Dynamic Modeling and Simulation of Working Regime of the Hydraulic Driven of Auger Bucket for Loader Using Matlab/SimHydraulics

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Abstract: *The paper focuses on modelling and simulation of the working operation with the auger bucket (0.7 m^3 capacity) from skid steer loader, with hydraulic acting, using Matlab/SimHydraulics environment. It was highlighted the dynamic behaviour of pressure, flow fluid, resistant torque and angular speed at shaft of hydraulic motor, subjected to the random loads that can appear when mixing concrete.*

Keywords: *Auger mixing bucket, hydraulic drive, working regime, Matlab/SimHydraulics*

1. Introduction

At present, increasing the efficiency of earthmoving machines, especially excavators and hydraulic loaders (as multi-function basic machines), is a desideratum. Starting from this aspect, for example, the efficiency of the operation of the loaders depends on their equipment with a lot of work accessories [1], one of them being the bucket with auger mixing system that can be built with different working capacities depending on the type and size of the basic machine on which it is mounted. Auger mixing is the most widely used technique of in-situ materials mixing and is especially useful for particular applications. Usually, execution of construction works consisting in concrete, mortar, cement or other granular mixtures pouring process (often used on sites) is done with its specialized equipment, such as concrete mixers or multifunctional base machine equipped with auger mixing bucket (see Figure 1).

Fig. 1. Working principle of the mixing bucket for loader [2]

It must remark main advantages of using of this equipment, as: eliminating the backbreaking labor of mixing, transporting and dispensing wildlife feed, sand, asphalt, agricultural grains and washed gravel (3/4 inch maximum). In addition, the auger buckets have a quick-attach frame on either side to control the discharge from the left or right and come complete with a chutes, hoses and couplers.

2. Conceptual design for auger bucket

Equipment design focuses on the basic conceptual principles taking into account by actual desideratum: to perform its working specific requirements with maximum economy and efficiency. Thus, the objective of this purpose were accomplishing the following engineering aspects: fast production, easy maintenance and control, minimum complexity of the mechanical parts, standard parts use, health harmless material, and mechanical safety [3, 4]. In above context and based on common solutions developed by manufacturers worldwide, a virtual prototype of auger bucket (with 0.7 m^3 capacity), it was drawn in Figure 2.

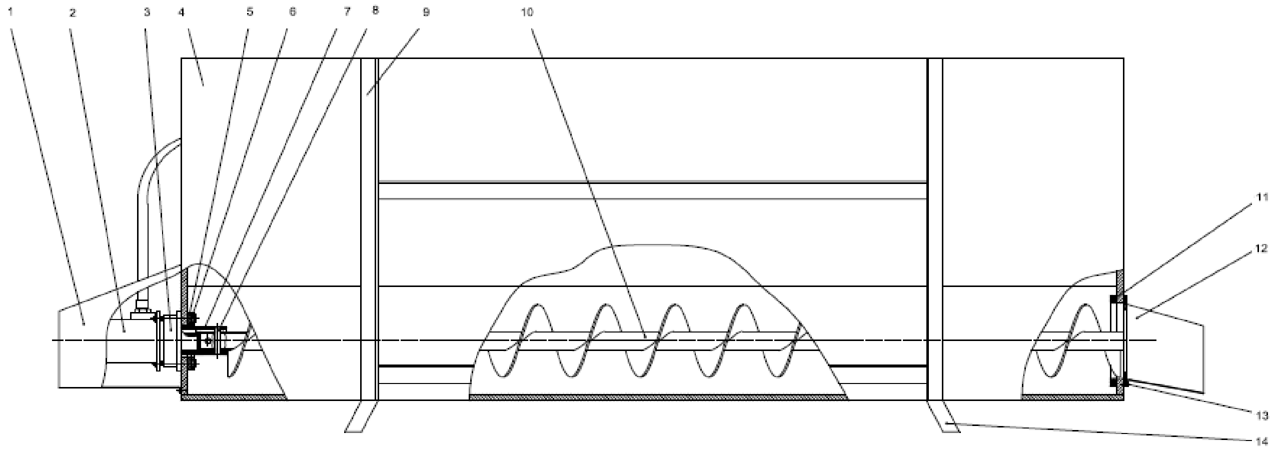


Fig. 2. Drawing in 2D CAD of the concrete mixing bucket for skid loader (rear view):
1. recessed cavity; 2. hydraulic motor; 3. bearing; 4. bucket; 5. protective flange; 6. protection fixing flange; 7. coupling; 8. coupling fixing bolt; 9. bucket support frame; 10. mixer shaft; 11. mixing ring guide ring; 12. unloading chute; 13. auger; 14. bucket support frame leg.

To operate the auger bucket, must need to be a skid steer loader (as base machine) able to provide a minimum flow of 2 m^3/h and always operate the bucket at idle speed. In this way, the hydraulic motor on auger bucket provide plenty of power to operate the auger, mix and feed product continuously without interruption. At adding heavier materials is necessary to increase the speed so the auger will not stall. Operating the auger in reverse will mix the materials and after obtained the desired consistency, the auger is stopped. The skid steer loader is driven by an engine with power P_m = 45 HP and angular speed n_m = 2400 rpm. The author will consider the higher density of the material (ρ = 2200 kg/m^3) that corresponds to the mixing of a mixture consisting of cement mortar or fresh concrete. The mixing bucket operates in two working modes: slow (for ready-processed materials) and fast (for on-site preparation of different mixtures). Thus, the mass productivity of the bucket of Q_m = 4.5 t/h corresponds to the operation in the fast regime and, respectively, Q_m = 1.26 t/h to the operation in the slow regime. Next, it will be considered the most intense case for the drive system, adopting the highest value of mass productivity.

3. Mathematical modelling of working regime for auger bucket

Mathematical modelling focuses on research related to the response of mixing equipment subjected to the random loads that can appear during working operation. Thus, the author has built a mathematical model for mechanical-hydraulic co-simulation of the auger mixing bucket, based on:
- the equilibrium equation of the fluid flow rate from hydraulic circuit;
- the equilibrium equation of the torque at drive-shaft of the hydraulic transmission of the auger.

Firstly, a database is set up with details about each component of the hydraulic system, according to constructive characteristics of equipment and base machine (e.g. pump, proportional distributor, command device, hydraulic motor etc.).The instantaneous flow of the pump (Q_p), by neglecting losses, will be given by the formula (1):

$$Q_p = \frac{V_0 p}{2\pi} \cdot \omega_p \,, \tag{1}$$

where: V_0 – pump specific volume of the fluid; p – pressure; ω_p - pump angular speed.
Fundamental equation for the hydraulic driveline will be derived by using the generalized Newton's second law of motion. The equilibrium equation between the input and output torque of the hydraulic driveline is obtained the formula (2) given below:

$$T_m - T_l = J_{eq}\dot{\omega}_m \,, \tag{2}$$

where: T_m – motor torque; T_l – load torque; J_e – equivalent moment of inertia; ω_m – motor speed.
Using these equations, it is possible to choose a proper software environment for virtual simulation

of dynamic behavior of hydraulic drive system of auger mixing bucket, among the most used by engineers being Matlab environment (with specialized modules, such as: Simulink, SimHydraulics, SimMechanics etc.) [5, 6, 7, 8, 9].

4. Simulation of working regimes of auger mixing bucket

To simulate the behavior of the hydrostatic driven mixer system, a scheme has been performed using the Matlab/SimHydraulics environment (Figure 3). It was implemented a simplified model of a closed circuit for auger acting from a hydrostatic motor with fixed-displacement volume. The global scheme contains the following blocks, namely: the main pump of the circuit subsystem with its mechanical driven subsystem, the pressure loss compensation subsystem for fluid pressure circuit, the hydrostatic motor subsystem, auxiliary equipment (directional valves, protection valves, pipelines), the controller block subsystem of the circuit, and the sensor blocks subsystems for instantaneous monitoring of the hydraulic parameters (input and output pressures, fluid rate flow). Visual representation of the main blocks has been marked separately, in different colors, for better understanding of functional components of the hydraulic scheme.

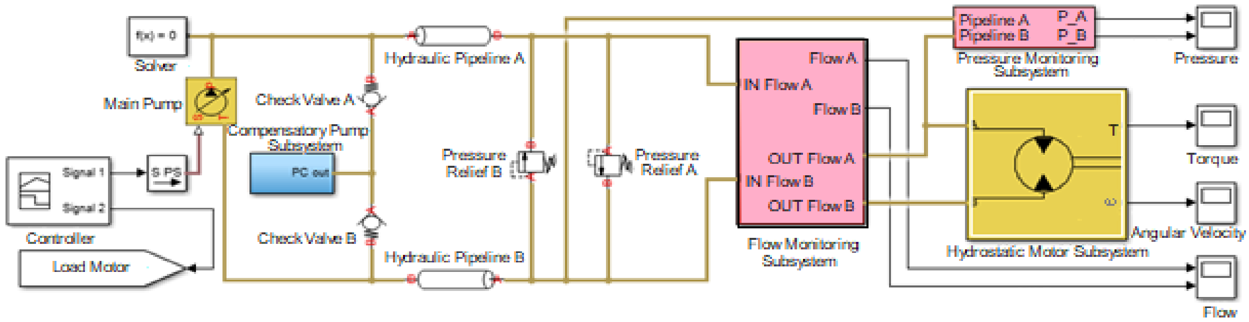


Fig. 3. Schematic of hydraulic circuit implemented in Matlab/SimHydraulics environment

The parameters that customize main blocks of the scheme in figure 3 are centralized in tables 1-3.

Table 1: Block parameters of hydraulic fluid

Parameter	Value
Type	MIL-F-5606
Density	847.4 kg/m^3
Viscosity	12.15 cSt
Flow discharge coefficient	0.7

Table 2: Block parameters of hydraulic motor

Parameter	Value
Motor displacement	8.5x10^{-4} m^3/rad
Nominal angular velocity	6 rad/s
Volumetric efficiency	0.92

Table 3: Block parameters of 4-way directional valve

Parameter	Value
Leakage area	10^{-12} m^2
Valve passage maximum area	5x10^{-5} m^2
Valve maximum opening	0.01 m

The model of pump with constant parameters will be assumed, functioning at 200 bar pressure. The control of the constant flow pump is provided by the controller, by inserting a generic signal conditioning block in the physical signal. The pressure / flow loss compensation circuit in the scheme has the principle diagram shown in Figure 4. This module was included a volume pump with constant displacement, mechanically putting into working regime by a constant rotational speed source. The discharge valve acts as a protection of the circuit when the maximum value of the working pressure is exceeded (preset to 180 bar). The block with the parameters of the hydraulic fluid used was also added to the scheme.

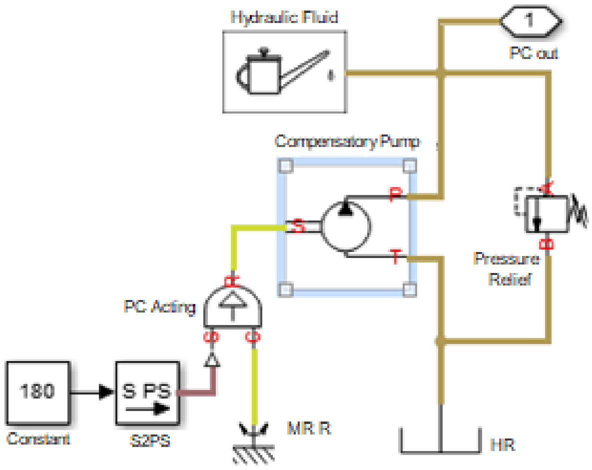


Fig. 4. Compensation circuit subsystem

Generally, knowledge of the dynamic behavior of rotational loads driven by hydrostatic system is mathematic modeled using equivalent models. In order to reduce the whole mechanical system (represented by auger mixing bucket with its transmission) into an equivalent one, we can assume that it can be modeled as two moments of inertia, one to model the hydrostatic supply power and one to model the auger [10]. The first one includes the moment of inertia of the motor, of the clutch disks, of all the rotating parts, reduced to the engine shaft (with equivalent moment of inertia $J = J_e$ = 0.042 kgm^2), while the moment of inertia of the auger loads and of are included in the second. In addition, the mathematical modelling of the mechanism of energy dissipation in mechanical systems [11] is often modeled through a damping element, in our case with D = 0.2 Nms/rad (see Figure 5).
The third element, denoted "Load" in Figure 5, is a constant torque signal generator. It maintains at its output a mechanical moment whose value is set by the connector, relative to a reference value which is usually zero. This block simulates the resistant torque that the auger bucket must overcome during working operation. The instantaneous value of this torque is configured in the control controller and taken directly, by means of a numerical scaling block, followed by a conversion from generic signal (Matlab/Simulink) to physical signal (mechanical moment, measured in Nm). It is specified that the hydraulic motor is reversible, with constant displacement flow.

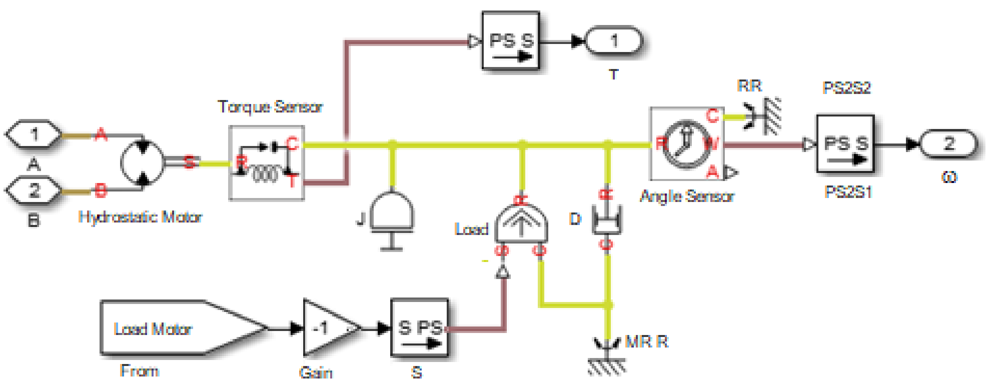


Fig. 5. Hydraulic motor subsystem

Thus, the subsystem in Figure 5 contains the all mechanical elements (above mentioned) next to the transducers specific to the monitoring of rotational motion (e.g. mechanical load of the hydrostatic motor). All these blocks help to simulate the dynamic behavior of the auger mixing bucket.
Sensors have an essential purpose in a simulated operating scheme, as in the case of this paper or physical case, in operation. Thus, it is necessary to monitor (continuously or periodically) the main parameters of the respective scheme. In this study, it is considered that the pressures and flows in the two main pipeline of the circuit constitute the set of parameters that require continuous monitoring, from the point of view of the hydraulic assembly behavior. On the other hand, from a mechanical behavior point of view, the torque resistant to the motor shaft and its angular velocity are the main parameters to be monitored. The pressure and flow sensor subsystems are shown in Figure 6, with the "mechanical" sensors being incorporated into the hydraulic motor subsystem (Figure 5).

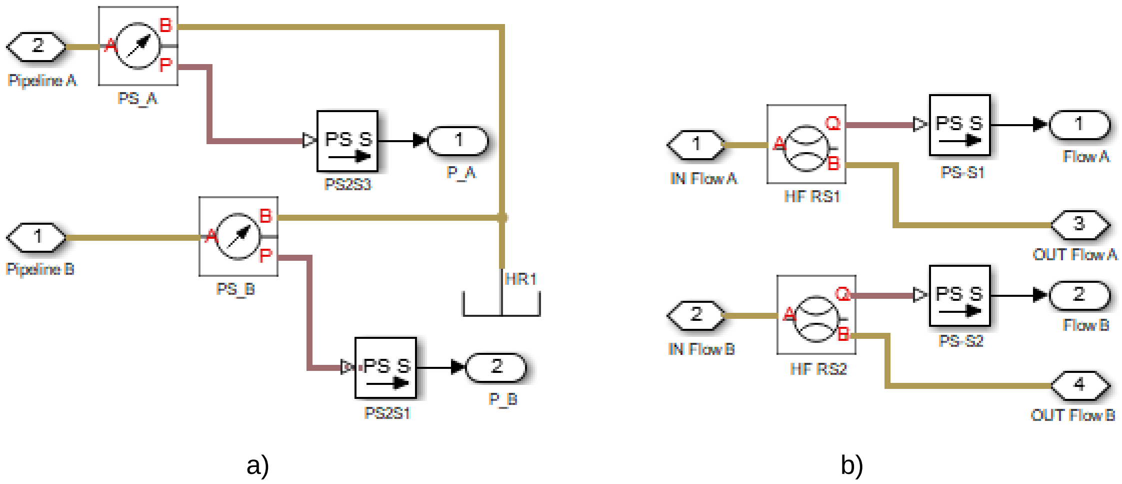


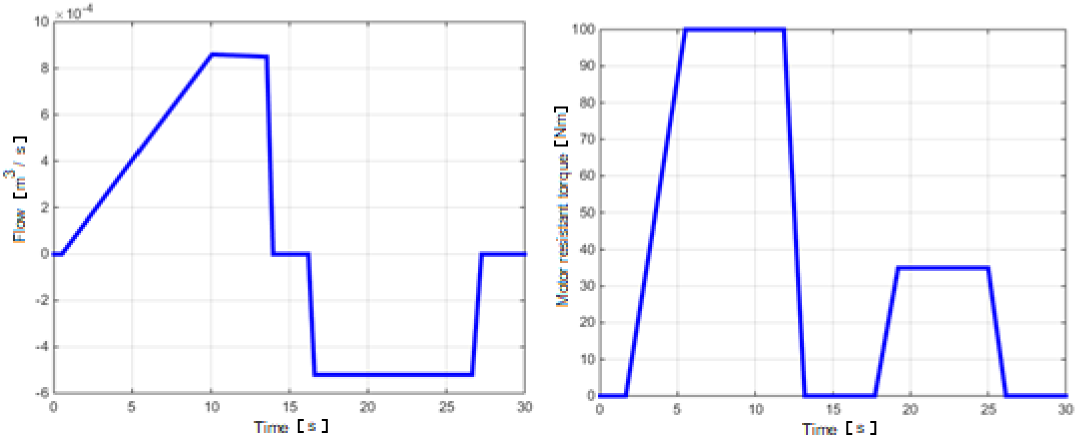
Fig. 6. Sensors diagram subsystems:
a) for pressure; b) for fluid flow.

5. Results

Simulation process is based on the model of the drive system of auger bucket (Fig. 3) that was created in Matlab/SimHydraulics environment. As numerical solver, the algorithm *ode45* (Dormand - Prince) with variable step was used. The minimum step size was set at 0.02 s, maximum step size at 0.14 s and the relative tolerance at 10^{-3}.
The simulation of the behavior of the auger bucket drive system was performed taking into account the following hypotheses, namely:

- detailed information about parameters necessary for the configuration of the hydraulic components and apparatus are provide from catalogs, and the values of the mechanical parameters for load model configuration are available from dynamic analysis;
- taking into account the variability of the dynamic working regime of the mixing bucket, the unfavorable working case corresponding to auger rotation with the maximum available rotational speed was considered (means random appearance of resistant moment reaching the maximum value resulting from equation applied to rotational motion of the auger shaft);
- the simulation was performed for 30 seconds, during which time the auger is actuated in a clockwise direction, at the maximum value of the engine torque and in the opposite direction at about 30% of its maximum capacity;
- two virtual simulation scenarios were performed corresponding to the two significant working cases in terms of auger loads appearance, such as:
    a) case I: independent simulation of the main pump control in the circuit and load on the motor shaft;
    b) case II: correlation of the two control signals so that the variations of the torque resistant are proportional to the variations of the angular speed of the motor shaft.

In this study, the pressures and flows in the two pipeline (A and B) of the circuit, respectively the torque and the angular velocity of the motor shaft, are the monitored parameters. The time evolutions of the two command parameters are shown in the diagrams in figure 7. It is mentioned that for case II the load control is performed with a signal proportional to the one for regulating the flow of the main pump, through a block of corresponding scaling of the values of the numerical function.



a) b)

Fig. 7. Command parameters for:
a) flow main pump control; b) mechanical load control at pump shaft.

Figure 8 shows the results obtained for the analysis in case I. The diagrams of the evolutions of pressures and flows in the main circuit are presented comparatively for both pipeline A and B. The behavior particularities of two parameters, in ranges where transient manifestations are present, can be observed on the details in figures 9 - 12.

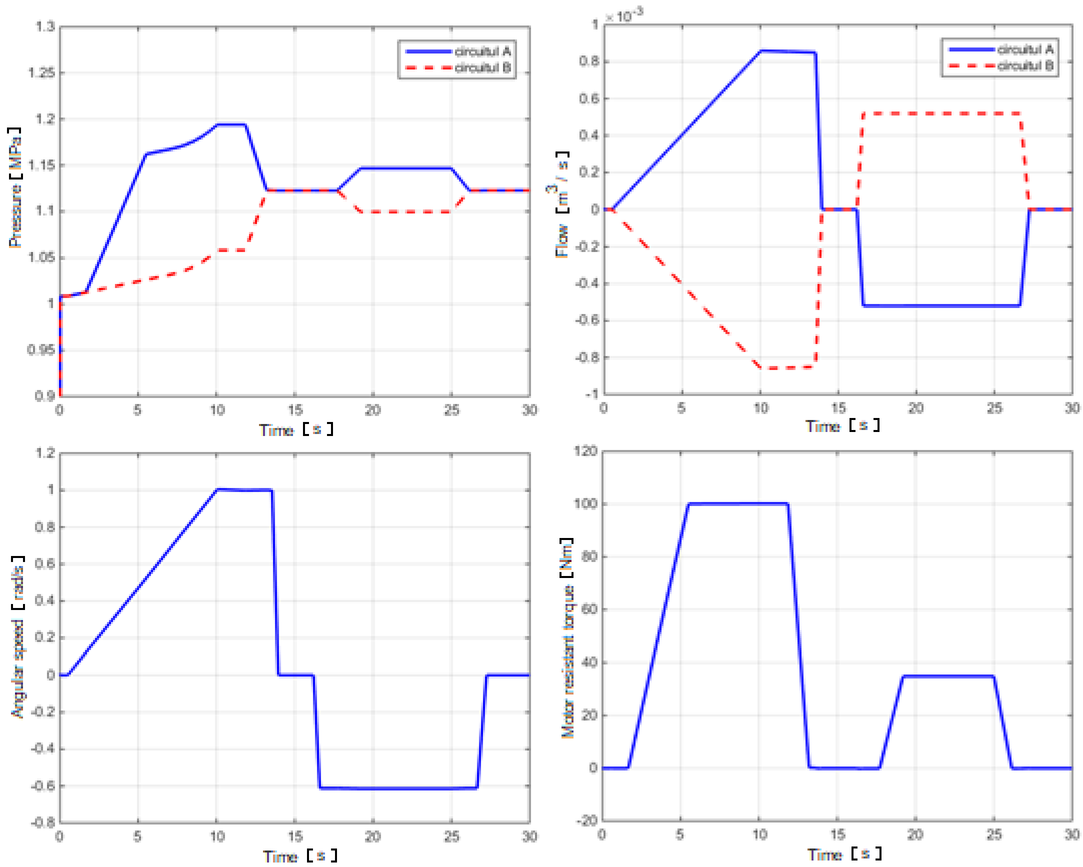


Fig. 8. Time evolutions of pressures, flow rates, angular speed and torque for the analysis in case I

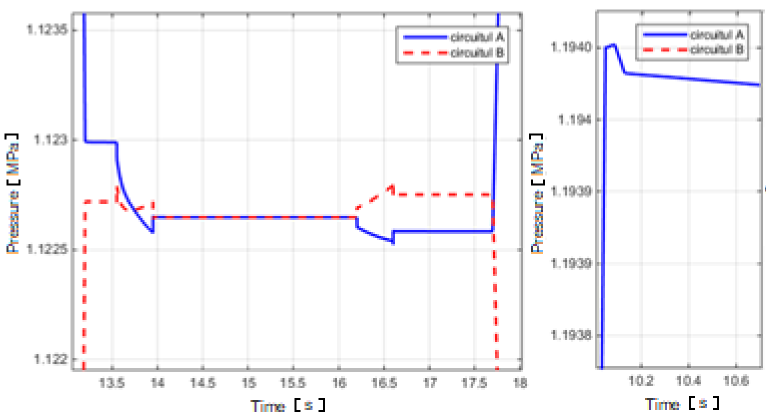


Fig. 9. Details for pressures (case I)

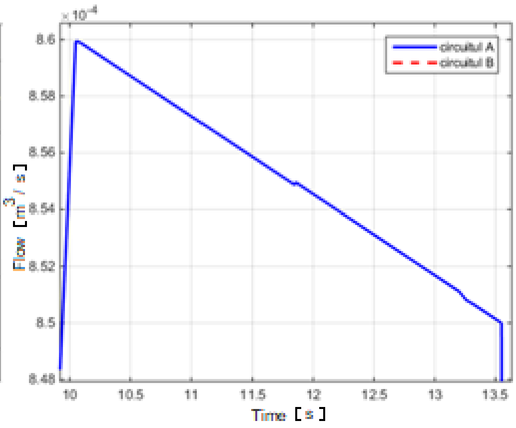


Fig. 10. Detail for flow (case I)

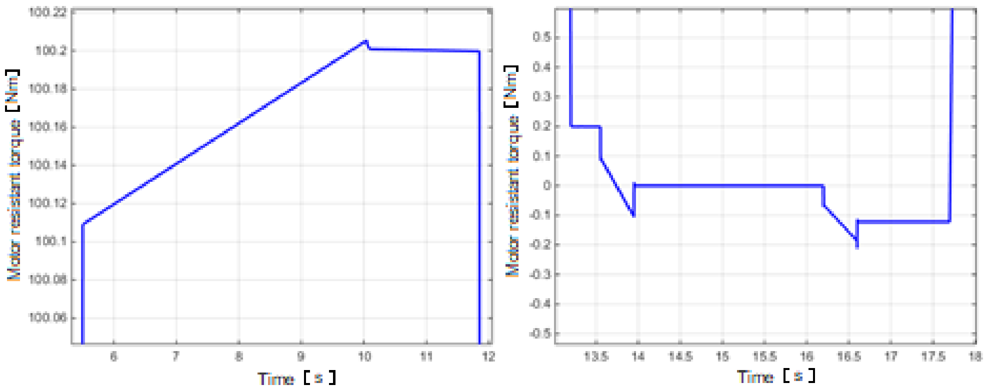


Fig. 11. Details for resistant torque (case I)

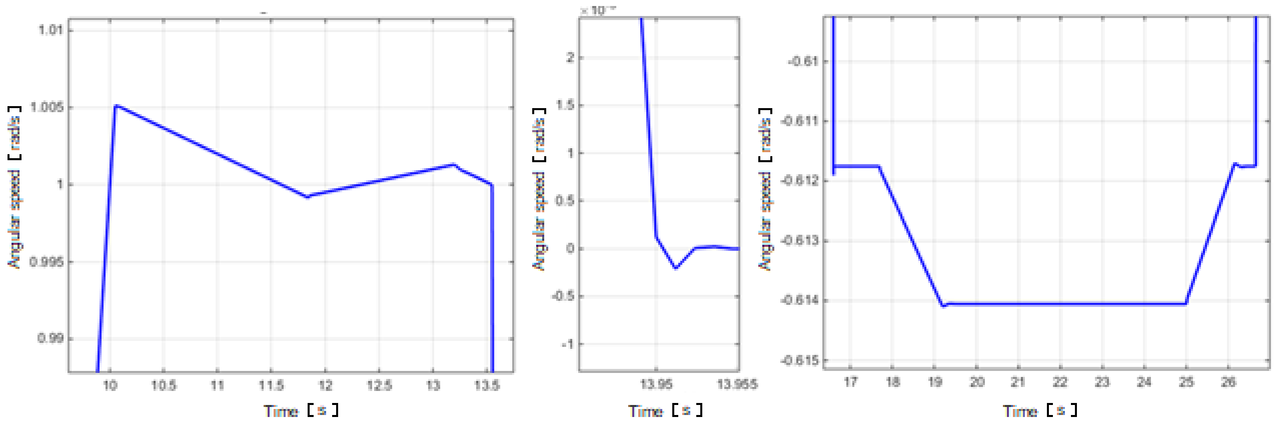


Fig. 12. Details for angular speed (case I)

After evaluating the parameters of the drive system, under the conditions of an imposed characteristic of the auger motion (case I), the control scheme is reconfigured so that the instantaneous mechanical load must be proportional with angular velocity of the motor shaft (by taking primary information on hydraulic fluid flow at the outlet of the main pump). This reconfiguration of the scheme leads to analysis in case II and the results obtained are presented in figure 13.

Similarly, to the case I, the diagrams of the evolutions of pressures and flows in the main circuit are presented comparatively for both pipeline A and B, and the behavior particularities of the monitored parameters evolutions can be seen in the details in figures 14 - 17.

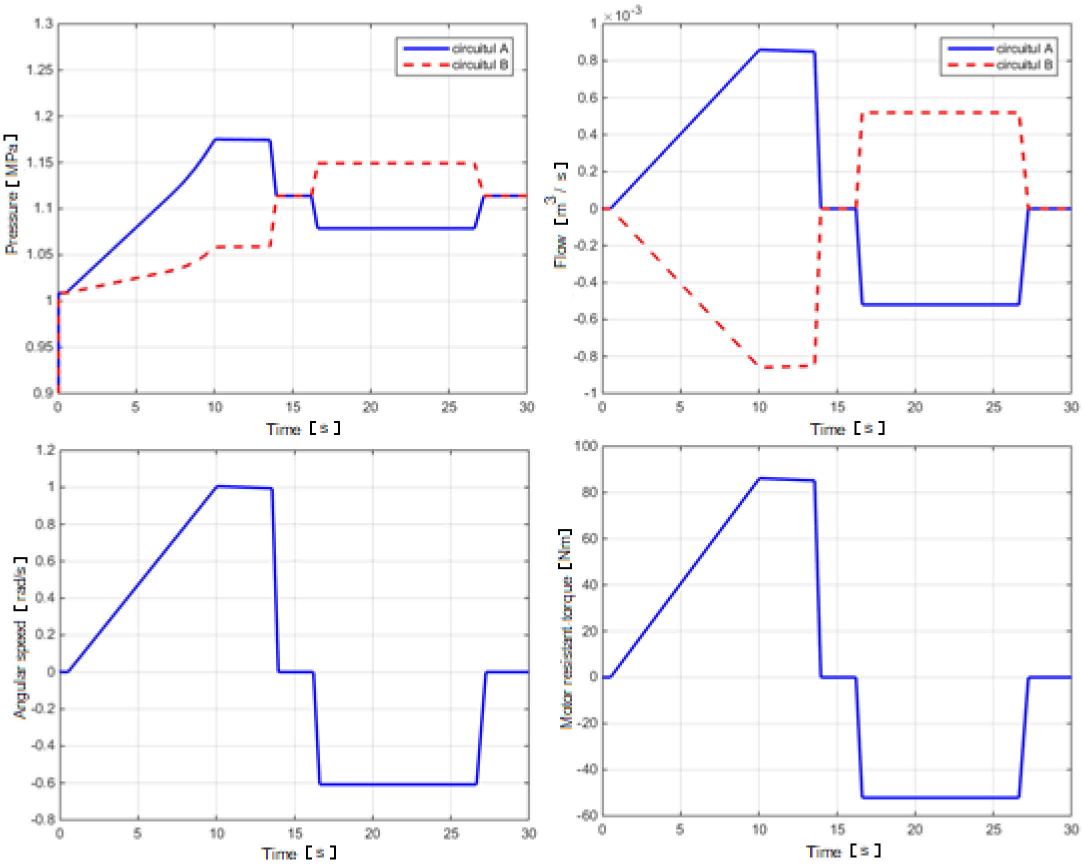


Fig. 13. Time evolutions of pressures, flow rates, angular speed and torque for the analysis in case II

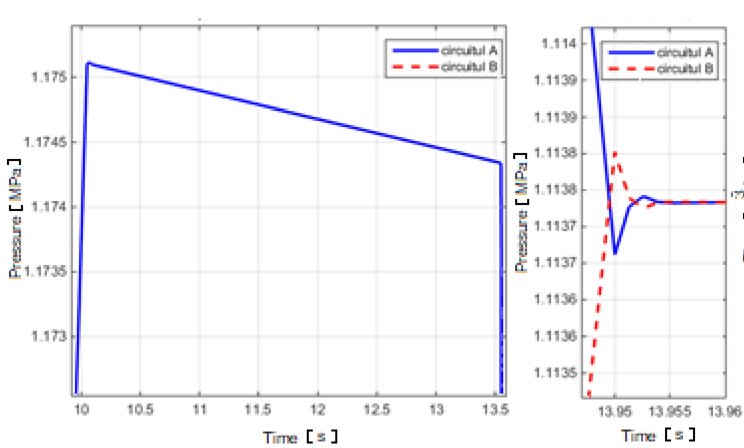


Fig. 14. Details for pressures (case II)

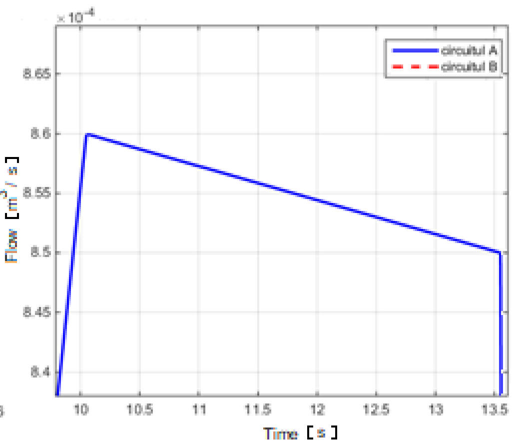


Fig. 15. Detail for fluid flow (case II)

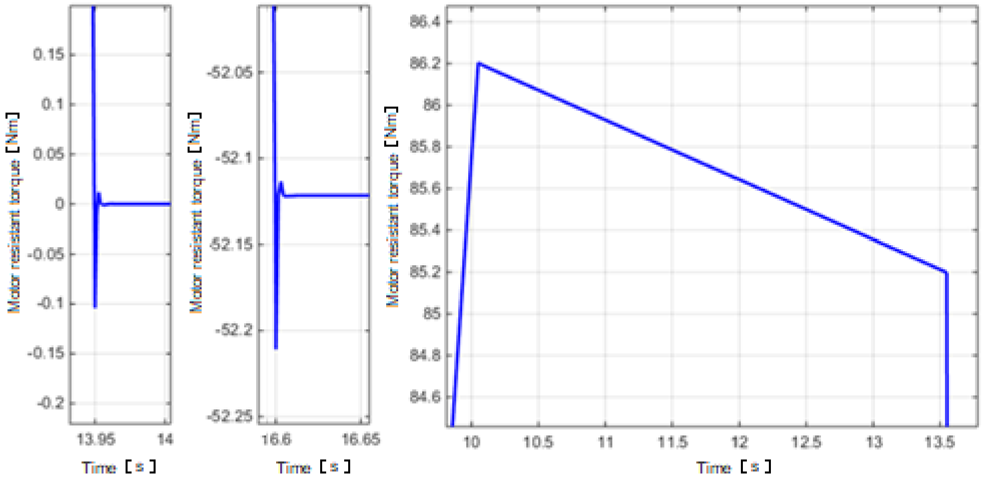


Fig. 16. Details for resistant torque (case II)

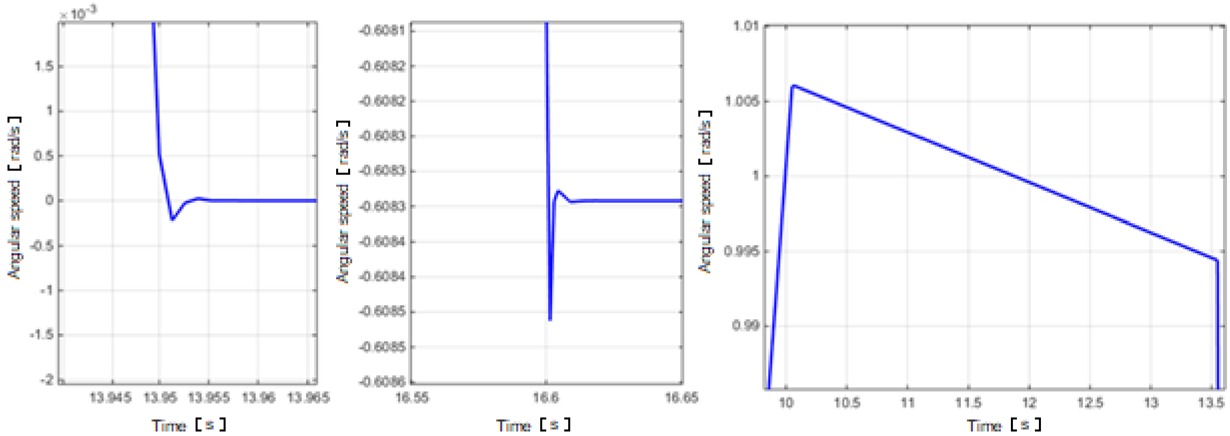


Fig. 17. Details for angular speed (case II)

It is obvious that the details presented in the paper, corresponding to the variations of the monitored parameters (both for the case I and II) must be analyzed together with the global diagrams corresponding to the evaluated parameter.
Since in case I but especially in the second, there are some manifestations of transient working regimes, which occur when the state of the drive system suddenly changes (starting, braking, auger sense changing, sudden change in the value of the mechanical load, etc.) it is a usual behavior, given that the model also includes inertial masses in rotating motion represent by the all components of the equipment ensemble.
Also, the dynamic model of hydraulic power transmission from the energy source to the auger further contributes to the appearance of transient dynamic regimes. The negligible amplitudes of these transient variations, as well as the very short time in which they are fully amortized, are the direct consequence of the determining factors, namely: very low angular speed at the axis of the hydrostatic motor and relatively high damping in the mechanical system work (reduced to the motor shaft).

6. Conclusions

The results of the aspects approached in the paper led to evidence the following conclusions:

- for this equipment (characterized by slow working regimes), without sudden or rapid transitions between working phases, the dynamic analysis approach is of secondary importance, justified mainly by the need to assess the load peaks that may occur during working cycle. This conclusion is justified by the qualitative and quantitative evolutions highlighted in the dynamics of the system analysed in this study;

- in accidental conditions (when the dynamic loads on the auger axis can reach very high values compared to the usual ones) such numerical approaches regarding the dynamic behavior of the analysed equipment are well justified, provided that the mathematical and simulation models used must take into account the whole consisting of mechanical parts of equipment and its hydraulic driven system. This conclusion is justified by the complexity of the approach of the presented study: the modeling of the drive system was made based on constructive example given in Figure 2, including all the components of such a drive scheme, as well as the determinants of the mechanical load generated by the auger simulated virtual scenarios.

In addition, using of the computer environments such as Matlab (with SimHydraulics and Simulink modules) simplifies very much the designer's efforts starting from the designing stage (conception and CAD modelling), allowing him to create the hydraulic circuit from the point of view of its, as well as to choose the functional parameters and the mechanical component parts of the equipment so as the energetic efficiency of the assembly should be as high as possible.

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