REPRESENTATION OF POWER FLOWS FOR THE CONCEPTUAL DESIGN OF HYDROMECHANICAL DRIVES

JEAN-CHARLES MARE, PAULINA ILJASZEWICZ
Institut Clement Ader, Toulouse, France
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jean-charles.mare@insa-toulouse.fr

This communication deals with the graphical representation of power flows in hydromechanical drives, for use in systems-engineering activities. It points out the need for standardized symbols in mechanics to complement the well-established standards in electrics and hydraulics. Once identified and listed, the mechanical functions are arranged by classes and subclasses, which define the main families of symbols to be designed. A functional view is favoured. Proposals are made for symbolisation in order to improve the readability of the diagrams dealing with multi-physical systems. This is illustrated with the example of the Airbus 320 yaw control, which combines mechanical, electrical and hydraulic devices in a complex architectural arrangement. This work contributes to make foundations for the development of a modern standard of mechanical symbols.

KEYWORDS
Architecture, conceptual design, hydromechanical drives, simulation, symbols

1 INTRODUCTION

Schematics of diagrams offer a powerful means of graphical representations to support of the Model-Based Design (MBD). When dealing with systems, these schematics involve numerous graphical symbols related to many technical domains. In most of the fields, these symbols have been standardised to facilitate the use of schematics as a shared and univocal means in collaborative or client/supplier activities.

When it is intended to represent graphically the power flows and their control, actuation systems are particularly concerned. Electrics and hydraulics, two main domains in actuation systems, provide good examples of symbols standardisation: IEEE/ANSI 315A or CEI 60617/60082 [IEC 2012] for electrics, e.g. SAE AS1290C [SAE 2021] for hydraulics. Both of them started to be developed in the mid-seventies. An example of diagram using standardised symbols from electric and hydraulic domains is given in Figure 1 for an Electro-Hydrostatic Actuator (EHA), like those recently introduced in the latest aircraft programs [Mare 2018].

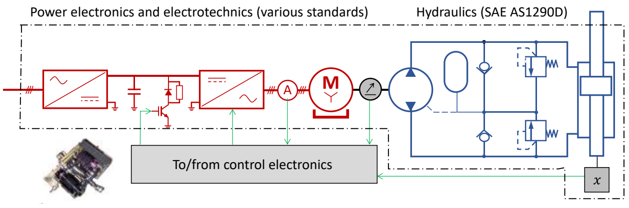

Figure 1. An example of schematics for an EHA

The left-hand side, depicts the electric drive while the right-hand side represents the hydromechanical part. If they are common with these types of schematics, the readers can rapidly identify the functions implemented. A glance is enough for the reader; a technician, an engineer or even a manager, to understand how the system works, identify its functions or proceed to troubleshooting. There are however other disciplines that lack from standardized symbols, causing potentially issues when it comes to e.g. synthesise architectures, analyse response to faults or even build lumped-parameters models for simulation. This is particularly true for mechanics, although it is present in any actuation or propulsion system. In order to compensate this lack, each actor (e.g. simulation software supplier) finally designs his own set of mechanical symbols. Of course, some authors already addressed the graphical representation of mechanical systems, for example [Muller 1991] and even [Wolf 1958]. However, they mainly address topologies or kinematics. Existing standards for mechanical power transmission (for example [ISO 2003] and [ISO 1981]) are only partial and to no suit the need for a top-level architectural view in power transmission. This lack puts a high penalty on work sharing, capitalisation and readability.

Instead of drawing provisional symbols, some get past this issue and represent elements by blocks with the description written inside them [Mare 2020]. This lacks of lack of efficiency because too many words are needed in comparison with a clear symbol (when possible) of the element considered. These considerations have suggested to engage the present work in order to define foundations for the symbolisation of mechanical devices.

In hydraulics, most of the symbols standards are structured in functions (or in purposes that the element serves) For instance, [SAE 2021] considers fluid conditioning, energy conversion, control of power, etc. This is not a common practice for electrics and electronics, which standards are mainly structured in components: switches and relays, resistors, capacitors, semiconductors, etc. Less frequent is the structuration by function, e.g. production/transformation of energy, or control and protection.

When it is found important to provide additional information, the symbols must be made more explicit This is achieved by variants, or sub-symbols that depict the secondary functions or features, or the technological realization of the element (which implies its merits and constraints). This is for instance the case in hydraulics for the symbol of hydraulic cylinders, which can be augmented to indicate snubbing or locks at rod end. Another example is found for accumulators, whether they are gas- or spring-loaded. Compound symbols are also of interest to represent in a compact and explicit graphics a set of elements that are combined to perform a given function, see e.g. filter assemblies in [SAE 2021].

2 IDENTIFICATION OF FUNCTIONS

Diagrams or graphical representations meet particularly well the need to represent a given system, i.e. an "organised set of elements interacting elements that interact with each other and with the system environment to produce functions that they could not provide individually". Therefore, a diagram involves basically symbols for elements and for connections.

2.1 *Mechanical elements*

In the present work, it is proposed to organize the symbols of mechanical elements at first by function. This makes it consistent with the development activities in the top-down Systems-Engineering process. This choice applies well to primary or secondary flight controls in aerospace, which often involve complex mechanical arrangements. A typical example is given in

Figure 2. It displays the diagram of the yaw control for the Airbus A320 family. The top figure mainly shows the topology of the system and the shape of the mechanical and hydromechanical elements. The bottom figure is more centred on the flight control topic and includes both electric signalling and mechanical linkages.

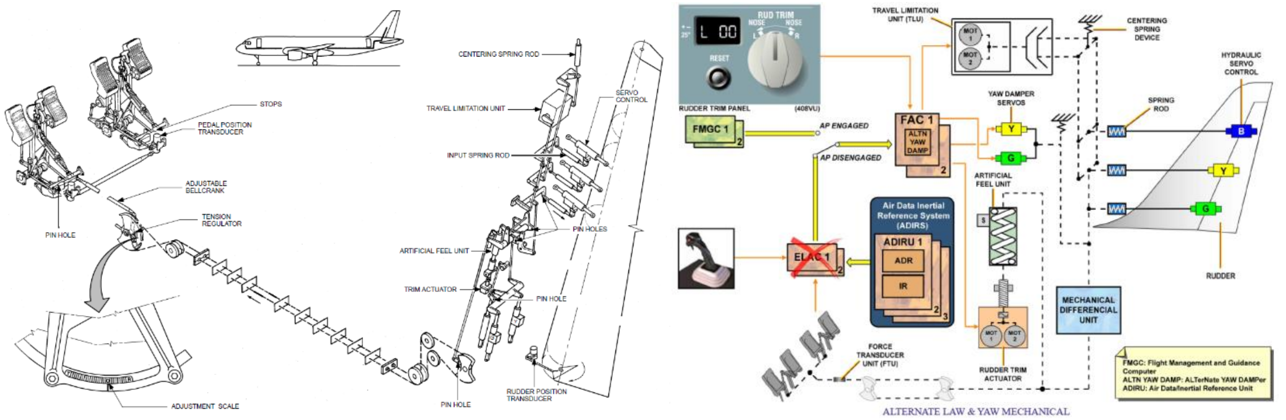

Figure 2. The Airbus A320 yaw control (left: representation centered on mechanical linkages [Lufthansa 1997], right: representation centered on flight controls [BAETC 2008]).

As these figures are made for training, they mainly display how the considered system works. None of them uses standardized symbols. They mainly mention the elements involved, making it difficult to identify with a system-level view the functions implemented and how they interact. Numerous other examples deal with complex mechanical power system, either between the actuator and the driven loads (e.g. slats and flaps actuation) or even internally to the actuator (e.g. trim horizontal stabilizer actuator or pylon conversion actuator [Maré 2018]).

As a first major task, the authors have made a detailed review of the functions used in mechanical power systems, with special focus on those involved in the power flows. Among all candidate options, they had to make decision regarding the definition of the classes of functions. This is not an easy task because there are multiple overlaps: depending on the context or the point of view, a given element can either be attached to one class or another. This limit has to be accepted. Finally, the authors have chosen to define four classes only, however with sub-classes:

a) Power conversion devices

Power conversion devices enable power to be exchanged between mechanics and other domains, basically electrics (e.g. motor or generator), thermal (e.g. engines), fluid power (e.g. cylinders or fans), muscular (e.g. pedals or push-buttons). Therefore, these elements are located at the boundary of the considered mechanical system, and can be seen as power interfaces between domains. In order to ensure consistency, the symbols of these power conversion devices must be identical to those already existing in other domains. As an external source of external force on solids, gravity or magnetic field can also be included in this class.

b) Power transmission

Transmission can be understood in different ways. E.g. in the automotive industry, transmission deals with the set of elements that transmit power from engine to wheels. In the present work, it has been found better to define the power transmission devices as single-input - single-output ones, being functionally power-conservative. Additionally, it is proposed to define two subclasses:

- Power transportation. This applies to devices that transmit power in space only (e.g. rod, flexible shaft or gimbal joint), without any functional change in the type and magnitude of the speed and force[1] power variables.

- Power transformation. This applies to devices that transmit power with a change in the power variables, either in type (linear or rotary, e.g. nut-screw or lever arm) or in magnitude (low/high speed or high/low force, e.g. nut-screw or gear pairs).

c) Power management

This class deals with mechanical devices that act on the propagation of the mechanical power variables. Two subclasses have been defined:

- Routing. The routing devices aim at setting how the mechanical power flows in the considered system. The power path is open or closed with a clutch (force to load made null when declutched) or brake (load speed made to null when braked). Merging power from multiple sources or splitting power between different users is commonly needed in redundant or hybrid systems. This is achieved by speed- or force-summing devices (e.g. differentials, combining gears, levers or horns).

- Protections. Protection devices aim at introducing limits in the propagation of the power variables, or of their combination. As some of them are not so common, a clarification[2] is welcome. In this attempt, two main sub-classes can be defined.

▪ Devices inserted in the power path

- Force limiter

  If the force to load reaches the maximal value, there is a slipping between the drive and load speeds at (functionally) constant transmitted force. In this situation, the load speed depends on the max force transmitted from drive and is no more imposed by the drive speed.

- Mechanical fuse

  If force reaches the maximal allowed value, then no more force is transmitted to the load. The fuse can be resettable or require a replacement. This is functionally equivalent to an irreversible declutching when the maximal force is reached.

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[1] The word "Force" has to be understood as force or torque depending it refers to translational or rotational motion.

[2] The view (power or signal) to be used for modelling the device may depend on the ongoing engineering task, e.g. simulation or architecting respectively.

  - Freewheel

    The force transmitted to the load can be only positive, otherwise the load is freed (its speed is no more imposed by the drive). This is functionally equivalent to clutching the load to the drive only when the load is opposite, not driving.

- Devices acting between the power path to load and housing (or supporting frame):
  - Ratchet wheel

    The load is blocked if it tends to move in the wrong direction. This is functionally equivalent to a brake activated by the direction of the load motion.
  - Irreversor

    The load is blocked if it becomes driving. This is functionally equivalent to a brake activated by the direction the power flow to the load.
  - End-stop/Travel limiter

    Bounds the position of the driven load. Travel limiter implements a variable end-stop.
  - Cushioning (or soft end-stop)

    Limits transient forces during shock on stops.

d) Power conditioning / miscellaneous

Several mechanical functions can be used to condition the power transmission. This is basically achieved with resort to energy storage (spring or inertia effect) or dissipation (frictional effect). This makes the first sub-class of basic effects. The most generic functions performed are:

- damping, to avoid vibrations with resort to energy dissipation;
- preloading, to remove backlash and increase the transmission stiffness by energy storage;
- storing kinetic energy, e.g. to limit the effect transient force demand transients on speed;
- avoiding overstress by increasing mechanical compliance, e.g. backlash or flexible joint, under hyper static or thermal dilation effects.

The second sub-class is introduced for interfacing the mechanical domain with the signal world. It deals for the sensing of mechanical quantities like position, speed and force.

All these proposals are summarised on Table 1, where the last column gives the most generic examples of technological realisation. It is worth remarking that a given mechanical element can belong to different classes depending its effective use in the considered system: for example a epicyclic reducer can be use to perform a high ratio power transformation, or to sum the power of two shafts to a third one, or both. The use of classes is however totally justified when focus is put on functions and not on technological components.

Class/sub-class	***Details***	***Examples of concept or technological realization***
Power conversion	From/to electric domain	Electric motor or genator, voice coil
	From/to fluid power domain	Pump, cylinder, fan, compressor, jet
	From/to human muscles	Pedal, push-button, lever
	From thermal	Engines
	From external field	Gravitational, magnetic
Power transmission		
Power transportation	Rigid	Shaft, rod
	or flexible - lumped	Gimbal
	or flexible -distributed	Rope or cable, flexshaft
Power transformation	Linear <--> rotary	Cam, nut-screw, lever arm, rack and pinion
	High speed, low force <--> high force/low speed	Positive: gear pairs (spur/bevel/worm), chain and pinion By friction: V-belt and pulleys
Power management		
Power routing	Split/merge power - Force summing	Combining gear, fixed joint
	Split/merge power - Speed summing	Horn, differential
	Open/close power path under control	Clutch, brake
Protections	In series in the power path	Torque limiter / spring rod, mechanical fuse (or shear pin), free wheel
	Between the power path and housing	Rachet wheel, irreversor, endstop, travel limiter, cushioning
Power conditioning / miscellaneous		
Basic effects	Pre-loading (potential energy storage)	Spring, gravity force
	Damping	Friction discs
	Speed smoothing (kinetic energy storage)	Inertia wheel
	Limiting overstess	Backlash or flexible joints
Sensing	Measurement of mechanical quantities	Position, speed, force sensors

Table 1. A proposal for symbol classes and sub-classes in mechanics

2.2 *Connections between mechanical elements*

a) Meaning

Connection lines display the structure of a diagram. The Bond-Graph formalism [Tiller 2001] uses power bonds, which are associated with the pair of power variables, e.g. volume flow rate and pressure in hydraulics, current and voltage in electrics, speed and force in mechanics. Although it provides a uniform and powerful means of representation and analysis, it has not spread out in industry because it takes time to learn and use it efficiently. In the standards dealing with graphic symbols, the connection lines are rather associated with a single power variable which the reader can imagine flowing (the "through" variable [Tiller 2001]): flow rate in hydraulics, current in electrics or even heat flux in heat transfer. By the way, the graphical representation has roughly the same topology as the real system. In mechanics it is therefore logical to associate the connection lines with motion (the speed power variable). This is also what is done in the simulation software.

As a consequence, any node between connection lines indicates that all the attached devices have the same motion (or pressure or voltage), while their forces (or volume flow rates or currents) sum algebraically. In mechanics, a connection node has finally to be understood as a force summing function action on a rigid assembly.

b) Variants

Using different representations for the connections lines facilitates reading and understanding. For example, it makes difference between the high pressure or low pressure in hydraulics, or the number of wires in electrics. In mechanics, it could be worth to make difference between translational and rotation motions, or between low- and high-power lines. It could also be proposed to add a label to each connection line to indicate the functional axis of motion, for example Tx_1 for translation on axis x_1, or Rz_3 for rotation around axis z_3 This would facilitate the links with the spatial view and the model implementation for simulation.

2.3 *Interfaces of mechanical elements and continuity with existing standards*

Two main issues can be identified when it is intended to make diagrams of Multiphysics systems. Firstly, the existing standards are designed for black and white graphics only. This puts a high penalty on readability, for example for the connection lines, as displayed in the second column of Figure 2. Secondly, the existing standards only consider the mechanical domain at their interface, generally. This is clearly illustrated by the last column of Figure 3 for hydraulics and electrics, where the lines or interest deal with hydraulic or electric, respectively.

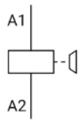
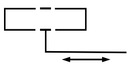
	Power line	*Brake*
AS 1290C (hydraulics)	High pressure	
IEC 60617 (electrics)	Wire	

Figure 3. Limitations introduced by use of black and white symbols only

In the 2020's, it might be time to introduce colours, in particular for making distinction between the technological domains, like already done in some simulation environments, for example Simcenter AMESim©. Assigning one colour to a given technological domain could offer an efficient means to keep all existing standard symbols. For multi-physical systems, it could greatly increase readability and avoid any ambiguity.

2.4 *Reaction load path*

In practice, any change in direction, magnitude or momentum in the functional line of a mechanical power transmission involves reaction loads. For example, linear electromechanical actuators need axial thrust bearings, and anti-rotation tabs or splines. Beyond the power path, the use of diagrams to represent the path of reaction loads has consequently many interests. Addressing the reaction load path is particularly important in conceptual design to properly choose, select and then size the involved elements. This is even magnified when it is intended to use multiple load paths to meet the reliability requirements by combining backup and active power channels and load paths. It is also important to pay attention to the parasitic motion of the supporting frame (or the device housing), for example regarding vibration or positioning accuracy under load. In this case, reasoning in terms of relative motion and assuming implicitly that the housing is at rest are no more sufficient (and acceptable if inertia effects are considered). Displaying the reaction load path will also implicitly facilitate friction calculation as it depends on the relative velocity, for example between inner and outer rings of bearings. This is why it is worth enabling the mechanical path of reaction loads to be displayed. This corresponds to the low (atmospheric, or vacuum) pressure in hydraulics and to the ground (or 0 voltage) in electrics. When it is worth to be considered, the reaction load path will add ports to the mechanical symbols. This is easily illustrated with the example of a nut-screw system. Displaying the reaction load path will show the elements that hold the rotating side in translation (making functionally a hinge joint) and the translating side in rotation (making functionally a prism-pair joint). Consequently, it becomes easy to include for example a shear pin in the axial force reaction path to free the actuator rod in case of nut-screw jamming (after shearing the hinge joints becomes a cylindrical pair).

3 APPLICATION

3.1 *Description*

The yaw control of the Airbus A320 family, Figure 2, is used to illustrate the above matters. This example is rich because it mixes mechanics, hydraulics and electrics. The mechanical chain is quite complex, with numerous mechanical functions involved. Basically, the yaw control of the aircraft is achieved by steering its rudder. For redundancy reasons, the single rudder is actuated by 3 hydraulically-supplied, mechanically-signalled, moving-rod linear actuators, which sum their forces on the rudder. Each actuator is energized by a different hydraulic power network (green, yellow or blue). In the human pilot mode, the position setpoint is imposed at the cockpit by the pilots through the pedals. It is then propagated to the input lever of the actuators, about 30 m far. Several functions make this mechanical chain, like:

- getting the pilot's demand through the pedals,
- limiting the pedals travel by end-stops,
- merging the pilot's actions through force summing,
- transmitting the demand to the aircraft rear,
- conditioning the push-pull cable transmission with a tension regulator,
- splitting the position demand to feed each actuator by force summing,
- making the actuators independent by ensuring tolerance to the jamming of one actuator main valve, with spring-rods at actuator demand input,
- forcing the position demand to neutral in case of broken mechanical transmission, with the centering spring device.

The yaw control also involves a lot of other functions to enable automatic and stable flight. Due to the step- by-step evolution of flight controls, they appear as add-ons that are integrated on the mechanical chain. Some of them act in a force summing arrangement:

- limiting the rudder travel to avoid overstress at high airspeeds, with adjustable stops, set irreversibly by torque summing duplex electrical actuation,
- adding an artificial force feel, with a spring effect, which preloading is irreversibly set by a simplex electrical solenoid.

Other act in position/speed summing:

- trimming the yaw position demand through duplex electrical, torque-summed actuators with torque limitation and non-locking stops,
- yaw damping to increase the aircraft stability and ensure turn coordination, with 2 electrically-signalled, hydraulically-supplied, force-summed linear actuators (the actuators are hydraulically declutched in case of failure, and the yaw dampers position is set to the neutral position with the yaw damper centering spring). In the auto-pilot mode, the yaw dampers are used to generate the position demand to the rudder actuators.

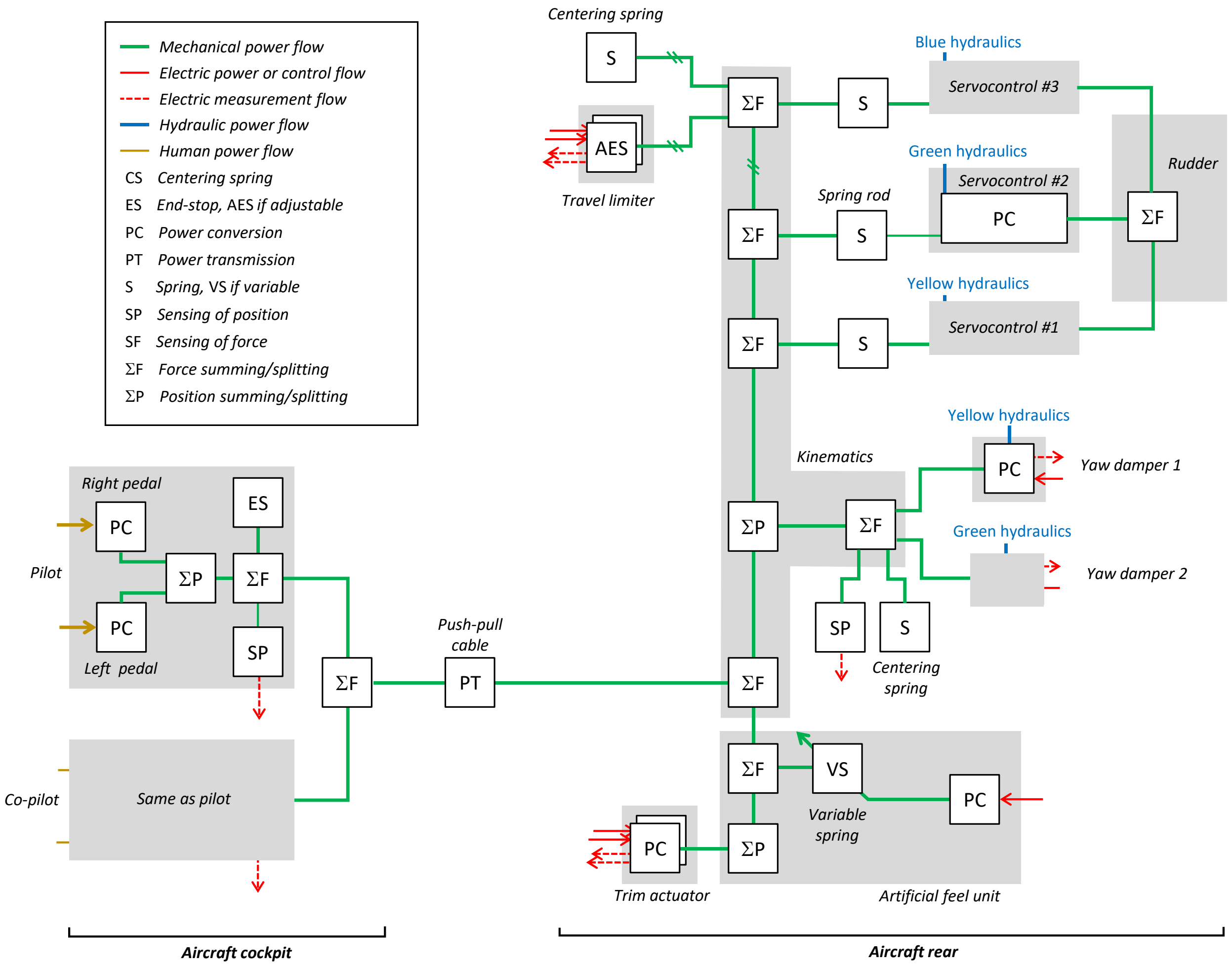


Figure 4. Tentative diagram for the Airbus A320 yaw control (no focus on electric signaling)

3.2 Diagram

The Figure 4 gives a tentative graphical representation of the power flows of the yaw actuation system. Emphasis is put on the mechanical domain. The figure only displays the interfaces to the electric/electronic domain as they are out of scope in the present context. For readability, the figure does not display the reaction load path. Waiting for pure graphical symbols, the authors have represented the functions by blocks showing the acronyms of the functions performed. A specific colour is allocated to each physical domain for connection between blocks. The displayed resulting functional architecture is augmented with the name of the physical unit or element. Redundant paths are represented by adding hatches on the connection lies as done for the travel limiter. For readability reasons, this is not applied to the electric connections.

3.3 Discussion

Several points of interests are worth being discussed:

- Force summing and position/speed summing. The figure could be simplified by replacing the ΣF or ΣP blocks associated with summing functions by a node and a sum symbol (as for control systems), respectively. In this case, all elements connected to a node have the same velocity, while all elements connected to the sum symbol sum algebraically their position and subject to the same force. There is however a risk that the reader only considers a single signal propagation (as in block diagrams) and forgets the real meaning of a connection line, which carries 2 power variables.
- Reaction load path. For readability, the figure does not display the reaction load path and focuses only on the functional degrees of freedom. In fact, any element interacts with its supporting frame towards its anchorage. A 3-D view would even consider the parasitic side loads generated in (or applied to) the moving bodies, for example for making a 6-Degrees-Of-Freedom simulation model. However, this 3-D view is out of the scope of a system-level diagram.
- Zoom in. The same type of diagram can be used to zoom in for a given element, as is done for example at a first level for the pedals assembly. This is facilitated by the presence of the element interfaces, which are displayed even if the element is not detailed. This applies for example to the servo controls and yaw dampers, which can be detailed using the standardized hydraulic symbols. This type of feature is well established for lumped-parameter models in the numerical simulation environments used for multi-physical systems, for example Matlab/Simulink, AMESim or Dymola.

- Evolution and update. Even if the inventory activity is done with care, it is impossible to imagine a priori all the symbols that may be needed, including for future products. Therefore, it is of prior importance to define rules or recommendations for the evolution and update of symbols, as done in [SAE 2021]. In particular because standards are revised every 5 years, in the best case.

4 CONCLUSION

Beside the well-established standards in hydraulics and electrics, a real need has been identified for symbols dedicated to the mechanical domain. However, it is clear that defining and standardizing graphic symbols (and associated rules for representation, extension, creation and combination) is a challenging task when it is intended to cover as much diagrams use cases as possible. This can only be achieved with an international collaborative work involving participants who cover the broadest fields of activities and applications. The present communication has provided a few considerations that could be used as foundations: identifying the functions performed as exhaustively as possible, organizing the symbols in functional classes, introducing colours to make distinction between domains, and enabling the reaction load path to be addressed, even for still housings or supporting frames. The proposals have been illustrated and discussed using the example of the Airbus A320 yaw control.

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CONTACT:

Pr Jean-Charles MARE
Institut Clement Ader - INSA Toulouse
135 Avenue de Rangueil, 31077 Toulouse Cedex 4, France
jean-charles.mare@insa-toulouse.fr

Paulina ILJASZEWICZ
Institut Clement Ader - INSA Toulouse
135 Avenue de Rangueil, 31077 Toulouse Cedex 4, France
p.iljaszewicz4312@gmail.com