Multi-domain and Multi-body Analysis of a Hydrostatic Hybrid Drive System

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Abstract. The paper present a complex study of a hydrostatic hybrid drive system where the simulation process comprises a 1D multi-domain simulation and a 3D multi-body analysis. The evaluation of different solutions is based on simulation approach, using LMS Imagine.Lab and LMS Virtual.Lab software packages. The main focus is on the analysis of an Axial Piston Motor system with a rotating swash plate and on the evaluation of the forces and torques acting on it.

Keywords: hydraulic drive system, multi-domain, multi-body analysis.

1 Introduction

A hydraulic drive system is a transmission that uses pressurized hydraulic fluid to put in motion mechanical machinery. The hydraulic propulsion system [1] transfers energy to another system and consists of three parts: a generator (i.e. a hydraulic pump, an electric motor or a combustion engine), piping assembly (with valves and filters) to guide/control the flow and the motor to power the vehicle.

The core of this analyzed model is a swash plate system that is put in motion by a series of hydraulic cylinders connected in series, in a three block sequence.

The simulations are separated in two different parts, a model based simulation (incorporates multi-domain simulation) and a multi-body analysis.

The first part is one 1D multi-domain simulation, here are incorporated the control, hydraulic and mechanical systems and is set to design a swash plate with fixed displacement axial piston pump to extract the pressure obtained from the actuator's pistons.

Second simulation, is a 3D multi-body computation where the pressures computed with the aid of the 1D software is used as inputs loads for the multi-bodies dynamics simulation in order to understand the behavior of the system, to quickly evaluate design alternatives, to optimize kinematic/dynamic performances and to further asses the loads of this complex system.

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2 Principles of Calculation

The swash plate rotary group is composed of multiple mechanical systems assembled together. A brief description of this systems will mention the input block, a number of pistons connected in a series of three blocks, which are actuated by one hydraulic control system, in order to apply pressure on one plate assembly that translates the reciprocating motion into a rotating one (swash plate).

For fixed displacement swash plate pump [2] the calculating pump size for drive speed and drive torque are determined from the relationships:

$$n = \frac{Q*100}{V_g*\eta_{vol}} \quad (rpm) \tag{1}$$

$$M = \frac{V_g*\Delta p}{20\pi*\eta_{mh}} \quad (Nm) \tag{2}$$

where n is speed (rpm), M drive torque (Nm), Q flow (l/min), η_{vol} volumetric efficiency, V_g geometric displacement per rev. (cm^3), Δp differential pressure (bar) and η_{mh} mechanical - hydraulic efficiency.

For calculating pump size the relations becomes:

$$n = \frac{Q*100*\eta_{vol}}{V_g} \quad (rpm) \tag{3}$$

$$M = \frac{V_g*\Delta p*\eta_{mh}}{20\pi} \quad (Nm) \tag{4}$$

3 Multi-domain analysis

LMS Imagine.Lab (Amesim) software [3] enables connection of several components working after various physical principles to capture the functioning of the mechanical joint and hydraulic drive systems. The making of the hydraulic hybrid simulation model involved the use of components from hydraulic and mechanical libraries of the software.

In order to convert mechanical energy into the hydraulic energy for propulsion goals, in our 1 D simulation, an internal combustion engine is used as a primary energy source to drive the main shaft of the system. The shaft turns the cylinder block which contains nine pistons disposed in three separate phases (three pistons in a phase). The pistons push against the swash plate, which makes the pistons move in a reciprocating way in the axial direction. The cylinder block is pressed against a stationary valve plate mounted on the end-cap. In the pump function mode the hydraulic medium is fed to the low pressure (inlet) side of the pump and pumped out by the pistons on the high pressure (outlet) side into the system and in motor operation, the process is reversed and pressure oil is fed to the inlet side of the unit.

In pump operation, mechanical energy is converted into hydrostatic power while in motor operation, inversely, hydrostatic power is converted into mechanical energy.

Multi-domain simulation is performed at constant angular speed 1000 and 1500 rpm's with a swash plate angle at 10 degrees within the shaft.

Because of the large size of the complete system, instead of a full model with nine pistons, the model presented in figure 1 is a reduced model who simulates a single piston interacting with the swash plate and which include some specific components marked with labels.

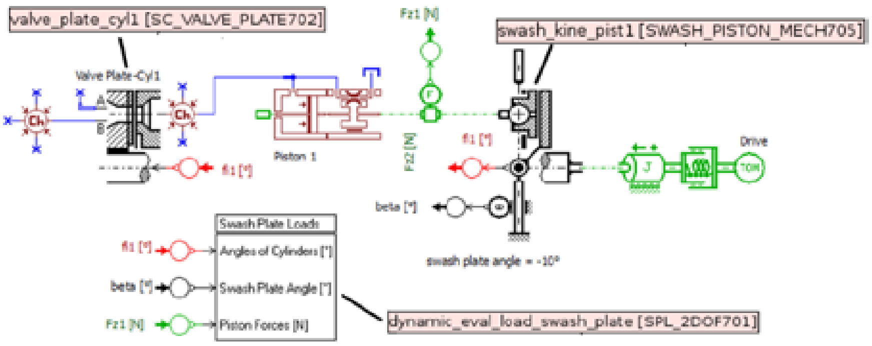

Fig. 1. Reduced model of an Axial Swash Plate Piston pump with fixed displacement

Figure 2 presents the Amesim model of a single pumping piston-cylinder block-swash plate mechanism which is a mechanism with 2 degrees of freedom (first DOF is the cylinder block rotation while the second DOF is the swash plate rotation) and right shows a specific sub-model for the evaluation of the swashplate loads, in particular: forces, torques and trajectories of forces.

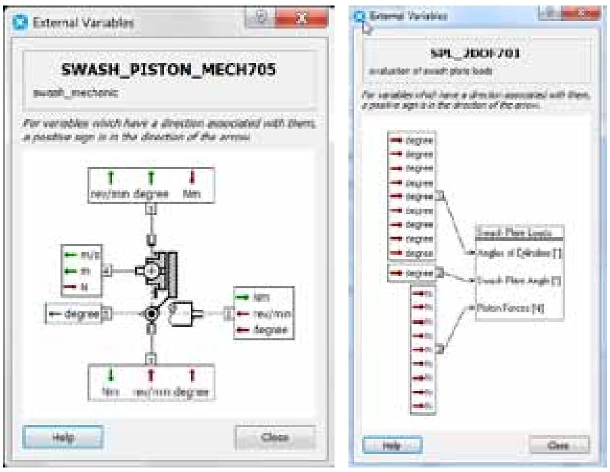

Fig. 2. Piston-cylinder block-swash plate mechanism (left) and calculation of swash plate loads (right)

After computing the multi domain system, figure 3 shows the resultant force acting in the normal direction to the swash plate for the two different revolutions per minute cases, 1000 RPM's on top and 1500 RPM's on bottom. The maximum corresponding forces values obtained from calculations for the two cases are 1900 N at 1000 RPM's and 3700 N at 1500 RPM's.

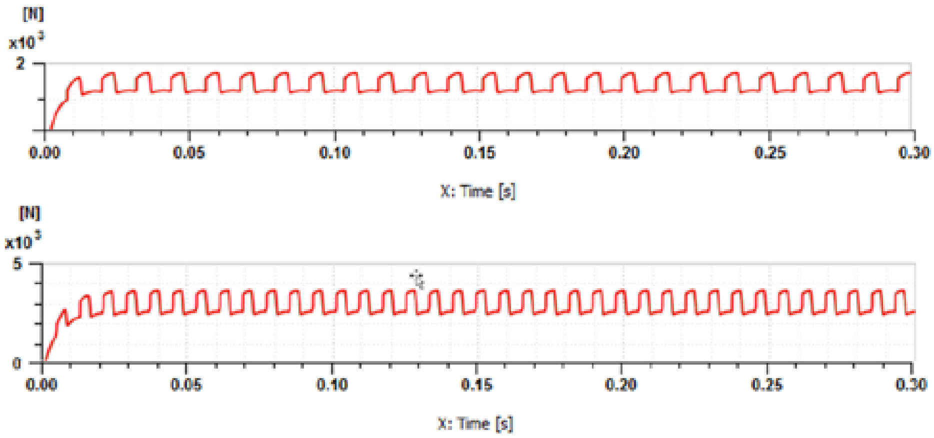

Fig. 3. Resultant force acting on the swash plate

Figure 4 shows the delivery pressure (250 bar) and the pressure inside one of the pumping cylinders at 1500 RPM's. Pressure ripples are well visible.

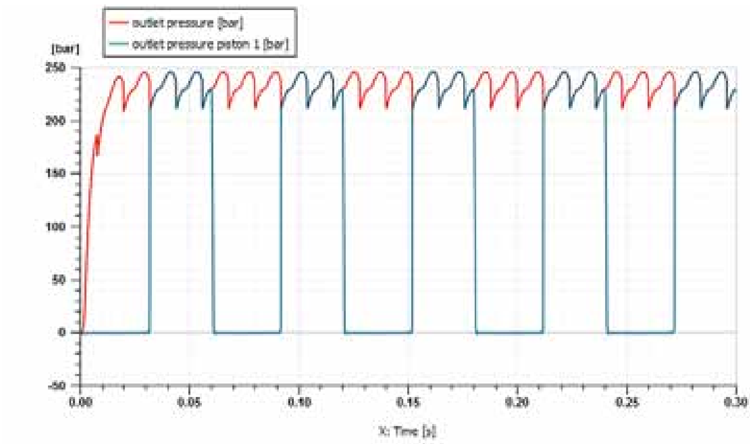

Fig. 4. Pressure at 1500 RPM's

4 Multi-body Analysis

After importing/creating the geometry it is necessary to attribute the mass characteristics of different parts (mass inertia matrix and mass).This is called in LMS Virtual.Lab, creation of bodies and is the link between the part's geometry and the dynamical analysis. To validate the simple motion, next step is to validate the kinematics of the system and to connect bodies through a number of constraints. Once the simple motion is understood, in order to create compliance in the model and provide the first view of the dynamics of the systems, forces are added between different bodies (i.e. translational spring-damper-actuator" ("TSDA") element).The combination of a value stiffness, a damping value, and a value for the actuation torque defines the TSDA force.

LMS Virtual.Lab Motion model will be solved for time domain load using multi-body simulation [4] and [5]. The motion equations of a generic structural system, in the time-domain, are described in equation 5:

$$[M]\{\ddot{x}(t)\} + [K]\{\dot{x}(t) + [C]\{x(t)\} = \{F(t)\} \quad (5)$$

where [M], [K] and [C] are the global mass, stiffness and damping matrices, {x(t)} is the displacement vector corresponding to the degrees of freedom of the structure, and {F(t)} is the vector of excitation forces, replaced in our simulation by the simulated RPM's.

The simulated system is illustrated in Figure 5 where with 1 is numbered the main shaft, 2 the exterior housing, 3 the rotor, 4 the swashplate, 5 the nine pistons assembled in a cylinder and 6 the hydraulic distributor. The CAD geometry is crated in LMS Virtual.Lab Designer software platform and the multi-body simulation in Motion Workbench.

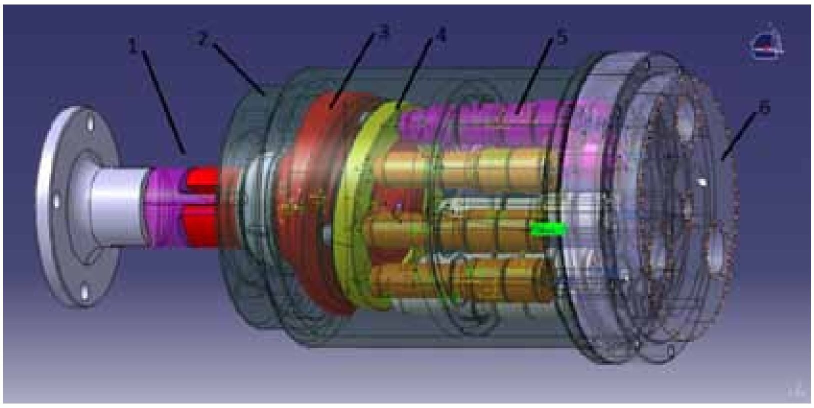

Fig. 5. Hydraulic motor CAD and its principal components

Two different cases were studied: engine mode and pump mode.

In the engine mode (figure 5) where the output speed is determined by the volume of flow into the motor, the hydraulic pressure generates a torque at the cylinder and thus the rotation of the drive shaft. In the multi-body simulation instead of hydraulic pressure the input loads are the forces obtained from the 1D simulation, forces that are applied on the nine axial pistons.

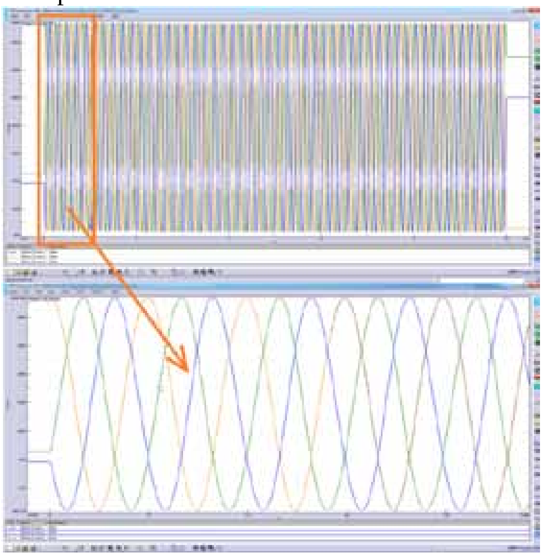

Fig. 6. The sinusoidal forces at 1500 RPM's for the three different phases

For the two simulation cases with maximum value of force 1900 N and 3700 N the resulted torque where 126 Nm, respectively 242 Nm (figure 7).

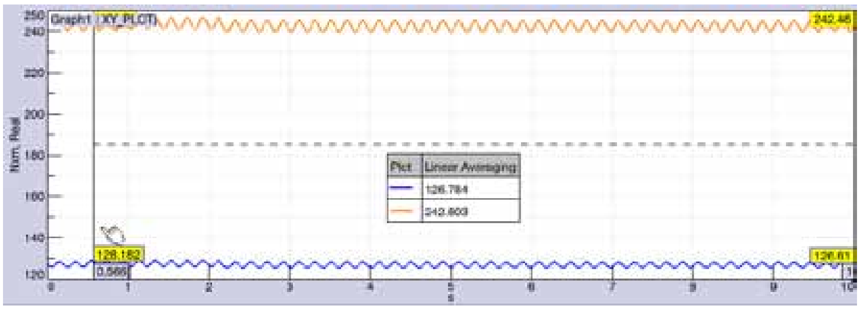

Fig. 7. Torque obtained in motor mode

On pump mode (figure 8), a two stroke motor drive the shaft and causes the cylinder to rotate, taking with it the nine pistons. The pistons carry out a stroke and transmit a translational movement to the opposite pistons which generates a torque and rotate the drive shaft. The pistons from the two opposite systems are connected between them with translational spring-damper-actuator elements. During this cycle the swash plate translate the motion of a rotating shaft into reciprocating motion, or translate the reciprocating motion into a rotating one.

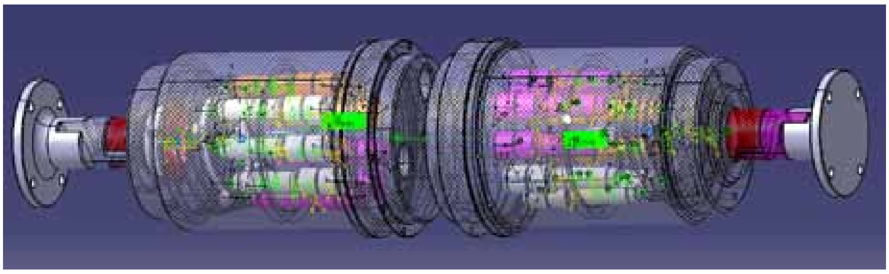

Fig. 8. Generator-motor system

A rotational spring-damper-actuator driving (RSDA) element is applied on the joint between the shaft and rotor. The RSDA is a torque-producing element that acts about the axis of a specified revolute or cylindrical joint.

The equations that describe the formulation for torque in a RSDA element are [6], [7] and [8].

$$\theta = \theta_j - \theta_u \tag{6}$$

$$T_1 = k_r * \theta + c * \omega + T_A + T_k(\theta) + T_c(\omega) + T_A(t) \tag{7}$$

$$T_2 = -T_1 \tag{8}$$

where: θ is current angular displacement of the RSDA, θ_j current angular displacement of the attachment joint (this angle is measured in the joint's first reference frame between the two x-axes; from the first reference frame's x-axis to second), θ_u $t$he undeformed angular displacement of the RSDA defined by the orientation angle variable, T_1 the moment applied to body 1 about the rotational axis of the attachment joint, T_2 moment applied to body 2 about the rotational axis of the attachment joint, k_r $r$otational stiffness constant coefficient, c rotational damping constant coefficient, ω relative rotational velocity of attachment 2 measured in body 1's reference frame, T_A constant actuator torque, $T_k(\theta)$ torque as a function of relative rotation (Variable Rotational Stiffness), $T_c(\omega)$ torque as a function of relative velocity (Variable Rotational Viscous Damping) and $T_A(t)$ torque as a function of simulation time (Variable Moment).

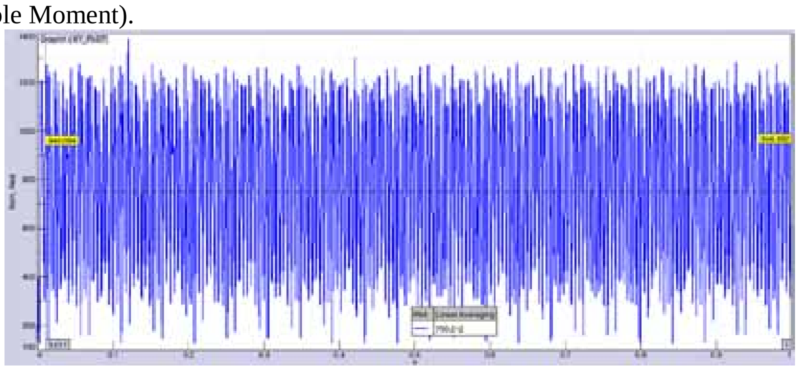

Fig. 9. Torque obtained in pump mode

For an applied torque 250 Nm on one of the shafts, the resulted torque has an average at 790 Nm on the other shaft (figure 9).

5 Conclusions

The paper presents the results of a multi-domain and multi-body study for a hydrostatic hybrid drive system and the resulted forces and torque obtained correspond with the expected result.

The synergy between the two simulations of the same system provides a good baseline for further studies regarding the mechanical behavior resulted after further system modifications (i.e. variable swash plate angle, increase resistive torque, drive-shaft torsional behavior). Although a number of items can be viewed and taking into account from the 1D model, without its 3D representation some aspects can never be revealed. Through further research the system can provides a valid alternative to hybrid technology for powering future's vehicles.

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