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MATEO

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Design description of the object-oriented library for mechatronic electrohydraulic systems

Deliverable 6.1

1 Document Scope

In this document the main characteristics of an object-oriented library for the dynamic simulation of electrohydraulic actuation devices are briefly outlined. The library, which exploits the unique features of Modelica language in terms of modeling acausality, modularity and reusability, allows user to simulate and analyze the dynamic behaviour of high performance electrohydraulic actuators, such as those based on recent DDV (*Direct Drive Valve*) technology. The library has been developed taking the best from existing Modelica libraries finalized to hydraulic systems modeling; in particular, two existing libraries has been considered:

- *Modelica HyLib* [3]: without doubt, the reference point for hydraulic systems modeling in Modelica, but unfortunately not up to date and deficient in actuator models. It is a commercial library.
- *Modelica Fluid*: it exploits advanced paradigms for a clever description of media but it appears too much complex for control oriented oleodynamics applications.

2 Library Structure

The library is structured in subpackages, in order to distinguish from different physical domains (hydraulic, mechanical, electrical) and different levels of abstraction (interfaces, basic components and extended components), using an approach typical of object-oriented languages for multidomain system description (see fig. 1):

2.1 Hydraulic Domain

The Hydraulic subpackage includes all the mathematical models and abstract interfaces necessary in the description of a generic fluid powered system:

1. Interfaces:
   - Definition of an abstract media object for hydraulic fluid (*PartialOil*), encapsulating the physical properties of a generic mineral oil (nominal density ρ, bulk modulus β based on Hoffmann's model, dynamic viscosity μ, vapour pressure, etc.)
   - Choice of specific mineral oil models (MIL-H-5606, MIL-H-83282, Constant bulk modulus, etc.), using an *extends PartialOil(.)* construct.

- Definition of a general hydraulic connector, including an abstract *replaceable package Oil* and using pressure p as effort variable and mass flow rate $\dot{m}$ as flow variable.
- Description of "Superclasses" of abstract hydraulic components, with 1,2,4,... hydraulic ports and monodimensional mechanical flanges (rotational and translational), having internal storage or not.

2. A complete collection of both basic and extended hydraulic components (fig. 2), among which ideal flow/pressure sources, volumetric pumps, hydraulic resistances (laminar/turbulent), lumped volumes, elastic pipes, check/relief valves, pressure/flow sensors, single/tandem proportional valves and single/tandem linear actuators.

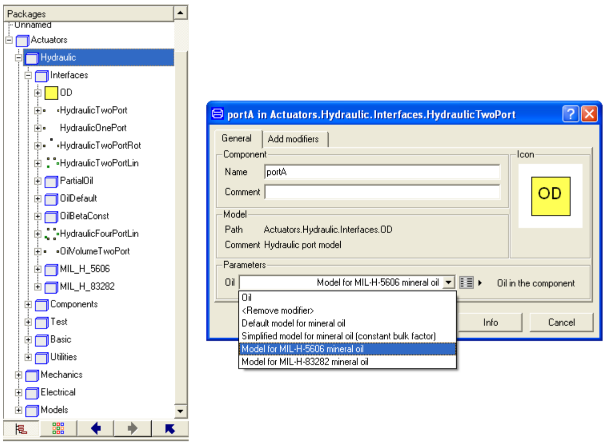

Figure 1: The structure of the library

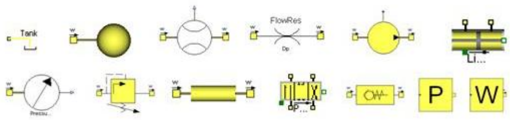

Figure 2: Hydraulic basic components

2.2 Electromechanical Domain

In this subpackage, different models are provided in order to ensure to the library the capability of describing the electromechanical components of the actuator with a high level of detail (eccentric shaft, stiff end stops, nonlinear translational/rotational LuGre friction model, quadruplex DC motor and driver, LVDTs,...). No specific interfaces are defined here, since the *Modelica Standard Library* already provided basic connectors and components for the mechanical and electrical domains.

2.3 Models

In accordance to the modularity principle, the components provided in the previous subpackages may be used in order to easily assemble models of electrohydraulic actuators of different level of detail, redundancy and complexity, depending on the specific modeling and simulation needs. Two DDV actuator models have been already included in the library:

1. High-detail, redundant, DDV actuator (fig. 3):
   - Proportional valve model with dual concentric assembly for the spool and tandem assembly for the valve body, internal leakages [2, 9], spool land overlap/underlap [1], internal flow forces [7], empirical transition from laminar to turbulent flow; jam condition can be simulated with a switched friction and inertial model for the spool.
   - Quadruplex DC motor and driver.
   - Tandem linear actuator model, with internal leakage, nonlinear friction, mechanical end stops, elastic support and external load.
   - Different fault conditions can be simulated (valve jam, pressure loss, electrical failures and control faults).
2. Medium-Low detail DDV actuator
   - Ideal 4/3 proportional valve with single hydraulic line, turbulent flow, land underlap/overlap and no internal leakage [5].
   - Steady-state electrical response
   - Single, linear, actuator with linear friction, internal leakage, elastic support and mechanical interface to external loads.

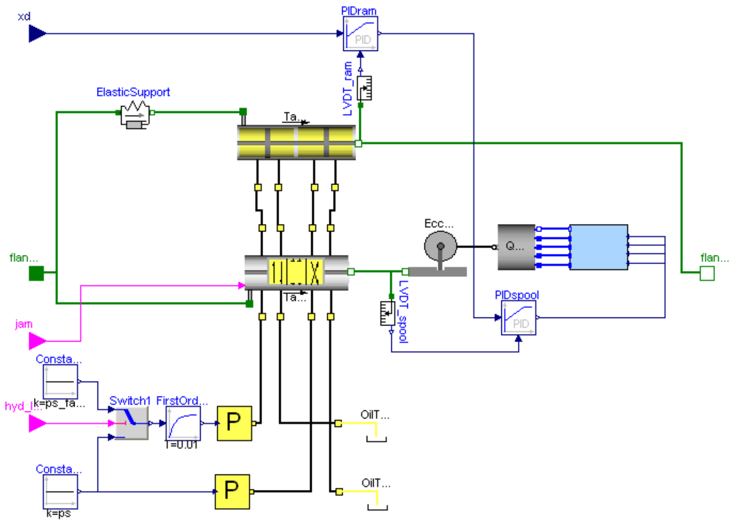

Figure 3: High-detail DDV actuator model for fly-by-wire applications

3 Proportional valve detailed model

This paragraph offers an overview of the mathematical model used for the description of the proportional valve. The main scheme adopted for a single valve assembly is reported in fig.4, where the four main volumetric flows of the valve are defined $Q_{1s}, Q_{1r}, Q_{2s}, Q_{2r}$. The ports signed with "s" and "r" connect the valve, respectively, to the supply line and to the return line, while the ports called "1" and "2" are the control ports, which connect the proportional valve to the linear actuator (hydraulic cylinder). Flow balance equations imply that:

$$\begin{aligned} Q_1 &= Q_{1s} - Q_{1r}, \quad Q_2 = Q_{2r} - Q_{2s} \\ Q_s &= Q_{1s} + Q_{2s}, \quad Q_r = Q_{1r} + Q_{2r} \end{aligned}$$

These flows are defined for every spool position, thus describing main flows and leakage flows. Each flow rate is related to the spool displacement and pressure drop according to a turbulent or laminar flow law, depending on Reynolds number. An easy way to describe a $\mathcal{C}^0$ transition from laminar to turbulent flow consists in adopting a semi-empirical model similar to [2], based on the definition of a critical spool displacement x_0, which takes into account spool land overlap or underlap conditions. For example, let us consider the case of flow Q_{1s}:

$$
\begin{aligned}
m_r &= C_d w \sqrt{\frac{2}{\rho}|p_s - p_1| \operatorname{sgn}(p_s - p_1)} \\
q_r &= \frac{\pi D C_r^3}{12\mu} \frac{p_s - p_1}{x_{up} - x_0} - x_0 m_r \\
x_0 &= x_{up} - \sqrt{\frac{\pi D C_r^3}{12\mu} \frac{p_s - p_1}{m_r}} \\
Q_{1s} &= \begin{cases} \dfrac{\pi D C_r^3}{12\mu} \dfrac{p_s - p_1}{x_{up} - x_v} & \text{for } x_v \le x_0 \\ m_r x_v + q_r & \text{for } x_v > x_0 \end{cases}
\end{aligned}
$$

where C_d is the valve discharge coefficient, w the valve area gradient, ρ the oil density, μ the dynamic viscosity, D the spool land diameter and C_r represents the spool radiance clearance. This approach allows to match in a fairly realistic way the experimental behaviour of real proportional valves, in terms of pressure sensitivity and internal leakage [9] (fig.5).

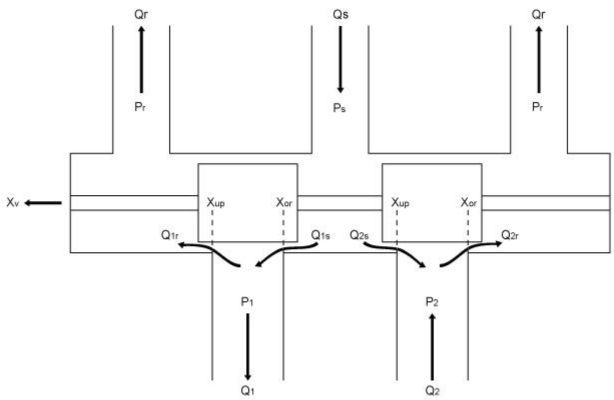

Figure 4: Geometry of 4/3 proportional valve

Moreover, the proportional valve model implemented in the library allows user to enable the effect of approximated flow forces acting on the spool, according to the mathematical model proposed in [7]; these forces enter in the spool dynamic balance performed in the mechanical domain. Figure 6 shows the model scheme for a generic tandem proportional valve with nonlinear friction model and centering spring: green lines represents 1D mechanical connections, while black lines represent hydraulic connections.

4 Hydraulic cylinder model

The pressure dynamics inside the two actuator chambers (in a single cylinder assembly) has been described using the well-known flow balance equations:

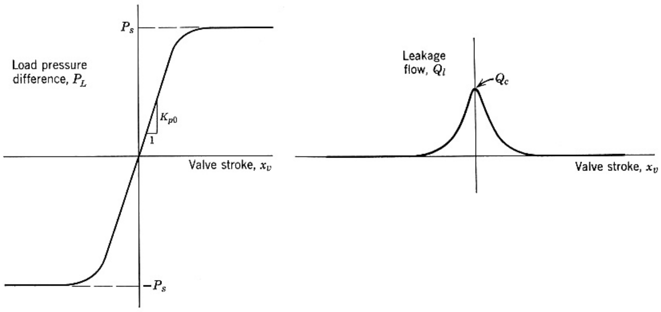

Figure 5: Typical experimental behaviour of proportional valves

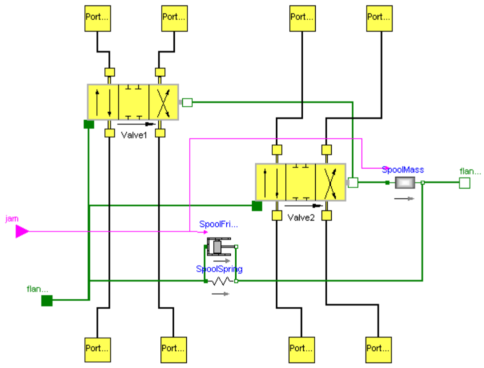

Figure 6: Tandem valve model

$$\dot{p}_1 = \frac{\beta}{V_1(x_p)}[Q_1 - A\dot{x}_p - k_l(p_1 - p_2)]$$

$$\dot{p}_2 = \frac{\beta}{V_2(x_p)}[-Q_2 + A\dot{x}_p + k_l(p_1 - p_2)]$$

where β represents the oil bulk modulus, V_i denote the volume of chamber i (variable with piston position x_p), A is the actuator area and k_l is the leakage coefficient. The force provided by the actuator, needed for integrating the overall actuator dynamics, is simple $F_m = A(p_1 - p_2) = Ap_L$. Using standard interfaces and connectors for 1D mechanical translational components and exploiting the hydraulic model described above, it's easy to assemble a complete tandem actuator system including nonlinear friction model and mechanical end stops, as can be seen in fig.7.

Exploiting the two external mechanical flanges, it's possible to connect an external load model to the ram and an elastic or rigid support constraint to the actuator body.

5 Conclusions and outlook

In this document a brief description of the object-oriented library for the dynamic simulation of electrohydraulic actuators was given. Starting from existing Modelica libraries, it was shown how to design a new library responding to the specific modeling requirements of fly-by-wire actuators, exploiting the advantageous features of the language. The library is structured in a hierarchical way, starting from the abstract definition of media, interfaces and connectors and arriving to the detailed description of complete and specific mechatronic systems. The assessment of the performances of the

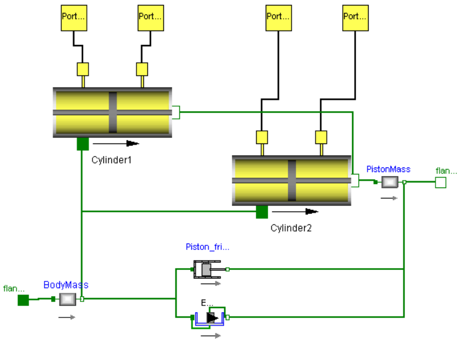

Figure 7: Tandem actuator model

implemented library in a realistic case study (helicopter boost servos) will be pursued and described in a forthcoming document.

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