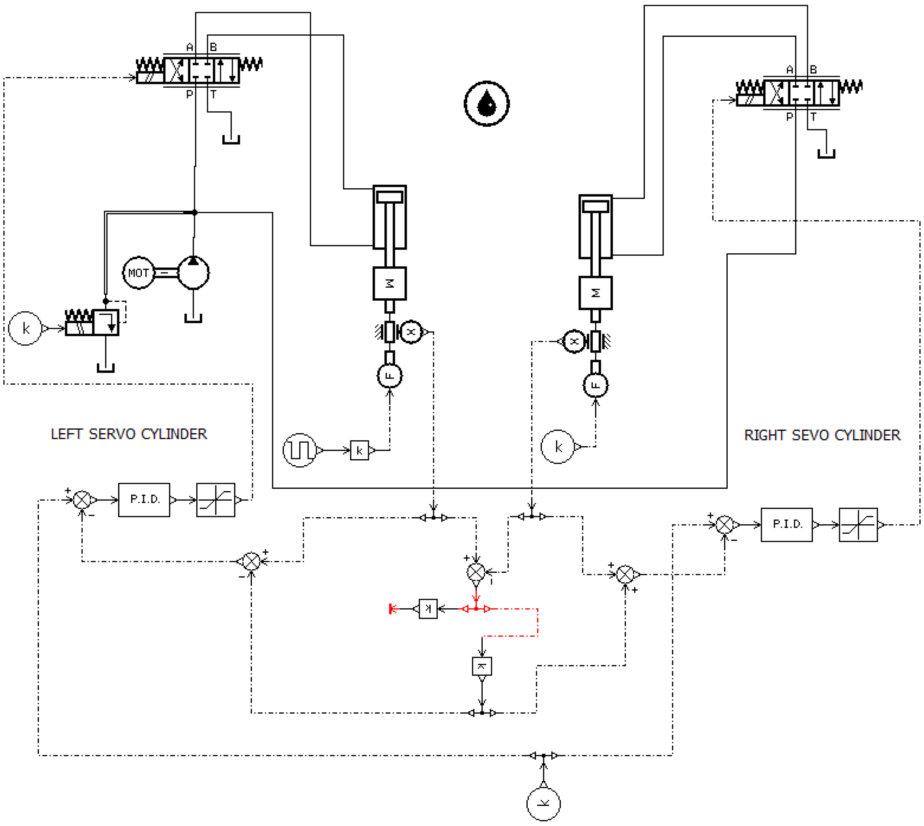

Fig. 14. Simulation network of the synchronization system with servovalves.

Two high-speed industrial servo valves of 100 l/min for a pressure drop of 0.5 MPa/edge are controling a mass of 450,000 kg. A periodical asymmetric load of 450,000 N (Fig. 15) generates a maximum error of 8 mm (Figs. 16 and 17). The diagrams from the Figures 18-23 are describing the synchronization process of two hydraulic cylinders of 600 mm / 220 mm with a stroke of 16 m during the the fall of the gate.

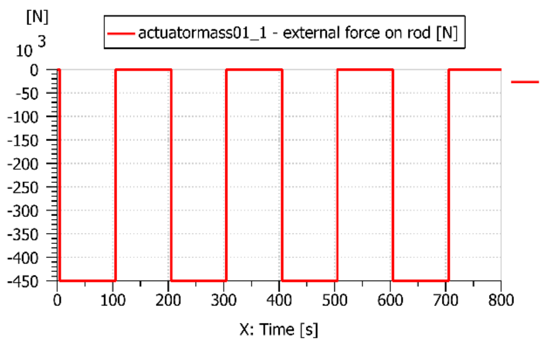

Fig. 15. Disturbance force applied to the left cylinder

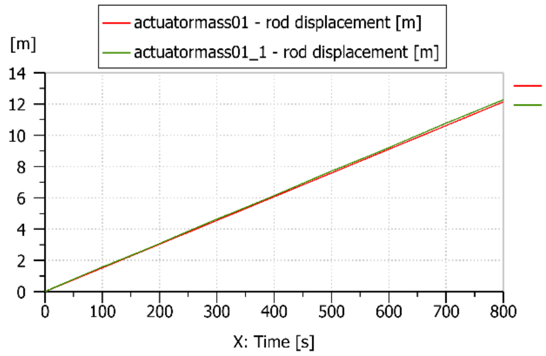

Fig. 16. Cylinders rods displacements

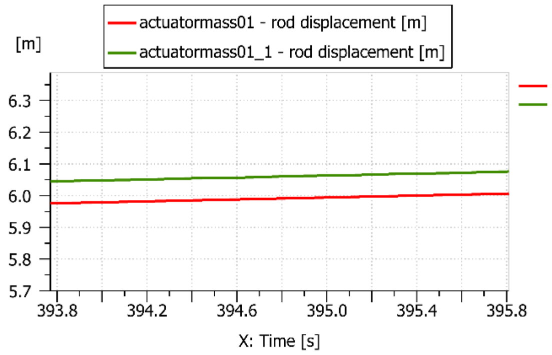

Fig. 17. Zoom in the two rods dispalcements.

The pressures in the chambers of the undisturbed cylinder (Fig. 18) is nearly constant. The excitation force is compensated by moderate pressure variations (Fig. 19) in the lower chamber of the left side cylinder (about 50 bar).

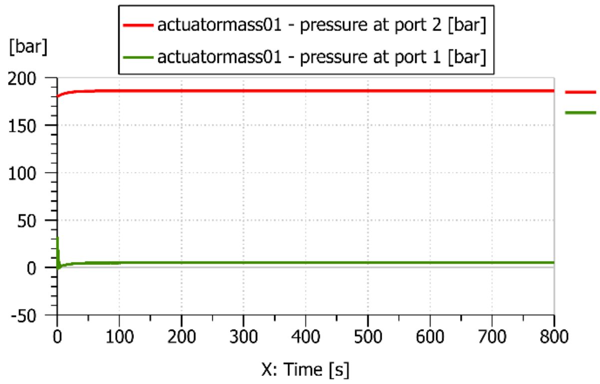

Fig. 18. Pressure variation in the right cylinder chambers.

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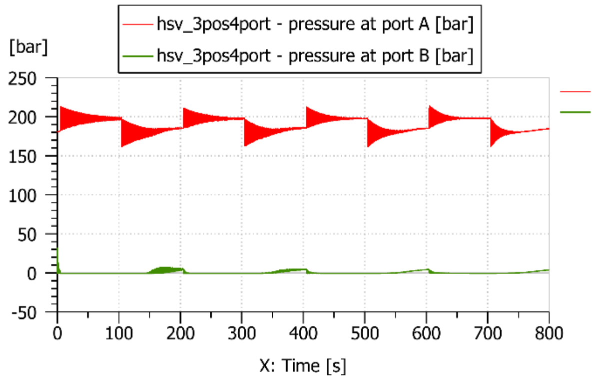

Fig. 19. Pressure variation in the left cylinder chambers.

The flow rate passing through the left side servo valve has small amplitude variations (Fig. 20).

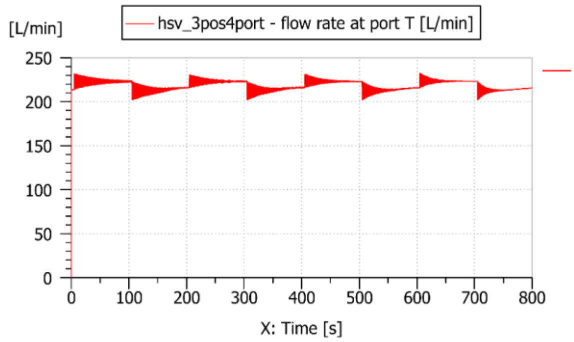

Fig. 20. Flow rate variation at the port T of the left servo valve.

The leakage flow rate in the left cylinder, between the chambers, is small enough (Fig. 21) for keeping the overall efficiency at a resonable level. At the same time, it is great enough to contribute to the motion stability.

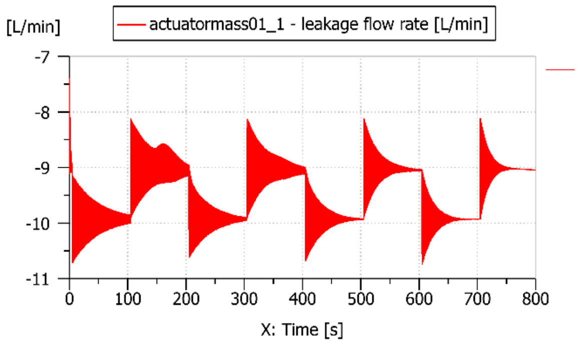

Fig. 21. Leakage flow rate in the left cylinder.

The maximum value of the sincronization error (Fig. 22) is found under the maximum level, which generate excesive stress in the gate structure.

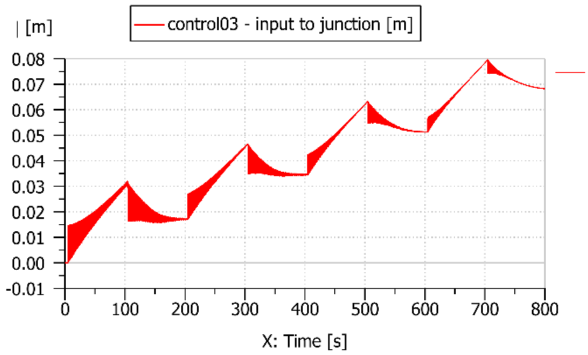

Fig. 22. Evolution of the sinchronization error.

The average measured frequency of the sinchronization error is about 1.6 Hz. The average natural frequency of a servomotor has the same value for a normal air content in the oil (Fig. 23).

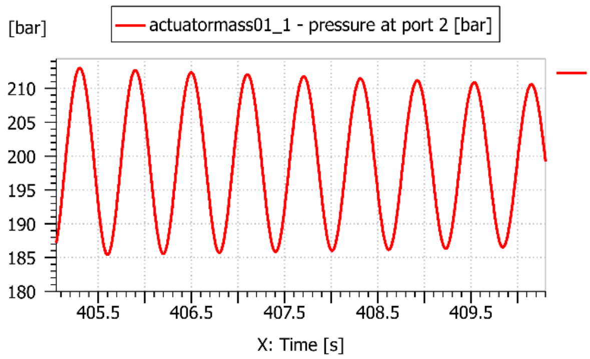

Fig. 23. Zoom into the pressure variation from the active chamber of the left cylinder.

4. Experimental identification of the relation between the synchronizing error and the maximum effort introduced in the gate

A good example of the practical importance of the hydraulic cylinders synchronization is offered by the study of the correlation between the stresses generated into a big metal structure by the velocity difference between two long hydraulic driving cylinders. The authors studied the stress and the displacements of the old water gate deserving the sluice of the IRON GATE I Hydro power station sited on the Danube River. After 30 years of service, many cracks appeared on the different components of the gate [8-9]. A complete strength analysis was performed by ANSYS program for the lower section of the gate. All the categories of loading forces were considered, including the weight, the water pressure difference, and the synchronization errors, which can introduce big efforts into gate sections. The driving system includes two hydraulic cylinders having a stroke of 16 m. The elastic rods are spherically jointed with the lower section of the gate. The mechanical structure is sliding on the dam surface by strong free rollers, which are not guiding laterally the gate. Under these circumstances, the vertical motion of the gate becomes vital. The vertical displacement generated by the gate mass is shown on Fig. 24, with a maximum value of 3 mm, checked by a laser theodolite from Leica Corporation. The pressure difference between the two faces of the gate reach 17.5 mm, precisely measured by the same device (Fig. 25).

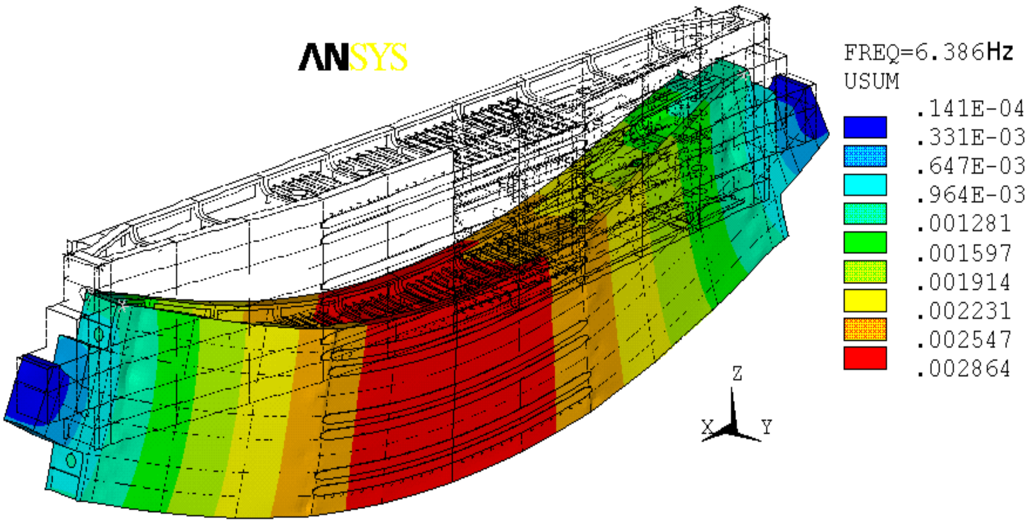

Fig. 24. The shape of the lower section of the water gate under the metal weight.

The authors set up in the gate a SCADA system including nine stress integrated transducers produced by H.B.M. [10] and calibrated by them in the Fluid Power System Laboratory. Figure 26 shows the evolution of the stress in the measurement points, detailed in Figure 27.

The stress recorded during two-gate motion cycle were found in good agreement with the predicted ones by ANSYS program. The maxim value of the tension is not exceedings 100 N/mm^2, much lower that the yeldstress indicated in the original gate project (360 N/mm^2). The biggest value of the tension is asociated with a synchronization error of about 100 mm, detected during the gate motion with a speed of about 12 mm/s.The stress recorded during two-gate motion cycle were found in good agreement with the predicted ones with ANSYS program.

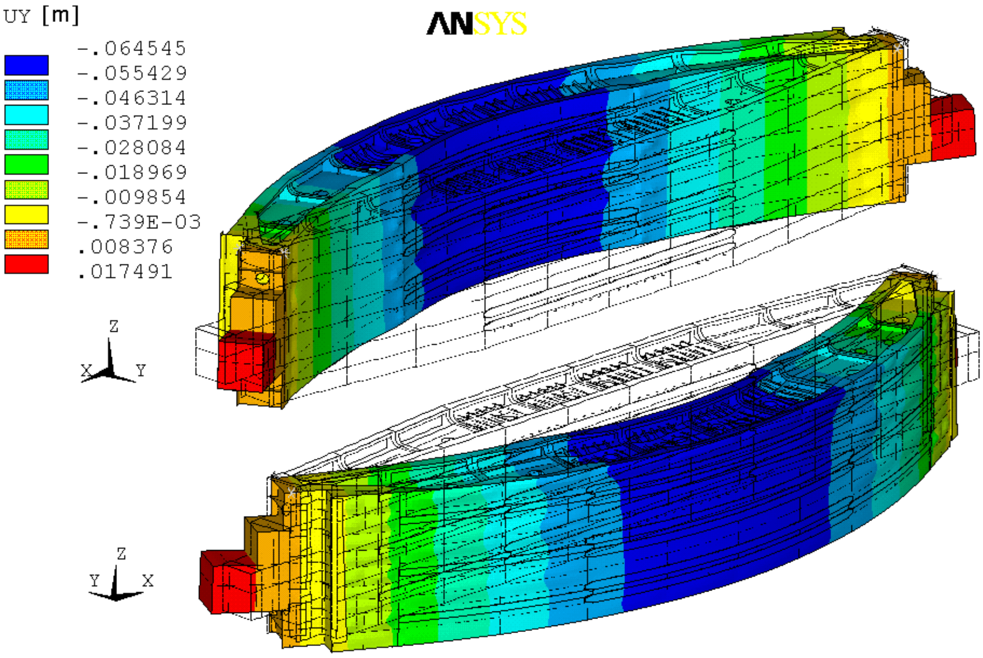

Fig. 25. Gate deformation under the water pressure force.

The SCADA system was built in the TestPoint program produced by C.E.C.

Fig. 26. Screenshot from the SCADA system for two complete cycles of motion.

The maximum stress was found at the end of the beam; the minimum stress (99.7 N/mm^2) was found always at one end of the beam for a synchronization error of about 100 mm.

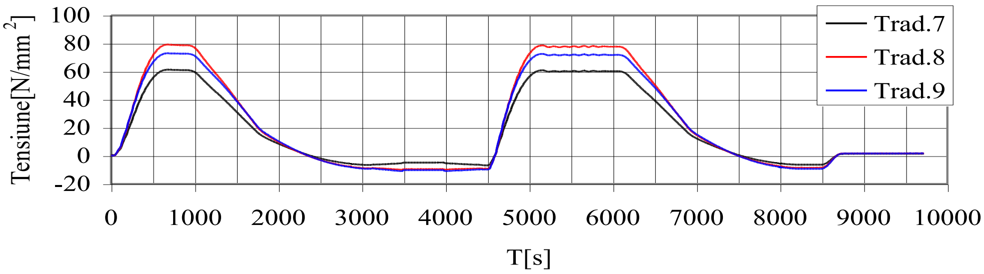

Fig. 27. Stress measurement in the intermediate water gate, lower section, and upper beam.

5. Conclusions

The modern synchronisation systems of the hydraulic cylinders using electrohydraulic servo pumps can satisfy the highest energy saving requirements under the condition of using high quality equipment, keeping the oil as clean as possible by constant recirculation through tank filters, and using high quality industrial controllers with redundant properties. At the same time, the fine-tuning of the error amplifiers can be very simple by the aid of a realistic numerical simulation of the whole system. A huge number of application of civil and power engineering like lock barriers for coastal protection, hydroelectric power plants or locks are important applications of this computational technology using Simcenter Amesim language. [6], [7], [11-12]. For very long strokes cylinders, the common PT1 controllors cannot satisfy the required accuracy. Some new high-level alghoritms, here including additional feedbacks [13], Sliding Mode Control [14], Genetic Algorithms [15], and artificial intelligence methods [16] could offer a better accuracy.

R E F E R E N C E S

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