Object-Oriented Behavior Modeling and Simulation of Hydraulic Cylinder

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The paper presents development of a hydraulic cylinder model with the application of the software development methodology, known as object-oriented approach. To form the conceptual model, energy mechanisms, from the bond graph methodology, are used. Transforming these concepts to classes, we come up to the models directly executable on the computer. The cylinder model is developed from complete modules through a few iterations. In the first step the cylinder is assumed as the static conversion mechanism. In the second step the model is expanded with the switch mechanism by which we represent piston displacement limits. In the third and forth iteration, the cylinder dynamics is assumed.

Keywords: *object-oriented modeling, hydraulic cylinder behavior modeling, simulation.*

1. INTRODUCTION

We rarely have the possibility to regard some system in all its complexity. The ability to see what is essential and what is less essential presents the very basis for work with such systems. The model presents such an abstraction, that is, it presents a simple reality description so that this reality can be easily understood. What is going to be included in some model depends on the perspective of viewing the system. There is not a single model to be comprising all the system aspects, but each of them contributes to the system picture from some point of view.

In order to move easily through modeling space, it is necessary to assume some methodology. According to [1], model development methodology is defined by three elements: work organization, modeling heuristics and modeling language.

The essential thing that defines one methodology is language for model description. What can be expressed in a model is determined by the language in which it is stated. The language specified what terms can be incorporated in a model (vocabulary) and how these ones can be meaningfully combined (grammar). According to concepts, which define language vocabulary, nowadays we can distinguish two modeling methodologies [1-5]:

- Process-oriented approach: system is structured by procedures (operations) that describe behavior from the highest to the lowest level.
- Object-oriented (OO) approach: system is decomposed into structural elements that can interact among themselves.

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In both cases the base is functional analysis but the way of model organization varies. In the first case, the model is organized about the one "who works" whereas in the second case it is organized about the one "to work with". At process-oriented approach the model is considered as the process, which contains functional blocks in the causal relationships. The system is viewed through the functions it performs. At the object oriented approach, the behavior model is described by the structure through which different functions can be performed. Constitutional structure elements are objects, which represent the instances of generalized abstractions from problems or solutions domain. With objects connection we come up to a typical graph, which represents the model architecture. The model architecture represents the base construction for different system functionality.

The most important thing in the appropriate model development is the essential knowledge of the system, which should be modeled. However, at the beginning of the model design, the modeler has the biggest design freedom, but the knowledge of the system is at minimum. At that phase, the model is the most useful but it is hard to come up to it. As the project advances, the system is better-known, but its meaning diminishes as the choice of possible solutions is narrowed in line with designer's previous decisions.

In order to solve this problem, there are some requirements to be met in modeling methodology:

- Higher model flexibility,
- Iterative way of model development.

Easy modification and reuse of existing models in a different context is necessary as in accordance with designer's wishes to test different solutions. The question is not how to make some model, but how to reuse the existing model (eventually upgrading) and share it in a cooperative team work, namely how to integrate the existing work. In many known models, the problem is how to organize them and how to manage them.

A model development based on the iterative way, enables us to start from the simple model during modeling, including only the most important concepts. Risk of not succeeding is maximal at the beginning, for the very knowledge about the system is minimal at the time. Possible errors are in accordance with our comprehension of the problem conception and this may have essential effect on the model itself. However, there are not consequences because we are at the beginning of the model process. In the next iteration, the model is extended with a number of new details in such a way that the previous results are the inputs to the next iteration. Possible errors are no more so dramatic as the most important decisions have been and verified in the previous iterations. With each of the following iterations, the risk of failure is smaller.

More flexible modeling and capability of model reuse are suggested as the most important advantages of the OO methodology [6-8]. Process developed model is rigid and harder for maintenance.

In the next section the hydraulic cylinder model is developed based on object oriented methodology. To form the conceptual model, energy mechanisms, from the bond graph methodology, are used [9-18]. Transforming these concepts to classes, we come up to models direct executable on computer.

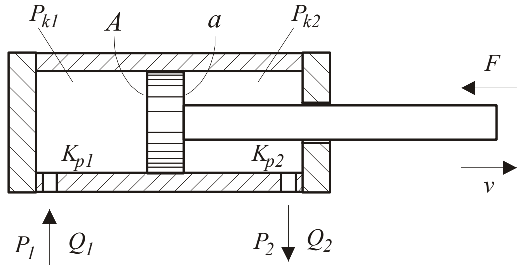
2. HYDRAULIC CYLINDER

Hydraulic cylinder (HC), as a fluid power element, has a wide application as a final element in many control systems. Fig.1a indicates the physical model of a hydraulic cylinder with one piston rod. Without the construction form, the base function of any cylinder is the transformation of the hydraulic to mechanical energy with the piston rod linear motion. This cylinder function is symbolically shown by the use case diagram (Fig.1b), using Unified Modeling Language (UML) notation [19-21].

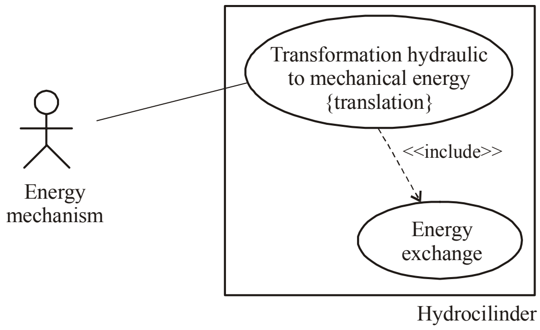
The use case diagram describes what the system does, but not how it works. It is very important because the function is necessary to divide from the way it performs. One of the same problems can be solved in different ways therefore the first description should not be burdened with realization ways. The use case is shown graphically by the ellipse in which its function is described.

Since no system exists by itself, actors graphically represented with the stylistic men figure, describe the environment that interacts with the system. The actor represents the role the environment plays in relation to the system. The relation between the actor and use case is shown by association, which marks the bi-directional communication. In our case the environment plays the multiport role, which interacts with the system through energy exchange. The diagram of Fig.1b, indicates that base functionality includes energy exchange via multiports. A system can be connected with many energy mechanisms but all of them have the same role and are, therefore, represented by one actor.

Looking from outside, HC model can be represented by composite structure that interacts with environment over interface with two hydraulic and one mechanical power port (Fig.2) [22, 23]. The composite structure defines the context in which we develop the cylinder model.



a) Physical model



b) Use case diagram

Figure1. Hydraulic cylinder

Everything that the environment needs to know about the model is contained in the interface. In orher words, environment needs to know how to use HC services, but not how they are performed. HC model has the obligation to answer every message with one forwarded power variable with the information about another power variable.

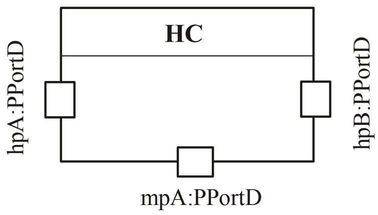


Figure 2. Hydraulic cylinder composition model

Through that interface, six functional HC models can be realized. During the development the model implementation can be changed, but the interface has to remain unchanged.

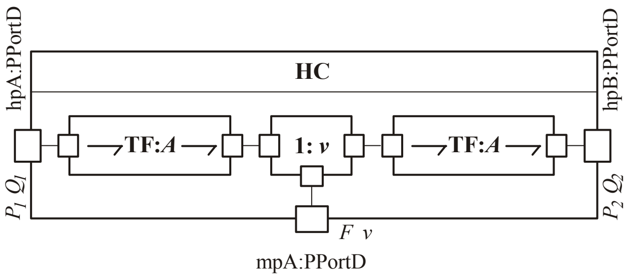
2.1 The first model iteration

In the first iteration, our HC conception understanding can be presented by a conversion mechanism (Fig. 3a). Energy from one hydraulic port (P_1Q_1 / P_2Q_2) is transformed by the conversion mechanism (TF) into the piston mechanical energy. On the piston, this energy, with velocity v, is divided into energy for outside work (Fv) and the part which by another transformer is conversed again into hydraulic energy (P_2Q_2 / P_1Q_1). In this course, at any moment, the following stands as valid:

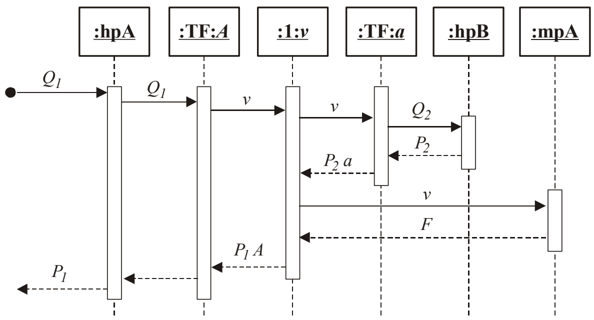
$$P_{k1}A + F + P_{k2}a = 0 \,. \qquad (1)$$

Since, 1-junction (1: *v*) introduces constraint that only one port defines velocity there are three possible scenarios in model execution. Each of the outside ports (*hpA*, *hpB* or *mpA*) can play the role of an independent piston velocity source. In case when on the first hydraulic port (*hpA*) we have an independent flow source (Q_1 - is time independent function) the model dynamic looks is indicated in Fig.3b.

Distributor 1-junction information about velocity forwards to the other two ports by the variable order, therefore, for model execution the one program threads is sufficient. It means that it is sufficient for the model to have one active object owning a thread and being able to initiate the control activity.



a) Composition model



b) Sequence diagram

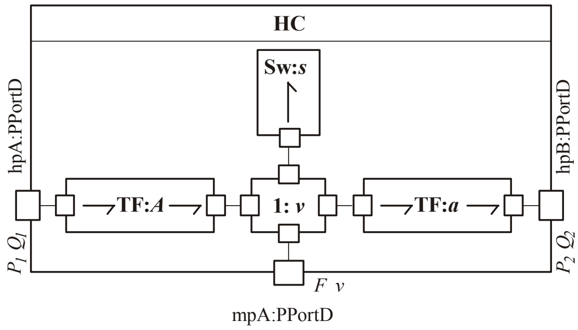
Figure 3. Model of Hydraulic cylinder - 1. iteration

In signal processing context, such cylinder model presents a node that the flow variables from one port multiply and effort variables from the other two ports algebraically add. In this case the phase of all signals remains constant.

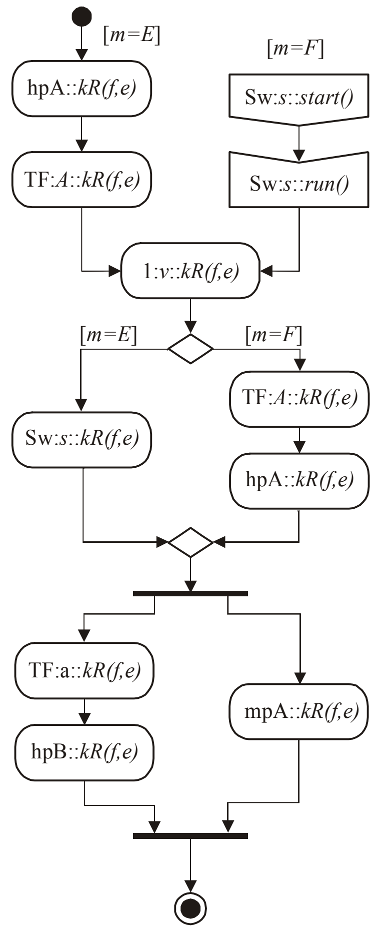
2.2 The second model iteration

In the model form Fig.3a there is not any constraint in regard to the piston motion. However, at the real cylinder the piston maximum displacement has some limit value (*h*). The piston movement constraint is modeled by the switch mechanism (SW) [5, 23] (Fig.4) making the discontinuation change of the work process.

Physically, SW conceptualizes cylinder body constraint on the piston displacement. When the piston is in interposition ($0 < x < h$) SW behaves as the zero effort source ($S_e : 0$) and therefore it doesn't have effect on the piston movement. In one of the last positions ($x = 0 \lor x = h$), SW takes over the role of the zero flow source ($S_f : 0$) (the piston is in contact with the cylinder body).



a) Composition model



b) Activity diagram

Figure 4. Model of Hydraulic cylinder- 2. iteration

Distribution mechanism 1-junction piston velocity ($v = 0$) forwards to other two ports. Structure form Fig.4 presents the infrastructure for the realization of different use case. Dynamics of the 2. Model iteration for one use case is presented by the activity diagram in Fig. 4b. For some other use case, the model architecture remains the same, only the message order that exchanges between architectural concepts will be changed. Thus, the idea is for the complexity to be realized by the combination of the small group of the simple concepts.

Fig.4b specifies that the activity sequence is realized partly through two threads. When piston is in interposition, the activity flow comes from the outside port *hpA*. When the piston is in one of the limit positions, the thread is activated from switch mechanism. During model simulation one or another thread includes in succession.

It is necessary to note that during the change of SW state, its causality changes. Therefore, it comes that environment needs to have the possibility to change causality on port *hpA*. When for SW is valid $s = E$, the environment through volume flow rate Q_1 defines piston velocity. In state $s = F$ roles change, then the environment reacts by pressure P_1 on the flow which defines cylinder ($Q_1 = 0$). That means that role of the input variable for 2. Model iteration plays alternatively Q_1 and P_1 . Physical meaning of this constraint is that the constant flow pump cannot be directly connected to the cylinder but that connection has to go through some element that changes causality (for example, through pressure relief valve).

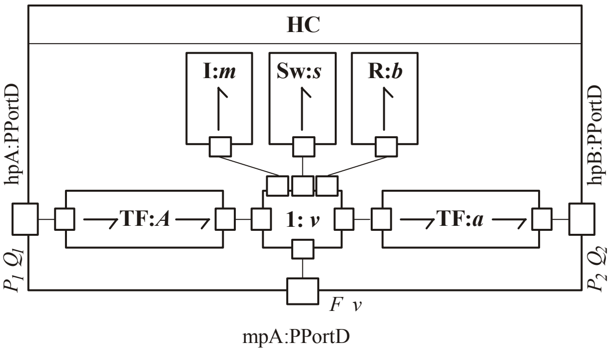
2.3 The third model iteration

If we take into consideration the piston insertion force (and all masses which are fixed for piston) and the viscous friction force, we come to 3. model iteration of the cylinder behavior (Fig. 5). We do not build the new behavior model structure from the very beginning, but we upgrade the existing one. The inertion concept we include over I-storage element and the friction over dissipation mechanism. At that interface, related to the outside world nothing changed. The cylinder model still realizes its obligation over the three ports (*hpA*, *hpB* and *mpA*). It means, if we change something in the cylinder model, then it is not necessary to change anything in the rest of the system model. In this way, all changes are localized on a defined part of model.

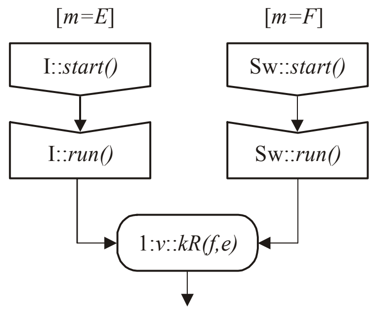
By the analysis of the model causality, it can be seen that, without the work process, the causality of the outside ports is fixed. On both hydraulic ports the environment defines pressure (P_1 , P_2). It means that we can't simulate the cylinder behavior for independent volumetric flow rate Q_1 and Q_2 . In the work regime $s = E$ ($0 < x < h$) the velocity (flow) defines I - storage mechanism. In the work regime $s = F$ ($x = 0 \vee x = h$) the velocity (flow) defines SW mechanism.

In the work regime $s = E$ on I-storage element there is integral (preferred) causality, therefore the cylinder behaves as the first order transfer element. Between the inert ion force and the piston velocity, there is the phase delay $\pi/4$. In the work regime $s = F$ on I-storage element, there is derivative causality, therefore the cylinder behaves as the state element. In other words, the cylinder dynamics changes in regard to the piston position.

The part of cylinder behavior is presented in Fig.5b. As in the previous case there are two flow activities. However, in this iteration sources of both threads are in cylinder model. In the work regime $s = E$ activities bier is the thread coming from I-storage and in the work regime $s = F$ activities bier is the thread coming from the switch mechanism.



a) Composition model



b) Activity diagram (part)

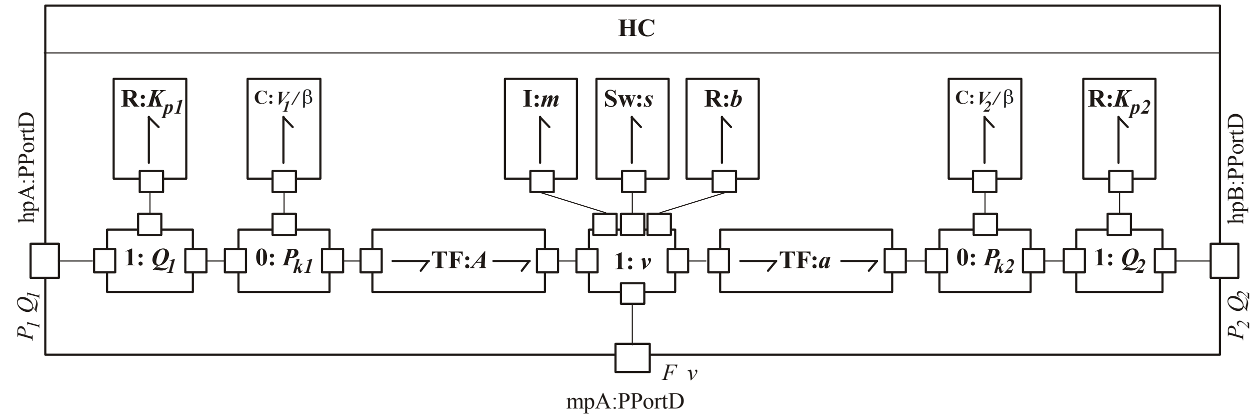
Figure 5. Model of Hydraulic cylinder- 3. Iteration

2.4 The forth model iteration

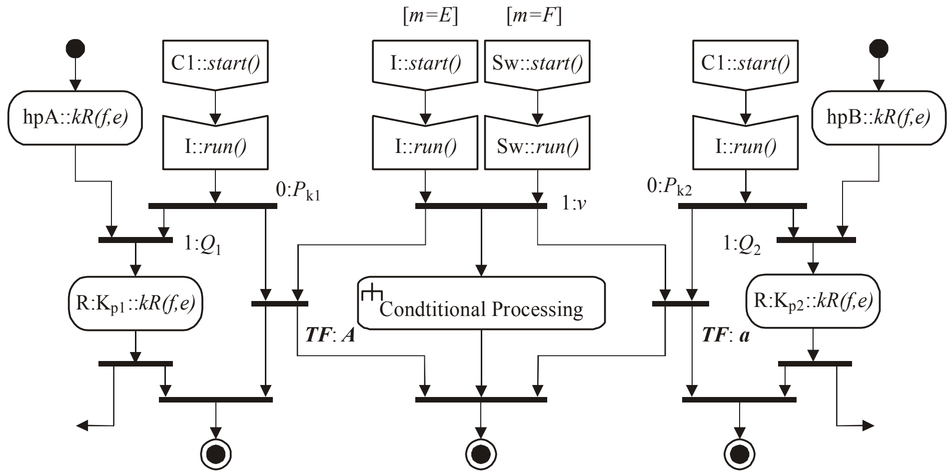
During the higher pressure change, the cylinder behavior depends on the fluid stiffness in cylinder chambers. From the energy point of view, the stiffness represents the ability of the fluid to accumulate part of energy, which can be transferred between the environment and the piston. Therefore, we introduce the stiffness concept by C-storage element (Fig.6). Chambers present place for joining the two of energy flows: one originates from the outside environment, whereas the other originates from the piston. 0-junction algebraic addition flow, and base on this C-storage form uniform chamber pressure. Between the pressure and the resulting flow, there is a phase delay $\pi/4$. In order to separate the fluid stiffness in chambers from the fluid stiffness in the rest part of the installation, we bind C-storage with the environment via two dissipation mechanisms ($R:K_{p1}$, $R:K_{p2}$). Physically, these mechanisms present orifices on cylinder input.

In the work regime $s = E$ on all of model accumulator, there is integral causality, therefore the cylinder model has the third order. In the work regime $s = F$ on I-storage, there is derivative causality, therefore, the model order is less by one. Dissipation mechanism in combination with C-storage mechanism can have arbitrary causality. Therefore, hydraulic ports causality of cylinder model is arbitrary.

Sequential model process is realized through three activity flows (threads), which come from storage mechanisms. In the work regime $s = E$ the piston



a) Composition model



b) Activity diagram

Figure 6. Model of Hydraulic cylinder- 4. Iteration

motion is simulated through thread originated from I-storage and in the work regime $s = F$ originated from SW mechanism. Chamber pressure changes are simulated through threads, which originate from C-storage elements. The meeting point of these three threads are transformers ($TF : A$ and $TF : a$). In case that independent energy flows are connected with hydraulic ports (*hpA* and *hpB*), it is necessary to have two threads more. The dynamics of 4. Model behavior iteration is presented in Fig.6b.

3. SIMULATION RESULTS

Here are given simulation results in regard to each hydraulic cylinder behavior model iteration as described in the previous section.

– *The first model iteration*

Simulation results of power variables changes on hydraulic port *hpA* and mechanical port *mpA* are given in Fig.7. Independent inputs are flow rate Q_1 and force *F*. In this given course, the piston velocity depends only from flow, and the input pressure only from the force. The possible connection between these two variables could be formed over outside load. Cylinder in this case has only two roles: as energy converter and energy distributor. During this simulation the model causality stays constant. In Fig.7a the piston stroke is presented and the input hydraulic power in Fig.7b.

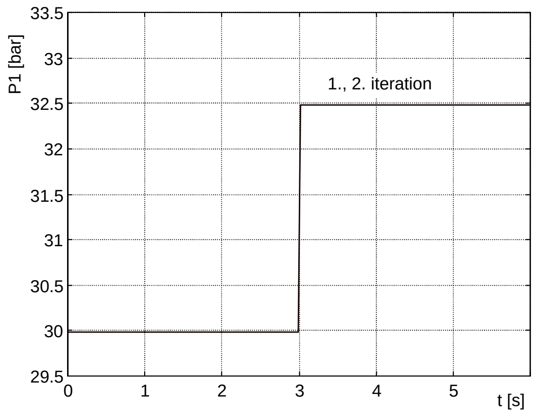
– *The second model iteration*

Simulation results are indicated in Fig.7. And in this case the relations between flow rate and velocity, as between pressure and force are straightforward. However, on the port *hpA* causality roles change alternately. In work regime ($0 < x < h$) the velocity is defined by flow rate, but in the regime ($x = 0 \ \vee \ x = h$) flow rate is defined by velocity. On the port *mpA* causality remains fixed. This figure denotes that SW mechanism includes limits on the piston displacement, in other words, discontinuity regime changes.

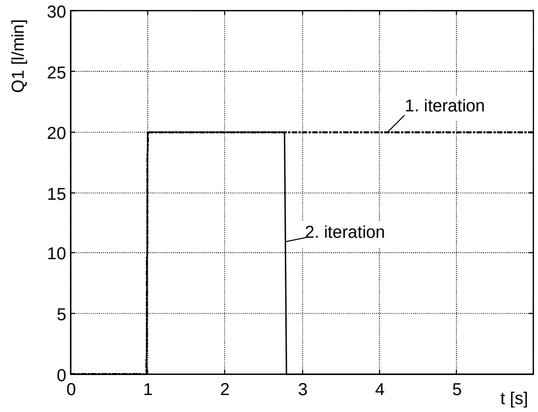
– *The third model iteration*

Simulation results are given in Fig.8. The relation between inputs and outputs is no more static but dynamic. Therefore, we have continual power change at the input. Besides, the piston dynamics makes extra relations between flow and effort variables. For example, outside force change in moment $t = 3$ s makes

port *hpA*

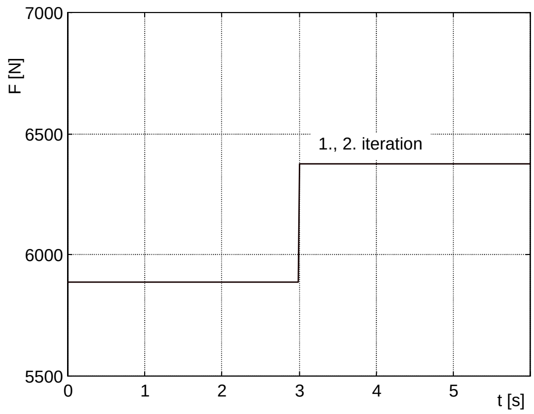


a) Input pressure

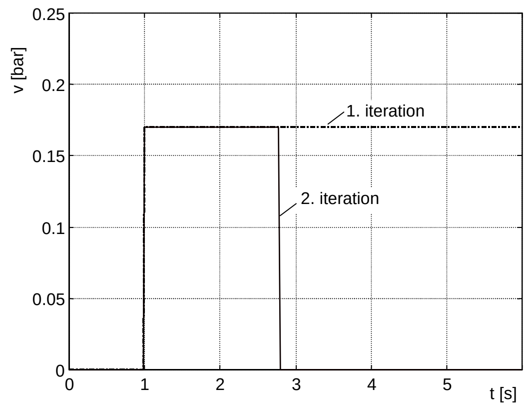


b) Input flow rate

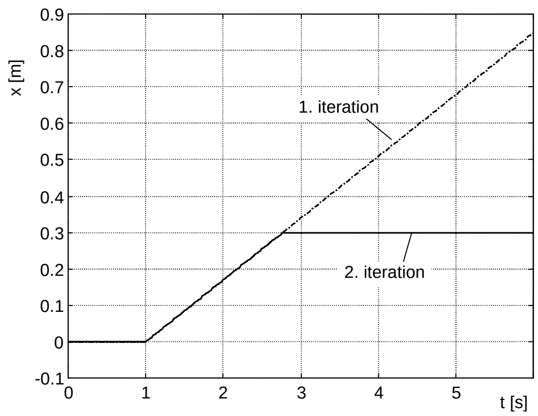
port *mpA*



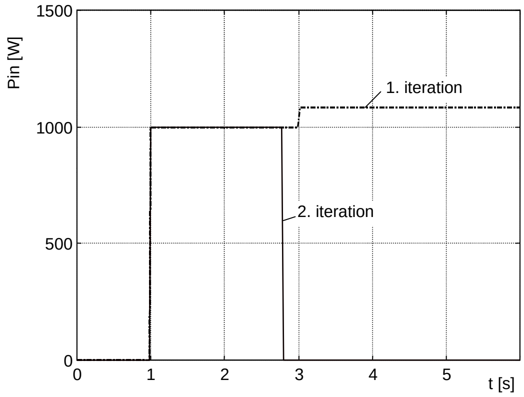
c) Outside force



d) Piston velocity



e) Piston displacement



f) Input hydraulic power

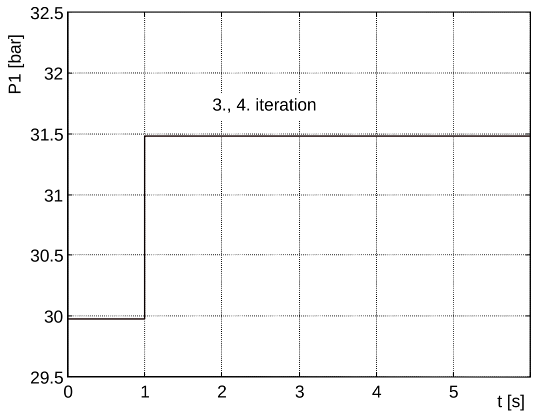
Figure 7. Simulation results of 1. and 2. model iteration

velocity change and input flow respectively. The pressure in this case is an independent time function.

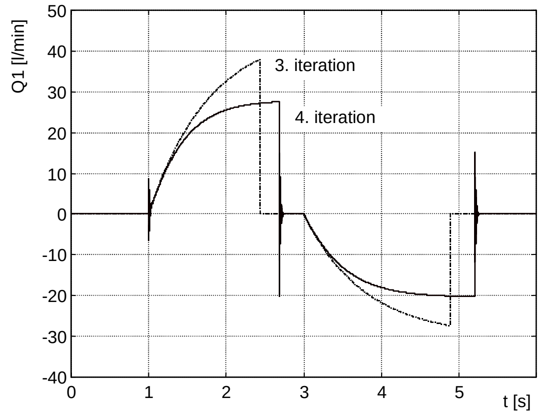
− *The fourth model iteration*

Simulation results are indicated in Fig.8. C-storage elements introduce extra inertion to the system response. Since there is an additional accumulation of input energy, velocity changes, for the same input pressure changes, are smaller than in the previous case. Furthermore, discontinue velocity change, during the regime change, is amortized on these accumulators.

port *hpA*

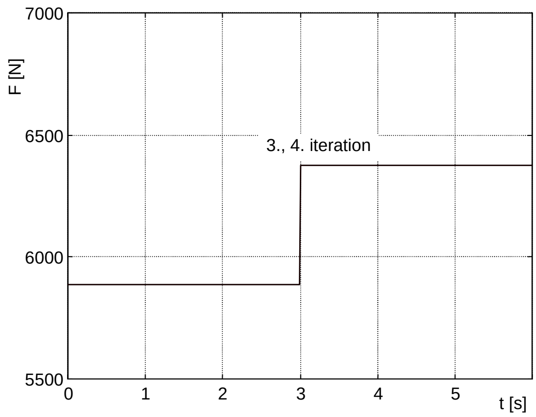


a) Input pressure

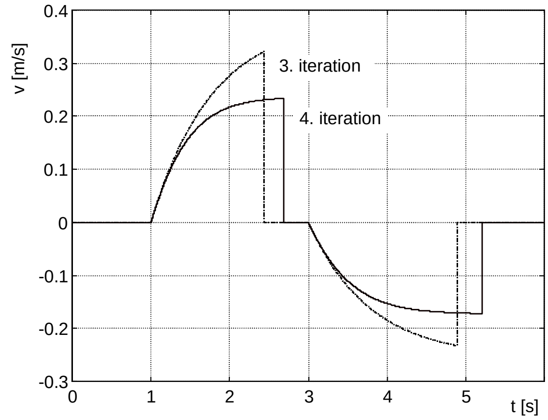


b) Input flow rate

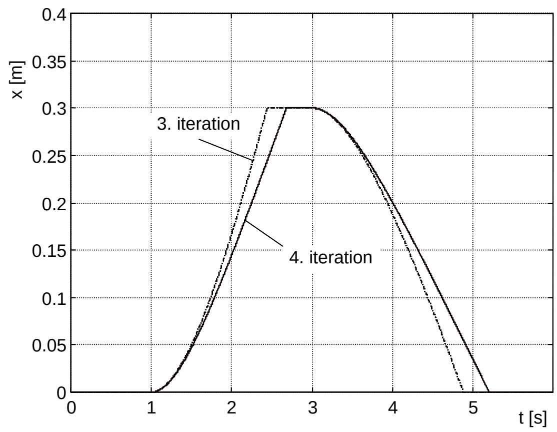
port *mpA*



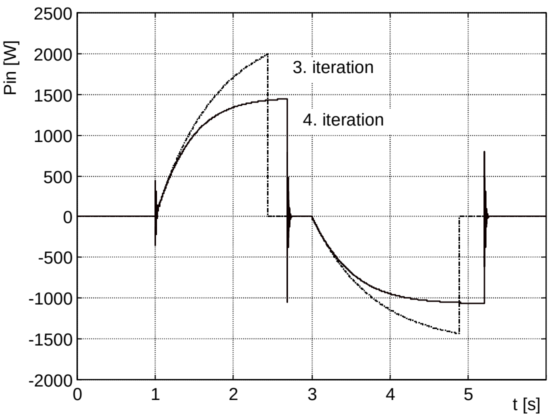
c) Outside force



d) Piston velocity



e) Piston displacement



f) Input hydraulic power

Figure 8. Simulation results of 3. and 4. model iteration

4. CONCLUSION

By applying the object-oriented concepts, the hydraulic cylinder behavior model is obtained. This model has a flexible structure and it is easier to be changed and maintained. As a result, the iterative model development process is possible with the choice desired level of complexity. Including interface, contained from power ports, the model is encapsulated. Therefore, the same functionality is possible to be achieved in different ways (polymorphism). In other words, the possible changes are localized in the desired part of the model.

Simulation results show that during cylinder behavior analysis, it is necessary to include the discontinue work regime changes in the model. These changes happen during the limit piston position.

In case of neglecting dynamics, the cylinder plays role of ideal energy transformer and distributor. The two independent signal flows runs through it. Between them there is not extra causality. On one port, the environment defines effort but on the other flow. During the work regime change, the cylinders causality changes, therefore, it demands causality change in the environment.

Including piston dynamics in consideration, the additional relationship between power variables (phase delay) on cylinder is formed. One energy part from the input leaves for accumulator (slow response) but another energy part irreversible transformed to heat (decreasing gain). Causality on all ports stays unchangeable without the work process on the cylinder.

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NOMENCLATURE

P_1, P_2	Pressures on cylinder hydraulic ports
Q_1, Q_2	Volumetric flow rates on cylinder hydraulic ports
F	Piston outside force
v	Piston velocity
A, a	Piston effective areas
P_{k1}, P_{k2}	Chamber pressures
X	Cylinder piston position
H	Cylinder piston stroke
M	Mass elements connected for piston
b	Viscous friction coefficient
B	Effective bulk modules
V_1, V_2	Cylinder chamber volumes
Q_c	Leakage flow
K_{p1}, K_{p2}	Flow coefficients
P_{in}	Input hydraulic power

ОБЈЕКТНО ОРИЈЕНТИСАНО МОДЕЛИРАЊЕ ПОНАШАЊА И СИМУЛАЦИЈА ХИДРАУЛИЧКОГ ЦИЛИНДРА

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У раду је приказан развој модела хидрауличног цилиндра применом методологије развоја софтвера. Полазна претпоставка ове идеје је да је и сам софтвер само специфична форма модела реалног света. За формирање концептуалног модела користе се енергетски мехенизми из бонд граф методологије. Превођењем ових концепата у класе долазимо до модела који се директно може извршавати на рачунару. Модел цилиндра се развија од готових модула кроз неколико итерација. У првом приближењу цилиндар се посматра као статички систем за конверзију енергије. У другом пролазу, помоћу механизма прекида уводимо ограничење у кретање клипа. Трећа и четврта итерација у разматрање уводе динамику клипа цилиндра.