Numerical analysis model of an Air Control Valve

The Bond Graph approach

Alexandru Giurgică[1,2*]

[1]Mechanics and Strength of Materials department at Universitatea Politehnica Timișoara, România
[2]Sensors and Actuators Continental Automotive, România

Abstract. Modern internal combustion engines currently use a multitude of electromechanical elements generically called actuators. Thus, within the high-level "engine" system, each actuator can be considered an element. At a further increase in detail, aforementioned high-level components can be regarded as lower level systems themselves commonly known as subsystems, with their corresponding components. Due to this aspect, the study and design of actuators is suited to a model-based systems approach where mechatronic elements need to be modeled hierarchically. The current paper proposes a method for obtaining such a model for an Air Control Valve, using the bond graph theory. Its target outcome is a numerically computable response (position) to an applied input (voltage) while keeping internal (design) parameters explicit. The model is intended for design space exploration and virtual system integration. The resulting dimensionally homogeneous model is given as a state-space representation along its graphical form as a block diagram in addition to the augmented bond graph.

1 Introduction

It can easily be observed that most functions of mechatronic systems are the result of multiple subsystem interactions in a multi-physics system. For example, adequate operation of a Diesel engines' common-rail fuel injection system relies on high pressure pumps, mechatronic pressure regulators and electronically controlled piezo-electric fuel injectors [1]. Such complexity makes it difficult to analyze the influence of a relevant parameter of a given component inside the mechatronic system without actually building and testing it. Multiple prototype loops add to cost and delay market entry. In order to avoid this and optimally design a product to fulfill the required functions, a model-based design approach is helpful. Barbieri et al described a model-based design methodology for the development of mechatronic systems in [2]. Virtual system integration in a high-level system model is employed in order to verify the functional compliance of subassemblies before fully developing and manufacturing the solution. Thus, multi-parametric numerical models are needed to enable the application of a model-based definition approach to mechatronic design. Due to the system under study having a multi-physics nature, the Bond graph method was chosen. This method allows the use of a generic set of elements and conventions, regardless of the physical domain to be modeled and is an ideal representation for mechatronic and micro-mechanical systems [11].

*giurgica.alexandru@student.upt.ro

The actuator under study is a control element belonging to a Diesel engines' emissions control system as can be seen in Fig. 1. The ACV is employed in order to modulate the pressure inside the engines' intake for the following functions:

1. Reaching the required volume of recirculated exhaust gas necessary for emissions regulation compliance.
2. Allowing Diesel particulate filter regeneration routines
3. Lowering engine shut-off vibrations by completely cutting the intake air supply (as opposed to fuel cut-off shut-down)

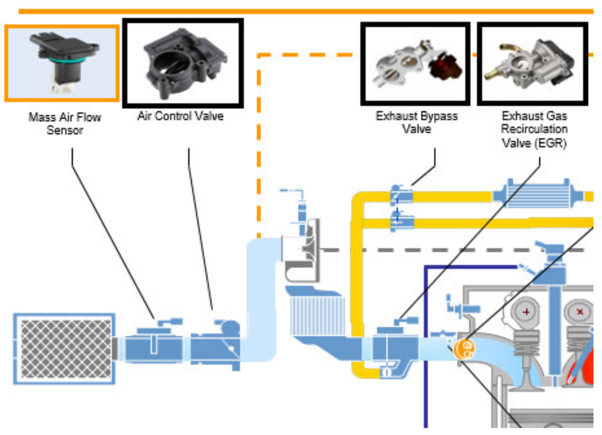

Figure 1. Air intake system. Generic Eu6 Diesel engine. Courtesy of Continental AG

The functional requirements of the ACV inside the higher level system are as following:

- Precise adjustment of flow
- Fast response time
- Default position current-less return
- Actuator position feed-back loop to the Engine Control Unit

It can be observed from the actuators' architecture exposed later on that the functions presented above are dependent on the devices' ability to quickly and accurately reach a desired position. Thus, from the functional point of view, the objective is proper positioning of a regulating element (throttle plate) to a required set-point.

A nearly identical device is the "Electronic Throttle Control" valve used in spark ignition engines. Its' main difference is the use of a second spring to enable a minimal intake flow in order to allow the driver to safely move the vehicle in a "limp-home" mode [3]. Such mechatronic devices were previously studied mainly from the control engineering point of view, and not from a mechatronic design point of view. An in depth review article on the subject is [3]. Virtually all mathematical models used in controller studies are in explicit, causal computable form (equations, block diagrams), as can be seen in [4], [5], [6], [7] among others. Notable exceptions are [8], [10] and [9] where acausal forms were used in the shape of Modelica models. In [8], the model is used for a multi-objective optimization in open-loop by a genetic algorithm, in [10] a set-based concurrent engineering approach is applied on the model for design space exploration while [9] uses it for preliminary validation of the controller. Bond graphs could provide an alternative to Modelica by removing the need for the user to rely on premade Modelica objects or programing custom ones. To date, the author has not found a published bond graph model of an electronic throttle actuator.

2 Methods

2.1 Bond graphs

Bond graphs are a diagrammatic form of writing the differential equations governing the dynamics of a system. The method uses the effort-flow analogy to describe energy interactions. These are represented by elementary components (bond graph elements) with one or more (power or signal) ports. The ports represent interfaces where interactions with other components are possible. The process found at a power port is described by a pair of variables: effort (e) and flow (f). These are called power variables, their product always resulting in a power function [15],[16]. Signal ports are ports where only information is exchanged (disregarding the power needed by the carrier signal), allowing a bond graph elements' characteristic parameter to be externally modulated. The particular aspect of interest in the method is the fact that it is not dependent on the physical domain to be modeled, allowing the creation of multi-physics numerical models [12], [11]. In the case of actuator study, this is advantageous because most actuators use a combination of mechanical, electromagnetic, hydraulic and other phenomena to fulfill the given function [14]. Aside from the multi-physics aspect, bond graph models can also be considered objects, making the method a form of "object-oriented physical systems modeling" [12], allowing models to be reused hierarchically. Last but not least, system models in bond graph form allow a separation of modeling itself from the resulting mathematical model and the solution derived from it. In this way, bond graphs can be used as a "visual modeling language" [17]. The fact has certain advantages for modelers coming from heavily visual engineering areas like mechanics / hydraulics and to some extent electronics [19].

2.2 Functional decomposition

The study was carried out on an existing actuator such that its' architecture shall be backwards analyzed in regard to its functional requirements. The actuator under study uses the transformation of electrical energy into rotational motion with the help of a permanent magnet brushed DC motor (PMDC) and a spur gear transmission. Their output shaft modulating the flow with the aid of a butterfly valve (throttle plate in a cylinder flow section). For devices using different operating principles, the same methodology can be applied, the only difference being the functional relationships between the parameters governing the physical phenomena involved. Invariably, the underlying law is the same, namely the conservation of energy [14]. In Fig. 2, a section through the actuator, it can be observed that the device was divided into the corresponding subsystems. Thus, we can identify these subsystems and the energetic interactions involved in fulfilling the functions mentioned earlier. Red arrows indicate energy accumulation and consumption while green ones represent supply.

- Precise adjustment of flow

  Involves all subsystems, starting from the motor as a source of movement, transformed through the gearbox finally reaching the throttle plate. At first, the spring has no direct role in the precise adjustment of flow but due to the fact that it always holds the system in balance by providing resistant torque, it helps mitigate the backlash in the gear-train thus eliminating start-up lag.

- Fast response time

  This function is influenced by the motor subsystems' performance, the total gear ratio, the spring characteristic, plate-shaft subassembly inertia as well as the total friction between moving parts.

- Default position current-less return

  Fulfilled by the spring subassembly in the case of power supply loss.

- Actuator position feed-back loop to ECU

  Function fulfilled by the magnet-sensor subassembly. Due to the fact that the magnet-sensor interaction is non-contacting, thus of marginal influence on the dynamics of the actuator, it was assumed that position sensing is done instantaneously. As such, this function is not under study in the current paper.

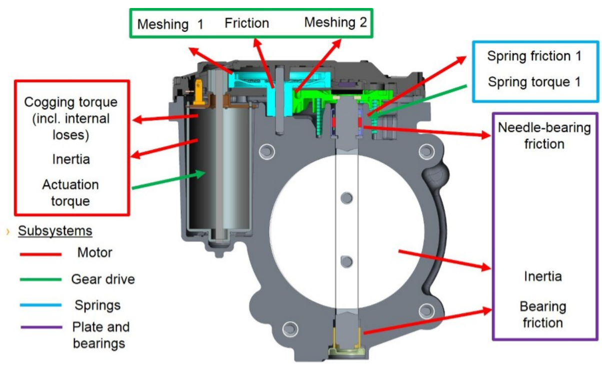

Figure 2. Section through the ACV actuator

Most functions are the result of multiple subsystem interactions. Due to this, the influence of a relevant components' parameter on the overall functionality of the subsystem is not easily assessed. If, for example, the motor is exchanged for one having a lower nominal speed at the specified voltage, keeping the gearbox identical will mean the response time would be increased. Potentially it could increase so much as to fail the requirement. Thus, building multi-parametric numerical models with which to evaluate the impact of such a change is justified. To facilitate in constructing the numerical model of the actuator, a schematic model was built. Here, only the relevant elements to actuator dynamics and the parameters describing them were represented (Fig. 3).

- Motor subassembly. The electrical part of the motor was modeled as a circuit with the armature inductance "L" and resistance "R" connected in series to the voltage supply (system input) "$e_{in}(t)$". The link to the mechanical domain is provided via the motor constant "k_m" as a transformation factor relating the armature current "$i(t)$" to the output torque "T". It was chosen as a non-controlled parameter because excitation is achieved by permanent magnets and not field coils. Lastly, regarding mechanical parameters, the armature inertia "I" and friction losses "F_f" were considered. Similar schematic abstractions of a PMDC motor is proposed in [16] and [13] among others but here the friction losses inside the motor bearings were also included.

- Gear drive subassembly. The two stage speed reducer of the actuator was modeled considering the number of teeth on each gear "N_1, N_{22}, N_{23}, N_3" ,the meshing losses "P_{A1}, P_{A2}" and the friction loss "F_F" on the mid-gears' bearing surface.

- Spring subassembly. The return spring was modeled taking into account its compliance "C" and the friction losses between coils "F_A".
- Plate and bearings. For this subsystem, bearing losses "F_{RA}" and "F_{LA}" as well as the subassembly inertia "J_C" were considered.

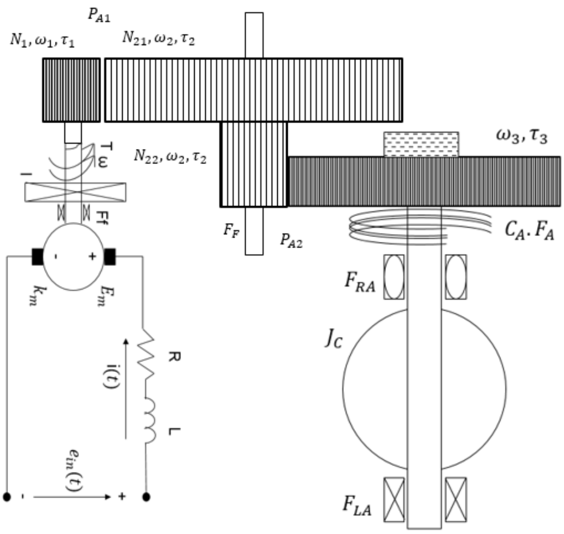

Figure 3. Schematic representation of the ACV actuator

2.3 Word model

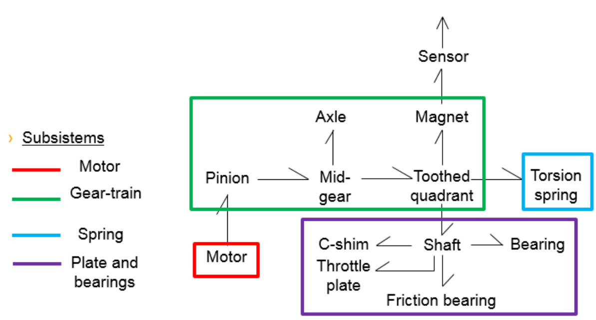

Figure 4. Word model of the ACV actuator

The first step in building the bond graph of the actuator is constructing the word model [17]. The word model is the transformation of the schematic representation of the system in a diagram consisting of the modeled components (represented by their designation) and the power bonds between them [13],[16]. Based on this word model, the components were individually modeled, taking into consideration only the physical phenomena relevant to the systems' dynamics.

2.4 Bond graph of the ACV actuator

The subsystems presented schematically above were then represented as bond graphs and combined to form the bond graph of the actuator (Fig. 5).

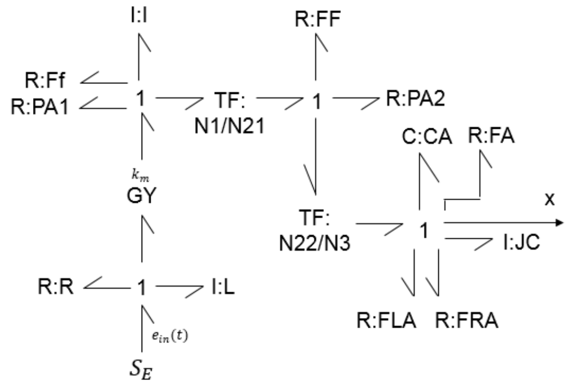

Figure 5. Bond graph of the ACV actuator

- Motor subassembly. The electrical part of the PMDC is modeled by a "1" type junction where the one-port elements: voltage supply "S_E", inductive element "$I : L$", resistive element "$R : R$" and the two-port gyrator "GY" are connected. The "1" type (constant flow) junction was chosen because the PMDC was modeled as a series circuit. As such, the electrical current represented in bond graph theory by the flow variable is constant. Next, because the armature is rigidly attached to the shaft and pinion they move at the same speed (equal mechanical flow). Due to this, the one-port inductance "$I : I$"(rotor inertia), resistance "$R : FF$"(motor bearing friction), resistance "$R : PA1$" (meshing losses on the first gear) and the two-port transformer "$TF : N1/N21$" are also connected to a "1" type junction.
- Gear drive subassembly. Its bond graph representation revolves around the "1" type junction between the two transformer elements "$TF : N1/N21$" and "$TF : N22/N3$". Here, the meshing losses on the second stage, represented by "$R : PA2$" and the friction losses in the intermediary gear by "$R : FF$" can be seen. The two transformer elements represent the speed reduction (as the ratio between the number of teeth on each gear) and losses can be expressed relative to speed, thus the common flow type "1" element is suitable.
- Spring, plate and bearings subassembly. Because the return spring (modeled by the capacitor element "$C : CA$" and resistor "$R : FA$") with the throttle plate (modeled by the inductor element "$I : JC$") are fixed together with the third gear of the gear-train, they are also connected to a "1" type junction. In addition, also attached to this junction are the resistor elements "$R : FLA$" and "$R : FRA$" modeling the speed dependent losses inside the bearings. The subassembly is connected with the rest of the system by the second port of the transformer element "$TF : N22/N3$". Finally, in order to output the position of the plate, a signal connection with the output variable "x" is added to the junction. Its value will be computed by integrating the common flow variable (angular speed) of the "1.4" junction as can be seen in Fig. 6.

$$x = \int f_4(t)dt \tag{1}$$

2.5 Causal analysis

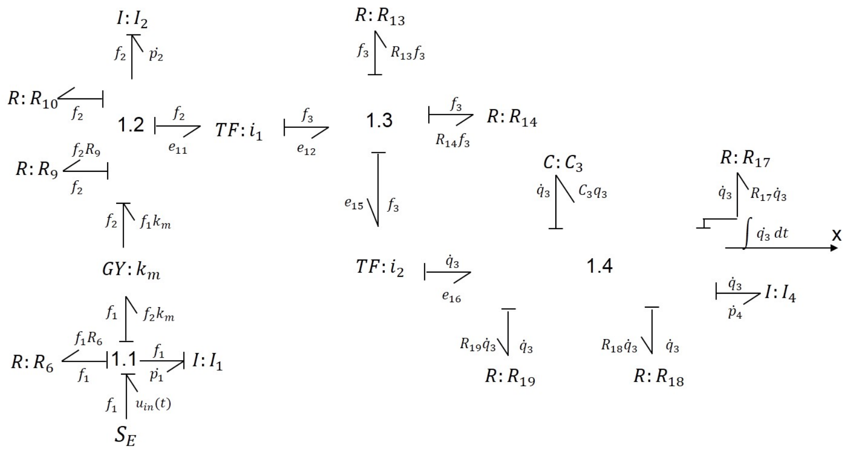

Figure 6. Causal bond graph of the ACV actuator

In order to derive a computable bond graph model, causal analysis was performed on each power bond. From the definition of the power bond, it is mandatory that the two power variables (effort and flow) are of opposite direction on each power bond [15],[16]. This is equivalent to the action-reaction paradigm used to describe physical interactions. Causal analysis can be restricted to attributing the port on which any of the two power variables is an input and, by definition, the other will be an output. Fig. 6 represents the causal bond graph, in which causality was determined on each power bond and the mathematical expressions for flow and effort were displayed. The energy variables were chosen as state variables, thus, the energy state of the system is defined at any point in time by the state variables. An energy storage element is independent if it can accept integral causality, consequently this is the preferred causality. If integral causality assignment is not possible, then the element is placed in derivative causality making it a dependent element, whose energy variable is algebraically related to the other energy variables in the system. This results in the state variables being represented by "p" type variables on I elements and "q" type variables on C-elements in integral causality [16]. Based on the system configuration, the junction properties and elements with imposed causality employed, each power bond was causally augmented. The sole element unable to be placed in preferential (integral) causality was the element "I:JC", meaning that the energetic state of the element "I:JC" is dependent (algebraically linked) on the state variables. This dependency has been accounted for while generating the state equations and resolved by algebraic manipulation. The sequential causal assignment procedure (SCAP) as described in [16] and [13] was used in order to generate the state equations. Onwards, the naming was done only by specifying the element type and adding a sequential index denoting its bond in the order causality was imposed (e.g. "R_{18}" represents the resistor type element attached to bond 18 and so on).

3 Results

By applying the primary and secondary conditions on the bonds' junctions (equality of flows and summation of efforts in the case of "1" type junctions) as well as the imposed causalities (on sources, gyrators and transformers) and solving the derivative causality of element

"I:JC" (by algebraic manipulation), the set of differential equations describing the systems' dynamics resulted:

$$\begin{cases} \dot{p}_1 = u_{in}(t) - a_{11}p_1 + a_{12}p_2 \\ \dot{p}_2 = a_{21}p_1 + a_{22}p_2 + a_{23}q_3 \\ \dot{q}_3 = a_{31}p_2 \end{cases} \tag{2}$$

With the coefficients involving only known (design) parameters:

$$a_{11} = \frac{R_6}{I_1} \tag{3}$$

$$a_{12} = \frac{k_m}{I_2} \tag{4}$$

$$a_{21} = \frac{I_2 i_1^2 i_2^2}{I_1(I_2 i_1^2 i_2^2 - I_4)} \tag{5}$$

$$a_{22} = \frac{i_1^2 i_2^2 (R_9 + R_{10}) + i_2^2 (R_{13} + R_{14}) + R_{19} + R_{18} + R_{17}}{I_2 i_2^2 i_2^2 - I_4} \tag{6}$$

$$a_{23} = C_3 \tag{7}$$

$$a_{31} = \frac{1}{I_2 i_1^2 i_2^2} \tag{8}$$

The parameters being:

$u_{in}(t)$ - Voltage at the motor terminals
k_m - Motor characteristic
R_6 - Electrical resistance of the motor
I_2 - Rotor moment of inertia
p_1 - Magnetic flux
p_2 - Rotor angular momentum
q_3 - Spring displacement
I_1 - Coil inductance
R_{10} - Mech. losses inside the motors' bearing
R_9 - Meshing losses in stage 1
i_1 - Gear ratio on stage 1
i_2 - Gear ratio on stage 2
R_{13} - Mech. losses in the bearing area of the mid gear
R_{14} - Meshing losses in stage 2
R_{17} - Mechanical losses in the spring
R_{19} - Mechanical losses in the needle bearing
R_{18} - Mech. losses in the friction bearing
C_3 - Spring compliance
I_4 - Shaft assembly moment of inertia

If the voltage at the motor terminals is considered to be known (because PWM voltage is the supplied input to the actuator) it is evident that the only unknowns of the system are the state variables p_1, p_2 and q_3. All other parameters are characteristic to the systems' chosen configuration.

 https://doi.org/10.1051/itmconf/20192902005

The system of state equations (2) above was put into standard matrix form:

$$\begin{bmatrix} \dot{p}_1 \\ \dot{p}_2 \\ \dot{q}_3 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & 0 \\ a_{21} & a_{22} & a_{23} \\ 0 & a_{31} & 0 \end{bmatrix} \begin{bmatrix} p_1 \\ p_2 \\ q_3 \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} u(t) \tag{9}$$

After generating the state equations and the state-space representation in matrix form, the bond graph was expressed as a block diagram (Fig. 7). This representation is easiest to follow for most engineers, given the much higher exposure of the engineering community to block diagram representation (eg. their ubiquitousness in automatic control systems as can be seen in the papers cited in section 1). The procedure used for expanding causal bond graphs into block diagrams of standard form is described in [16] and [12] among others. Comparing Fig. 7 to the "Mathematical model block diagram of electronic throttle body" in [3] it can be observed that they are nearly identical, proving the initial assumption that bond graphs are suitable for describing such mechatronic systems.

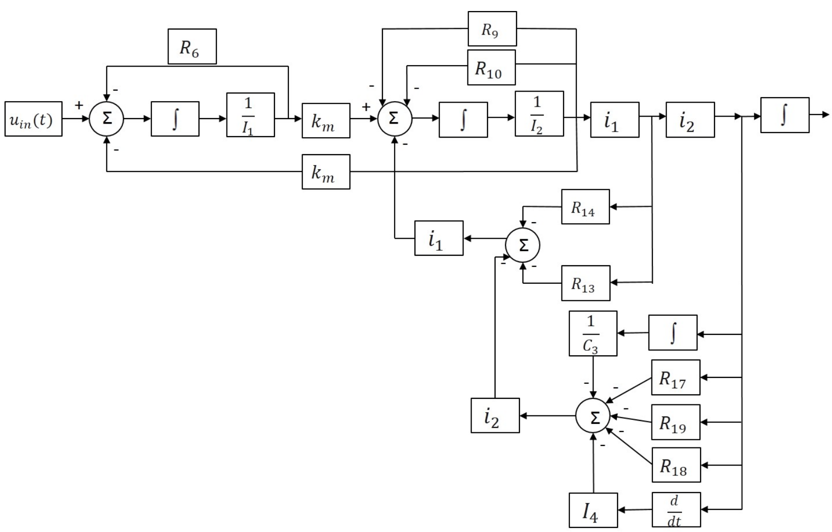

Figure 7. Block diagram of the ACV actuator

Although the model, as expressed in computable form by the augmented bond graph in Fig. 6 and the resulting system of state equations (2), can be used with a computer algebra system to study the dynamics of the actuator and the same with its corresponding block diagram but with signal analysis tools, this is not the bond graphs' main advantage. The power of the model lies in its acausal form as shown in Fig. 5. Here, one can easily attach controllers (simulated or implemented) via signal ports, other subsystems (simulated or implemented) via power ports and vary the system structure without invalidating the complete model. For example, an actuator with only a one stage gearbox can be considered. Starting from the acausal bond graph of Fig. 5, one can derive the bond graph of the one stage version simply by removing the "1" junction and its attached elements between "$TF : N1/N21$" and "$TF : N22/N3$" as can be seen in Fig. 8

Through the same sequential causal assignment procedure as used in subsection 2.5, the computable forms of the model can be derived. Although not previously mentioned, this step can be fully automated and one can go from inputing an acausal bond graph to a computable

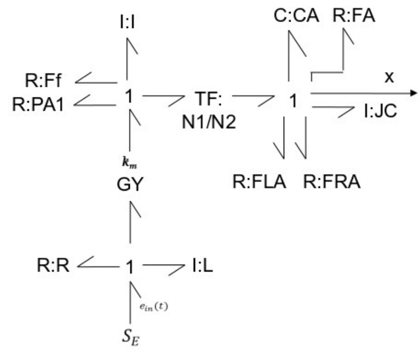

Figure 8. Block diagram of the ACV actuator with a one stage gearbox

form and its simulated behavior by various integrated modelling and simulation environments such as "20-sim®" [20] and "SYMBOLS Shakti™" [21].

4 Conclusions

The paper presented proposes the application of bond graph theory in the analysis of the dynamic behavior of a control subsystem included in the engine management system of an internal combustion engine. The target was to find a suitable abstraction of such a system in order to be able to evaluate the effect of parameter or system structure modifications on operating performance in the context of a model-based design approach. Such models are needed for virtual system integration and parallel development in different engineering domains (electrical, mechanical, control) for quick design space exploration. The effort was put in with the intention of checking the suitability of numerical modeling with the aid of bond graphs in the context of mechatronic elements used in internal combustion engines thus creating a backbone or central model for virtual validation of future designs. Common elements in many actuators, like the electric motor or the gearbox, can be elaborated once and reused or modeled in further detail due to the object oriented nature of bond graph representations. The quantities and notions used are generic, proposed abstractions of physical phenomena involved in the operation of actuators of the studied type. Experimental study is necessary to validate and generate the numerical values needed for quantitative evaluation of the systems' dynamics. Independently from the quantitative side of the analysis, qualitatively, the elaborated model is a suitable abstraction from the point of view of the energetic exchanges found in an actuator of the proposed configuration (Dimensional analysis was successfully performed, the systems' dynamic equations yielding physically homogeneous units).

References

[1] Bosch Professional Automotive Information, *Diesel Engine Management: Systems and Components* (Springer Vieweg, Wiesbaden, 2014)

[2] Barbieri G., Fantuzzi C., Borsari R., *A model-based design methodology for the development of mechatronic systems*, (Mechatronics, 2014)

[3] Ashok B., Ashok S.D., Kumar C.R., *Trends and future perspectives of electronic throttle control system in a spark ignition engine*, (Elsevier, Annual Reviews in Control, 2017)

[4] Ashok, B.; Kumar, R. et al., *An integrated pedal follower and torque based approach for electronic throttle control in a motorcycle engine*, (Engineering Journal, 2017)

[5] Corno, M.; Tanelli, M.; Savaresi, S. M.; Fabbri, L., Nardo, L., *Electronic throttle control for ride-by-wire in sport motorcycles*, (IEEE International Conference on Control Applications, 2008)

[6] Pavkovic et al., *Adaptive control of automotive electronic throttle*, (Elsevier, Control Engineering Practice, 2006)

[7] Pan et al., *Variable-structure control of electronic throttle valve*, (IEEE, IEEE Transactions on industrial electronics, 2008)

[8] Mcharek et al., *Modeling and multi-objective optimization of an Electronic Throttle in open-loop*, (11th France-Japan / 9th Europe-Asia Congress on Mechatronics, 2016)

[9] Mcharek et al., *Validation approach of a mechatronic system controller in upstream phase*, (12th France-Japan and 10th Europe-Asia Congress on Mechatronics, 2018)

[10] Borchani et al., *Mechatronic System Design using Model-Based Systems Engineering and Set-Based Concurrent Engineering Principles*, (12th France-Japan and 10th Europe-Asia Congress on Mechatronics, 2018)

[11] Borutzky W., *Bond Graph Methodology*, (Springer-Verlag, London, 2010)

[12] Broenik J.F. , *Introduction to Physical Systems Modelling with Bond Graphs* (Springer, Twente, 1993)

[13] Kypuros, *System dynamics and Control with Bond Graph Modeling*, (CRC Press, Boca Raton, 2013)

[14] Das S., *Mechatronic Modeling and Simulation Using Bond Graphs*, (CRC Press, Boca Raton, 2009)

[15] Paynter Henry M., *Analysis and design of engineering systems* (M.I.T. Press, Cambridge Massachusets, 1961)

[16] Karnopp D. C., Margolis D.L., Rosenberg R.C., *System Dynamics, Modeling, Simulation and Control of Mechatronic Systems*, (John Wiley and Sons, New Jersey, 2012)

[17] Damic, Montgomery, *Mechatronics by Bond Graphs*, (Springer, Berlin, 2015)

[18] Witelski T, Bowen M., *Methods of Mathematical Modelling*, (Springer, Switzerland, 2015)

[19] Thoma J. U., *Simulation by Bondgraphs: Introduction to a Graphical Method*, (Springer, 1990)

[20] Kleijn, C ., Groothuis, M.A., Differ H.G., *20-sim 4.7 Reference Manual*, (Controllab Products, Enschede, 2018)

[21] Samantaray, Arun et Mukherjee, A., *Users Manual of SYMBOLS Shakti*, (High-Tech Consultants, STEP, Indian Institute of Technology, Kharagpur, 2006)