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COMPOSING MULTI-POLE-MODEL BLOCK SCHEMES FOR A LOAD-SENSING HYDRAULIC DRIVE

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Abstract. This paper discusses a mathematical model composed for a complicated technical system – a load-sensing hydraulic drive. The drive is composed of functional elements and subsystems, which are described by multi-pole models. Mathematical relations for the functional elements can be composed on the basis of oriented graphs. Multi-pole models for simulation of the transient responses are considered. Simulation is conducted by the help of the two-level calculation method and the computing system NUT.

Key words: mathematical model, load-sensing hydraulic drive, multi-pole model, causality, oriented graph, two-level calculation method.

1. INTRODUCTION

The simulation of technical systems accelerates new product and system development, improves quality, and reduces expenses of experimental work.

A continuous increase in the possibilities and processing capacities of computing techniques is the current trend. More and more powerful simulation packages are offered. However, simulation packages for mechanical and hydraulic systems, which could satisfy the demands of all customers, have not been developed.

For simulation, a suitable mathematical model (MM) is needed. To create a model of a technical chain system, the following demands and expectations should be satisfied [1–3]:

- methodical procedure
- ease of surveying, based on principal and functional schemes, block schemes of multi-pole models, oriented graphs, and graphic settings of the task on the screen

- description of a system with a joint operation of mechanical, hydraulic and electromechanical elements, with electric and electronic control and regulation systems
- use of a wide set of models of functional elements (FEs) and subsystems (SSs)
- simple insert of completely new modules and simple modification of existing modules
- offering a set of elementary modules (micromodules) to enable the composition of new complex models graphically
- enabling subsystem composition
- recurrent use of the compiled complex subsystems
- taking into account the nonlinearities and restrictions
- taking into account the system variable structure (i.e., overswitchings of the devices)
- description of the models as "black boxes"
- avoiding the "mathematically stiff" dependencies
- composition of the MMs for static, steady-state motion, frequency response, and transient response of the system.

2. POSSIBLE DESCRIPTION METHODS OF MATHEMATICAL MODELS

The conventional description methods of the technical system are as follows.

1. Equations: CASCADE, XANALOG.

Composition of the equations depends on the intuition of the programmer. This method complicates the consideration of all loop relations. It is not possible to compose MMs, avoiding "mathematically stiff" dependencies.

2. Special simulation languages: ACSL.

Composition of MMs is based on block schemes for analog simulation. The method is oriented to systems of equations.

3. Block schemes of mathematical operations: SIMULINK, VisSim.

Block schemes of MMs are too detailed. The block schemes are composed proceeding from equations, but not conversely.

4. Block schemes of signal flow planes of two-pole transfer function blocks and nonlinear elements [4].

The method is suitable for electrical control systems, but not for mechanical or hydraulic systems.

5. Matrix-topological method [5,6].

For a system model, it is necessary to compose the equivalent electrical circuit (ALLTED). This is inconvenient, furthermore proper results are not always acquired. The resulting system of equations has a large unsymmetrical weakly filled matrix.

6. Bond-graphs [7].

The power flow graphs are insufficiently perspicuous for the relations among variables.

7. Signal flow graphs of multi-pole models [8–10].

Derivation of transfer functions for a linear system with loops is possible. For the calculation of frequency response of a nonlinear system, the method of harmonic linearization should be used. The method of splitting the graph nodes enables one to write the iteration equations for a system with loops and nonlinear relationships.

8. Functional and component schemes, causal modelling [11–16].

Proceeding from a functional or a component scheme, a MM is automatically composed. As a result, the MM is as a large system of ordinary differential equations or of the differential-algebraic equations.

9. Functional and component schemes, non-causal modelling [17,18].

The relations are given in the non-causal form. For any relation, the causality must be given separately.

10. Functional and component schemes, non-causal modelling with multi-formalism, multi-domain-modelling languages [19].

A program package which enables the use of various modelling methods, orienting to a system of equations.

11. Schemes of multi-pole models, generation of Lagrange equations [20].

It is used for composing the MMs of manipulators.

12. Distributed models [21].

To connect the elements, the unit transmission line (UTL) elements with time delay are used. The UTL elements have only one form of causality (the inputs for hydraulic UTL four-pole elements are the volume flow rates).

13. Block schemes of multi-pole models and oriented graphs [22–24].

This method is described below.

3. LOAD-SENSING HYDRAULIC DRIVE

A load-sensing hydraulic drive (LSHD) is shown in Fig. 1, and its load-sensing pump is illustrated in Fig. 2. The hydraulic cylinder of the LSHD is connected with an actuator through elasticity. In the LSHD, the load-sensing control system assures that the pressure and the volume flow rate at the pump depend on the need.

The load-sensing system guarantees a constant pressure drop *p*2–*p*4. For this purpose, the variable displacement hydraulic pump (Fig. 2) is regulated by the hydraulic cylinder to control the hydraulic pump, which is, in turn, controlled by the hydraulic proportional valve (HPV). The HPV, which regulates the pressure *p*3, is controlled by pressures *p*2 and *p*4. The pressure *p*4 depends on the pressure *pls* (*p*1*pv* or *p*2*pv*) at the output of the electrohydraulic proportional valve (Fig. 1). The relief valve RV2 restricts the maximum value of the pressure *p*4.

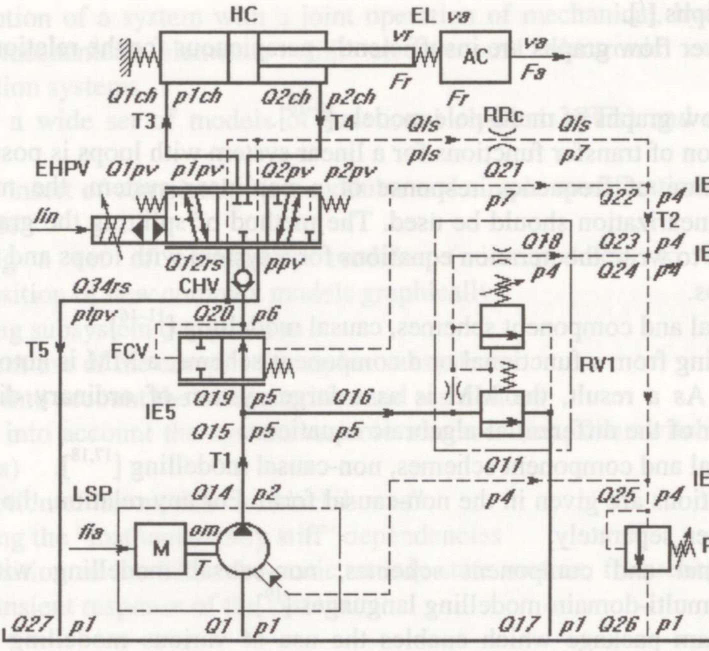


Fig. 1. Functional scheme of a load-sensing hydraulic drive. Notation of the functional elements and subsystems:

AC	actuator	IE1...IE12	interface elements (tee couplings)
HC	hydraulic cylinder	LSP	load-sensing pump
CHV	check valve	M	driving motor
EHPV	electrohydraulic proportional valve	RRc	hydraulic resistance (orifice)
EL	elasticity	RV1, RV2	relief valves
FCV	flow control valve	T1...T5	tubes

Notation of the variables:

fia	position angle of the accelerator of the driving motor	*pls*	load-sensing control pressure
Fa	input or output force of the actuator	*ppv, ptpv*	feeding and exit pressure of the EHPV
Fr	input or output force of the piston rod	*Q1...Q27*	volume flow rates
Iin	control input current	*Q1ch, Q2ch*	volume flow rates in the left and right ends of the cylinder
om	angular velocity of the driving motor	*Q1pv, Q2pv*	volume flow rates in the output from the pairs of EHPV slits
p1...p7	pressures	*Qls*	volume flow rate in the load-sensing pressure chain
p1ch, p2ch	pressures in the left and right chambers of the cylinder	*T*	hydraulic pump shaft torque
p1pv, p2pv	pressures in the connecting of the EHPV with the tubes T3 and T4	*va*	actuator velocity
		vr	piston rod velocity

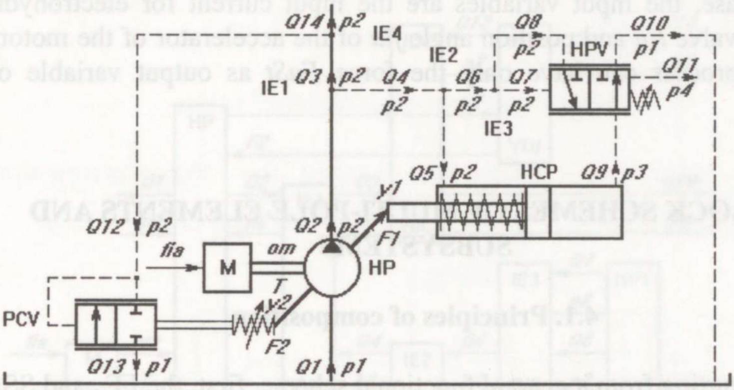


Fig. 2. Functional scheme of a load-sensing pump. Notation of the functional elements and subsystems:

HCP	hydraulic cylinder for control of the hydraulic pump
HP	hydraulic pump
HPV	hydraulic proportional valve
IE1...IE4	interface elements (tee couplings)
M	driving motor
PCV	power control valve

Notation of the variables:

fia	position angle of the accelerator of the driving motor
F1, F2	forces for control of the load-sensing hydraulic pump
om	angular velocity of the driving motor
p1...p4	pressures
Q1...Q14	volume flow rates
T	hydraulic pump shaft torque
y1, y2	shifts of the control actuators of the load-sensing pump

The flow control valve (Fig. 1) assures constant volume flow independent of pressure drop $p5 - (p1pv$ or $p2pv)$. The relief valve (Fig. 2) protects the hydraulic system from overpressure and also unloads the pump. The power control valve (Fig. 2) limits the pump power.

The processes in a LSHD are given in the table.

Processes in a load-sensing hydraulic drive with the main variables

Process nature	Input variables	Output variables
Steady-state	*IinSt, fiaSt, vaSt*	*FaSt*
Transient response of an actuator velocity	*Iin, fia, Fa*	*va*
Transient response of an actuator force	*Iin, fia, va*	*Fa*

In each case, the input variables are the input current for electrohydraulic proportional valve Iin and position angle fia of the accelerator of the motor. The steady-state process can have only the force $FaSt$ as output variable of the actuator.

4. BLOCK SCHEMES OF MULTI-POLE ELEMENTS AND SUBSYSTEMS

4.1. Principles of composition

Usually, starting from a general functional scheme, first, the FEs and SSs will be chosen. Then the variables in pairs (a potential and a flow rate variable) and their positive directions will be denoted. For each FE and SS, a multi-pole block has to be chosen [1,2,22–24]. The multi-pole block form (causality variant between the variables) will be selected, guided by:

- given input and output variables
- table of multi-pole blocks of FEs and SSs being used
- possibilities of connecting the multi-pole blocks
- block schemes of typical SSs and systems
- wish to avoid the “mathematically stiff” relationships.

Every block may have several MMs, differing in estimated factors. Thus, different kinds of MMs must also be chosen.

For the LSHD, we must build the block scheme of multi-pole elements and subsystems for steady-state motion and for the transient responses, separately. Let us follow the composing of the block scheme of multi-pole elements for the transient response of an actuator velocity va.

4.2. Load-sensing pump

The block scheme of multi-pole elements for a LSP is shown in Fig. 3 (the notations of the FSs/SSs and those of variables are given in Fig. 2).

The input variables to control a HP are the forces $F1$ and $F2$. The pump regulates the output volumetric flow rate $Q2$. Input variable for the HP from the driving motor M must be the angular velocity om. An accelerator controls the driving motor with position angle fia as input variable. The HPV has the following input variables: pressures $p1$, $p2$, $p4$ and volume flow rate $Q9$. The output variables are: the pressure $p3$ and volume flow rates $Q7$, $Q8$, $Q10$, and $Q11$. The relationships of the tee elements are expressed by interface elements (IE1...IE4).

As a subsystem unit, the LSP has the input variables fia, $p1$, $p2$, $p4$ and output variables $Q1$, $Q10$, $Q11$, $Q13$, and $Q14$.

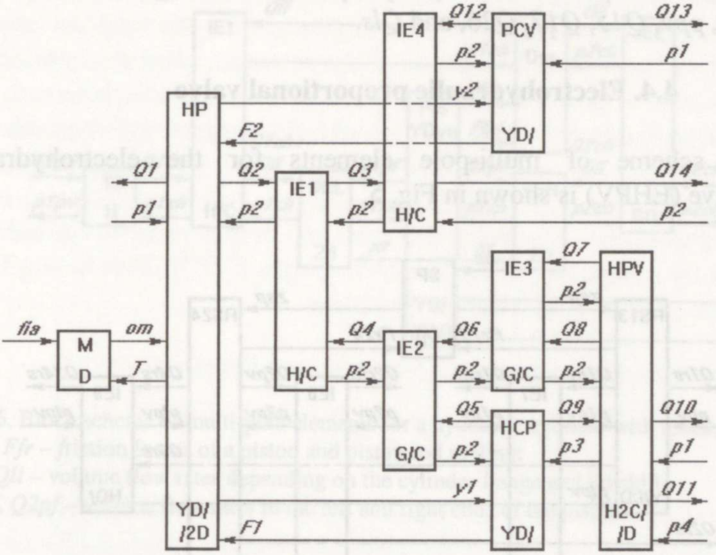


Fig. 3. Block scheme of multi-pole elements for the load-sensing pump.

4.3. Load-sensing pressure chain

The block scheme of multi-pole elements for the load-sensing pressure chain (LSPC) is shown in Fig. 4. The block scheme consists of the flow control valve (FCV), check valve (CHV), relief valves (RV1 and RV2), tube (T2), resistor (RRC) and tee elements (IE5, IE10...IE12).

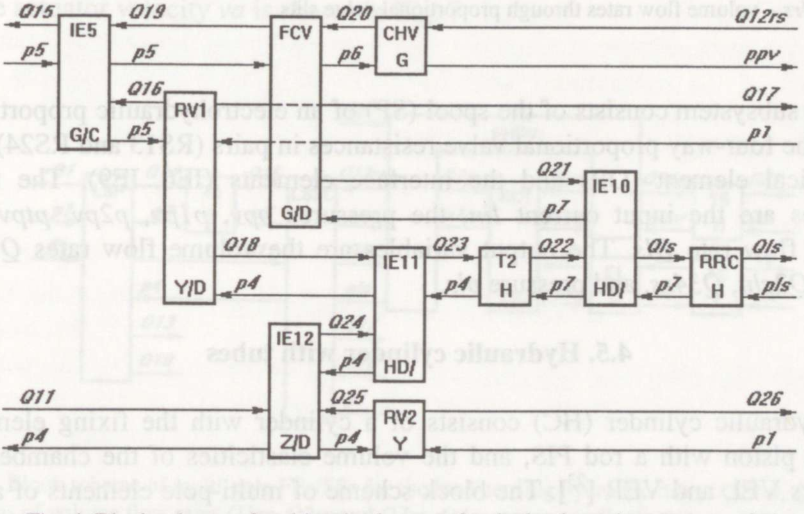


Fig. 4. Block scheme of multi-pole elements for the load-sensing pressure chain.

The LSPC has the input variables: *p1*, *p5*, *pls*, *Q11*, and *Q12rs*. The output variables are *p4*, *ppv*, *Q15*, *Q17*, *Q26*, and *Qls*.

4.4. Electrohydraulic proportional valve

The block scheme of multi-pole elements for the electrohydraulic proportional valve (EHPV) is shown in Fig. 5.

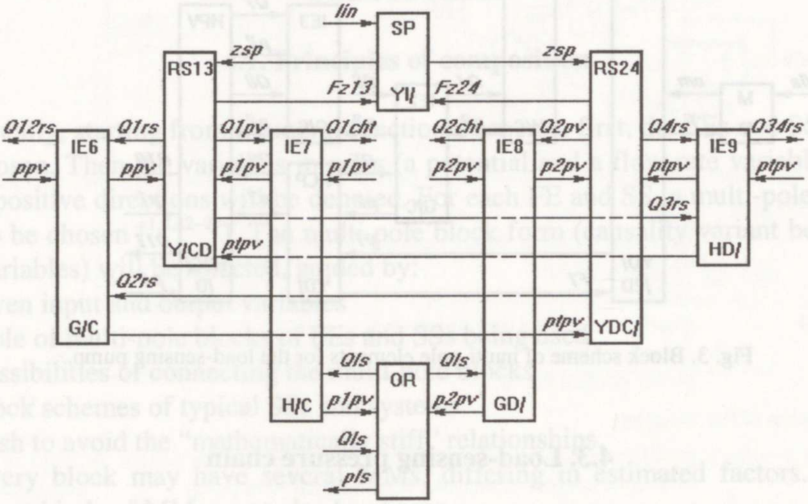


Fig. 5. Block scheme of multi-pole elements for the electrohydraulic proportional valve:
Fz13, *Fz24* – sums of hydrodynamic forces of jets of the proportional valve slit pairs;
Q1cht, *Q2cht* – volume flow rates in the input of the tube T3 and in the output of the tube T4;
Q1rs...Q4rs – volume flow rates through proportional valve slits.

This subsystem consists of the spool (SP) of an electrohydraulic proportional valve, the four-way proportional valve resistances in pairs (RS13 and RS24) [23], the logical element (OR) and the interface elements (IE6...IE9). The input variables are the input current *Iin*, the pressures *ppv*, *p1pv*, *p2pv*, *ptpv* and volume flow rate *Qls*. The output variables are the volume flow rates *Q12rs*, *Q1cht*, *Q2cht*, *Q34rs*, and pressure *pls*.

4.5. Hydraulic cylinder with tubes

A hydraulic cylinder (HC) consists of a cylinder with the fixing elements CYL, a piston with a rod PIS, and the volume elasticities of the chambers of cylinders VEL and VER [23]. The block scheme of multi-pole elements of a HC with tubes T3 and T4, called HCT, is shown in Fig. 6.

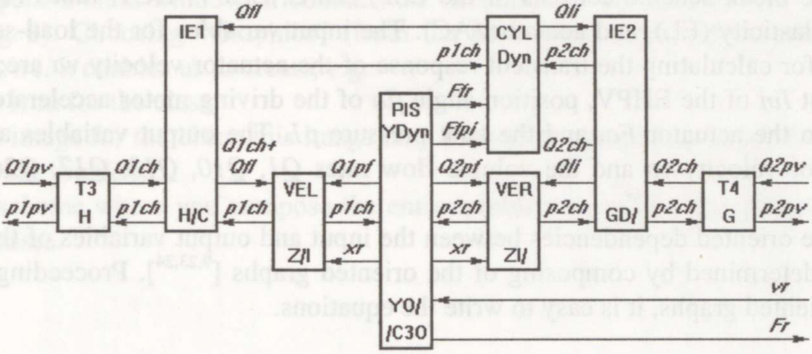


Fig. 6. Block scheme of multi-pole elements for a hydraulic cylinder with tubes:
Ffpi, *Ffr* – friction forces of a piston and piston rod sealing;
Qfl, *Qli* – volume flow rates depending on the cylinder flange and lid shift;
Q1pf, *Q2pf* – volume flow rates in the left and right ends of the piston.

A six-pole model of a HCT for calculating the transient response is chosen in the form Z/C shown in Fig. 7. The input variables are volume flow rates *Q1pv*, *Q2pv*, and piston rod velocity *vr*. The output variables are the pressures *p1pv*, *p2pv*, and piston rod force *Fr*. The tube T3 is applied as four-pole model form H and the tube T4 as four-pole model form G [2].

4.6. Load-sensing hydraulic drive

The block scheme of the whole LSHD for calculating the transient response of the actuator velocity *va* is shown in Fig. 7.

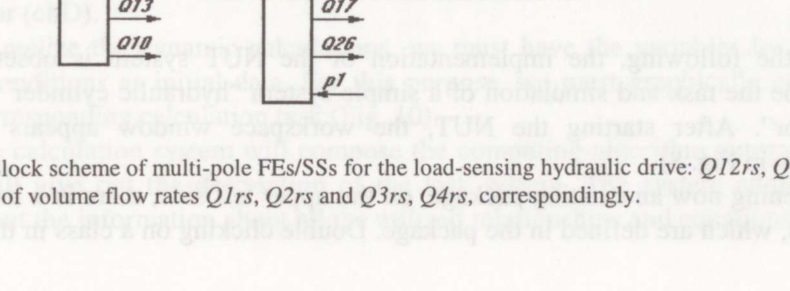


Fig. 7. Block scheme of multi-pole FEs/SSs for the load-sensing hydraulic drive: *Q12rs*, *Q34rs* are the sums of volume flow rates *Q1rs*, *Q2rs* and *Q3rs*, *Q4rs*, correspondingly.

The block scheme consists of the LSP, LSPC, EHPV, HCT, tubes (T1 and T5), elasticity (EL), and actuator (AC). The input variables for the load-sensing drive for calculating the transient response of the actuator velocity *va* are: input current *Iin* of the EHPV, position angle *fia* of the driving motor accelerator, the load to the actuator *Fa*, and the tank pressure *p1*. The output variables are the actuator velocity *va* and the volume flow rates *Q1*, *Q10*, *Q13*, *Q17*, *Q26*, and *Q27*.

The oriented dependencies between the input and output variables of the FEs were determined by composing of the oriented graphs [9,23,24]. Proceeding from the oriented graphs, it is easy to write the equations.

5. CALCULATION

To calculate the characteristics of hydraulic systems, the distributed two-level method will be used. For the first level, characteristics of isolated FEs or SSs must be calculated (algebraic equations, integration, differentiation, etc.). Any method of calculation may be used.

The integration on the first level for numerical non-stiff continuous functions will be carried out by the standard Runge–Kutta method. Numerical stiffness problems may be avoided by using MMs with the differentiation procedure. Then the Newton's iteration method will be used. In the case of loops, iteration procedures are widely used.

On the second (global) level, all the connecting pressure variables between the FEs/SSs will be calculated. This is necessary in order to avoid loops between them, where all values are unknown. The calculation will be carried out with the help of the Wegstein iteration procedure.

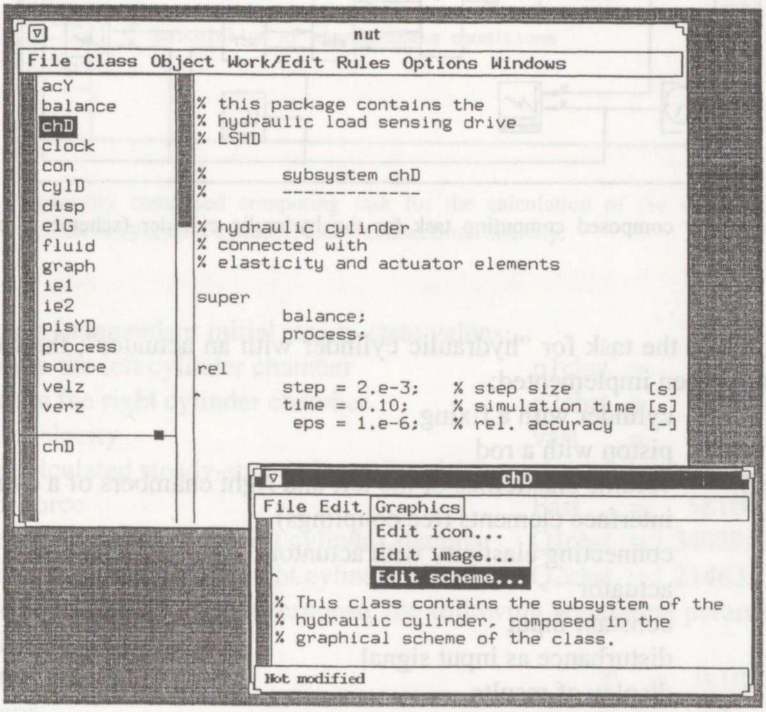
The automatic composition of the algorithm and the computing program, the execution of the calculations and the graphical display of the results were realized by the computing system NUT [25]. In the NUT, the task setting appears through graphical composition of the block schemes of multi-pole FEs/SSs and of the whole system on the screen.

6. SIMULATION EXAMPLE

In the following, the implementation of the NUT system is observed to describe the task and simulation of a simple system "hydraulic cylinder with an actuator". After starting the NUT, the workspace window appears (upper window in Fig. 8).

Opening now an existing package, on the upper left side, there is a list of all classes, which are defined in the package. Double clicking on a class in the class list opens a class window. It contains the definition of the class (lower window in Fig. 8). Choosing "Graphics" (from the pull-down menu) opens additional windows. It enables us to create, e.g.:

- an icon for the class;
- an image for the class; this image may be used to compose a larger SS or the entire problem;
- a scheme where you compose the entire problem or a SS consisting of other classes.



```
% this package contains the
% hydraulic load sensing drive
% LSHD

%       sybsystem chD
%       -------------

% hydraulic cylinder
% connected with
% elasticity and actuator elements

super
        balance;
        process;
rel
        step = 2.e-3;   % step size        [s]
        time = 0.10;    % simulation time  [s]
         eps = 1.e-6;   % rel. accuracy    [-]
```

```
% This class contains the subsystem of the
% hydraulic cylinder, composed in the
% graphical scheme of the class.
```

Fig. 8. Workspace and class windows in the NUT system.

As an example of a scheme, Fig. 9 shows the hydraulic cylinder with an actuator (chD).

To realize the dynamic calculations, we must have the variables by steady-state conditions as initial data. For this purpose, we must graphically compose the corresponding calculation task (Fig. 10).

The calculation system will compose the computing algorithm automatically and will give out the description of the task setting. The system additionally gives out the information about all the utilized relationships and equations.

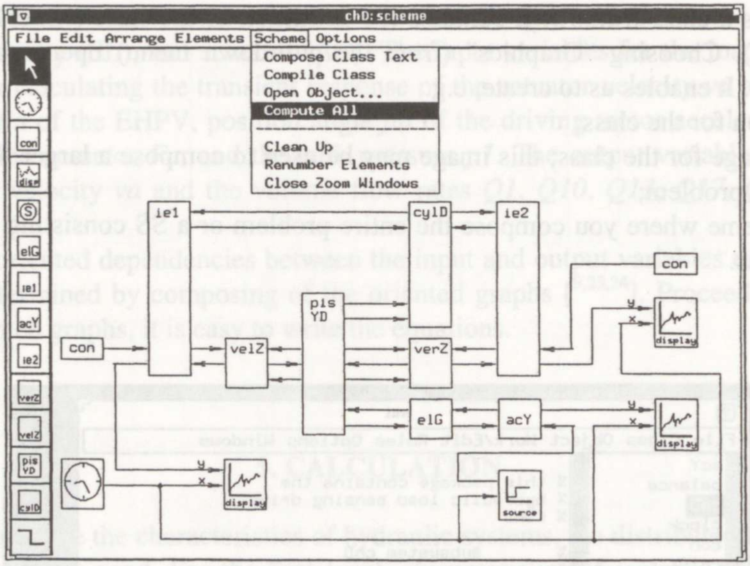


Fig. 9. Graphically composed computing task for the hydraulic cylinder (scheme of class chD window).

To describe the task for "hydraulic cylinder with an actuator", the following classes have been implemented:

cylD	cylinder with a fixing
pisYD	piston with a rod
velZ, verZ	volume elasticities of the left and right chambers of a cylinder
ie1, ie2	interface elements (tee couplings)
elG	connecting elasticity with actuator
acY	actuator
con	constant input
source	disturbance as input signal
display	display of results
clock	setting the current time

The key data of the system "hydraulic cylinder with an actuator" are as follows:

piston diameter	dpi	$= 0.1$ m
piston rod diameter	dr	$= 4.0\times10^{-2}$ m
maximal piston stroke	ls	$= 5.0\times10^{-1}$ m
initial piston position	xs	$= 2.3\times10^{-1}$ m
orifice diameter in piston	d5	$= 1.0\times10^{-3}$ m
total mass of piston and rod	mpi	$= 13.0$ kg
mass of cylinder	mcy	$= 30.0$ kg
fixing elasticity of cylinder	efi	$= 1.0\times10^{-9}$ m/N
connecting elasticity with actuator	el	$= 1.8\times10^{-8}$ m /N
mass of actuator	ma	$= 200$ kg

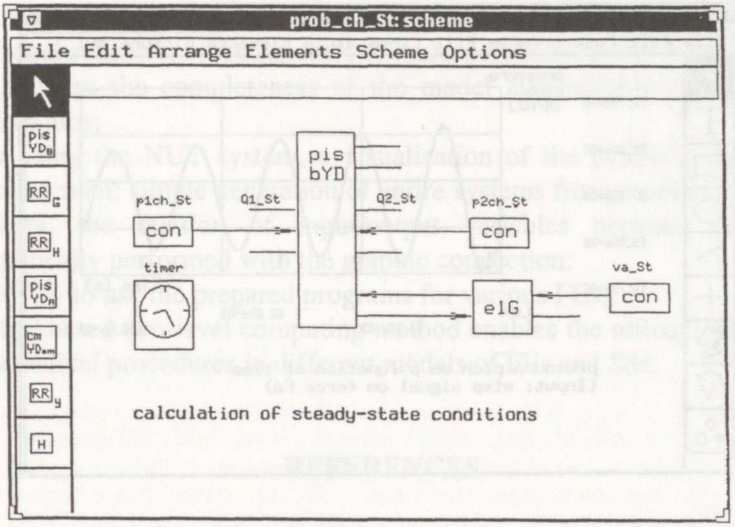


Fig. 10. Graphically composed computing task for the calculation of the steady-state motion: pis bYD – piston in hydraulic cylinder, elG – connecting elasticity.

Chosen independent initial steady-state values:

pressure in the left cylinder chamber p1chst = 2.0e7 Pa

pressure in the right cylinder chamber p2chst = 1.5e7 Pa

actuator velocity vast = 0.01 m/s

The calculated steady-state values of variables as initial data are:

actuator force Fast = 58100 N

volumetric flow rate in the left cylinder chamber Q1chst = 1.34029×10^{-4} m^3/s

volumetric flow rate in the right cylinder chamber Q2chst = 1.21463×10^{-4} m^3/s

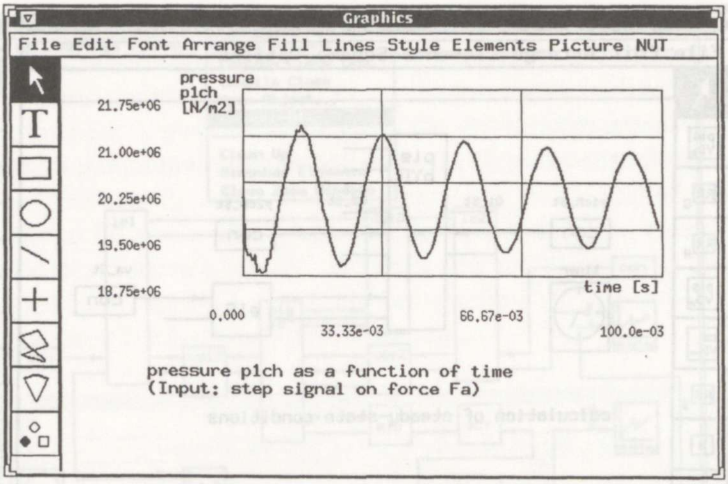
To calculate the transient response, the following simulation parameters have been given:

simulation time T = 0.100 s

time steps n = 400

allowed relative calculation error in the second level eps = 1.0×10^{-6}

The calculation results will be displayed graphically. The graphic window enables us to insert additionally graphic elements and text. The process run of the pressure *p1ch* in the left chamber of the cylinder is shown in Fig. 11, and the process run of the actuator velocity *va* in Fig. 12.



pressure p1ch as a function of time
(Input: step signal on force Fa)

Fig. 11. Process run of the pressure *p1ch* in the left chamber of the cylinder (input: step signal of force on the actuator *Fa*).

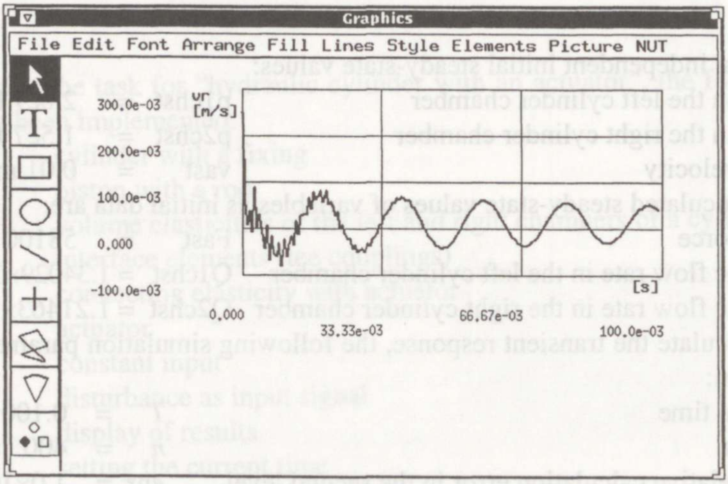


Fig. 12. Process run of the actuator velocity *va* (input: step signal of force on the actuator *Fa*).

7. CONCLUSIONS

The described model generation concept provides the following advantages:

- the implemented multi-pole models of the FEs or SSs describe the ports, which have oriented input and output variables, as it happens in most real physical systems;

- methodical and visual development of various MMs, using the principle and functional schemes, block schemes of multi-pole models and oriented graphs;
- it guarantees the completeness of the model and suitable causality of the relationships;
- when using the NUT system, a visualization of the problem appears on a graphic screen: simple generation of entire systems from user-defined graphic elements; the relation of input/output variables between elements is automatically performed with the graphic connection;
- possibility to use the prepared programs for various FEs;
- the distributed two-level computing method enables the utilization of various mathematical procedures in different models of FEs and SSs.

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KOORMUSTUNDLIKU HÜDRAULILISE AJAMI FUNKTSIOONIELEMENTIDE MITMEPOOLUS-MUDELITE PLOKKSKEEMIDE KOOSTAMINE

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Koormustundliku hüdraulilise ajami näitel on kirjeldatud keerukate tehniliste süsteemide staatika, statsionaarse liikumise ja siirdeprotsesside arvutamise matemaatiliste mudelite koostamise põhimõtteid. Uuritav tehniline süsteem on jaotatud funktsioonielementideks (FE) ja alamsüsteemideks (AS) ning tähistatud paariviisi kõik muutujad. Iga FE ja AS on esitatud mitmepoolus-mudelina, millistest on koostatud kogu uuritava tehnilise süsteemi plokkskeem. Arvutused on tehtud kaheastmeliselt algoritmi ja programmi automaatgenereerimist tagava programmeerimissüsteemi NUT abil. Esimesel astmel on arvutatud iga üksiku FE tunnusjooned, teisel astmel aga ühildatud iteratiivselt kõik potentsiaalsed muutujad. On vaadeldud hüdrosilindrilt käitatava töömehhanismi siirdeprotsessi arvutamist.