STRUCTURED MATHEMATICAL MODEL GENERATION, SIMULATION AND CONTROL OF HYDRAULIC AND PNEUMATIC DRIVE SYSTEMS WITH HYPAS

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1. INTRODUCTION

Modern design and simulation tools oriented for specific application areas are interactive and offers the user pre-defined modules at different levels of models organisation. To create a software tool, that is very easy to handle not only for specialists but also for those users who do not have much experience in the field of computers, programming and/or mathematical modelling, is an important trend in CAD techniques. This trend can be observed in hydraulics too [7, 8, 9]. Most of these software products have own specific defined graphical user interfaces (GUI) and allow the set up a, with limited field of application, the model self being achieved in several steps, also by using pre-defined modules. The multipurpose generally oriented software MATLAB/SIMULINK dispose not of a database of pre-defined mathematical models.

This paper is a limited report on the present stage of realisation of the assisted modelling and simulation with HYPAS of hydraulic and pneumatic drive systems. After a general presentation of the philosophy, the mathematical modelling and of two examples, the papers present several information on auxiliary instruments of HYPAS as working with diagrams, data bases, tools and other facilities [9].The HYPAS software environment has been created to assist the design, modelling, and simulation of hydraulic and pneumatic installations and their mechanical compliant structures. Different controllers such as: PID, Kalman, Observer, Fuzzy, self tuning, and differential were developed and implemented as the control library of HYPAS.

2. OVERVIEW OF HYPAS

2.1. Generalities

HYPAS is an object oriented and multitasking software that uses Windows facilities [15, 16, 21]. Its major task is to interactively assist the engineer scientist by the deriving of appropriate mathematical models of hydraulic and pneumatic installations and its compliant mechanical driven structures, to achieve a simulation and to graphically represent the obtained results. Thus deliver him of the most critical task by any modelling, as those of writing non-linear differential equations. No restriction or limitation are incorporated in the global concept of HYPAS so that other systems could be modelled and simulated, data bases, with all kind of diagrams can be created. HYPAS disposes of a the formal mathematical description of structure parameters and the automatic/dynamic or manual allocation of the integration procedures as well as of many smart facilities, as different tools for helping during the work with it.

The interface of HYPAS is user-interactive and requires no extensive modelling and programming experience. The background of HYPAS is the Modular Structured Mathematical Modelling set by author over several years. This is endowed with pre-defined mathematical operations and modules of mathematical models (MM) stored in appropriate libraries, at the present time, available for hydraulic, pneumatic and mechanical elements, layer properties and controllers. The user may build own models or improve those delivered by the database. Different types of diagrams assist the user to better understand the modelling and operation of the installation.

2.2. Mathematical Modelling in HYPAS

Mathematical Modelling in HYPAS occurs upon an own mathematical description called: ***Systemic Model Description*** (SMD) [3, 4, 5]. It refers to the design mode for a generalised physical system in the simulation program. The SMD concept is based both on the objective reality and on its scientific perception as one can observe in the following picture

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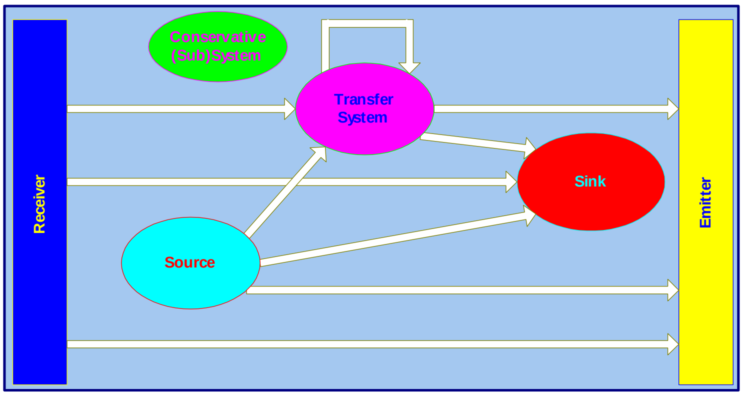


Figure 1. Systemic dichotomical representation in HYPAS.

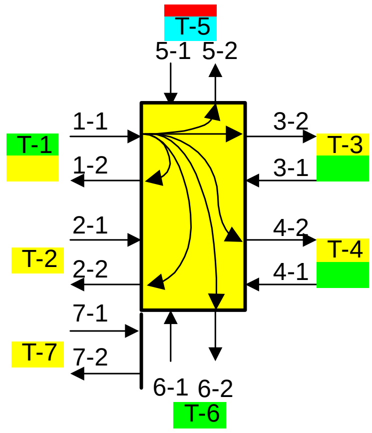


Figure 2. Generalised block presentation of an element in HYPAS, as multiport.

The Systemic Model Description assumes the Model Systemic Dichotomy:

1. According to the *energy exchange* with the environment*:* ***Transfer***-Exchange of energy with the environment; ***Conservative* -** No energy transfer with the exterior

2. Terminal energy exchange blocks: ***Source***-Specialised energy spring; ***Sink***-Energy flow terminal.

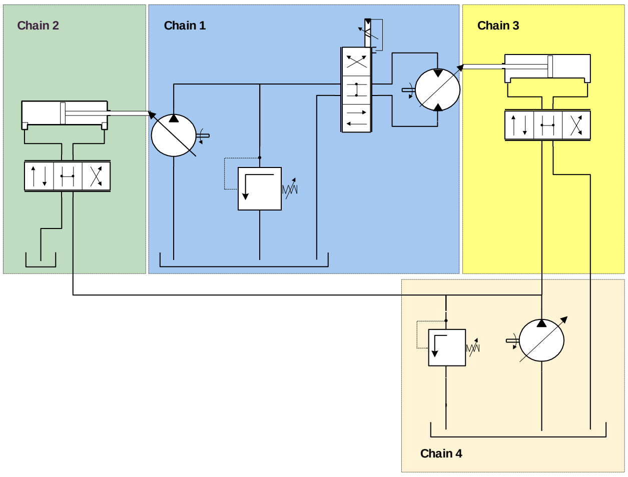
3. ***Surface energy exchange units***: ***Receiver***-Input, ***Sensor***-translation unit that is directed from environment to the inner world of the system; ***Emitter***-Output-energy translation unit to the environmental world.

The description hides in its background the diagrams' creation mechanism of large compound systems. Except the surface subsystems, all subsystems can be at their turn aggregated. By means of this method, one can form a hierarchy with different depth description levels [1,…, 4]. Other information concerning the mathematical description are presented in [7, … , 21].

If one consider the installation in the figure 3,a, one may see, that contents (simplified) then elements: two pumps with variable displacement, two actuators, three servovalves and two pressure valves. Each of them being described by at least a differential equation second order, without to mention that internally the two pumps are driven by two actuators. One obtain twelve differential equations second order, or twenty four equations first order, it means matrix 24 $*$ 24. Only the simple deriving of this equations are rising big problems. More that that, the graphical association of these equations into analogical-block-diagrams and the overview on the phenomena became more an more difficult with the growth of the number of equations and necessitates an appropriate experience from the scientist.

This "*natural*" way of systems description proposed and adopted by HYPAS offers the possibility to implement the *Object Oriented Technique*. Thus the MM of any installation occurs by generating/designing a standard-diagram to which HYPAS automatically associates its corresponding MM in the form of an analogue block diagram and is proposing the integration algorithms, mostly appropriate for the present layer properties [15, 17, 21 To this purpose an appropriate MM is assigned to each module. The MM of the designed installation is automatically generated, when the graphical connection of modules is finished [8, 9, 22]. On the figure 3,b one may see the standard diagram of the installation presented above.

The figure 3,b shows the standard diagram of the installation presented above. Appropriately to the thinking way of the engineer, modules of which the installation consist and to whom MM are created an deposited, were graphically transported as diagrams from the data base of modules, and putted on the construction screen of HYPAS. The logical connection of the individual MM of the modules will be achieved through the connection of each input and output of all modules. After setting the individual sets of numerical data of modules, the simulation can be started. Afterwards be means of different graphs, as: transient, space of state and frequency representations the achieved results can be visualised.



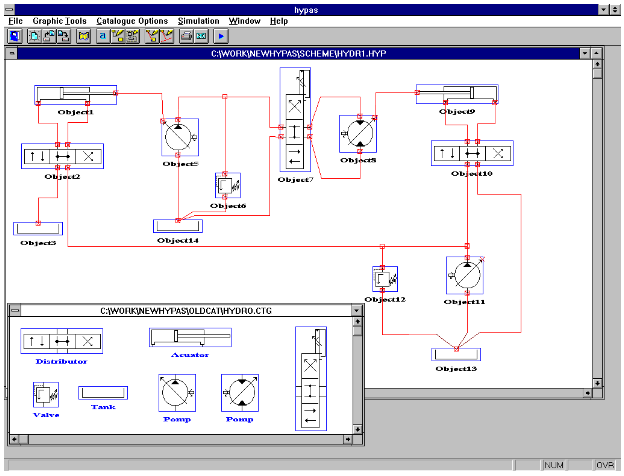
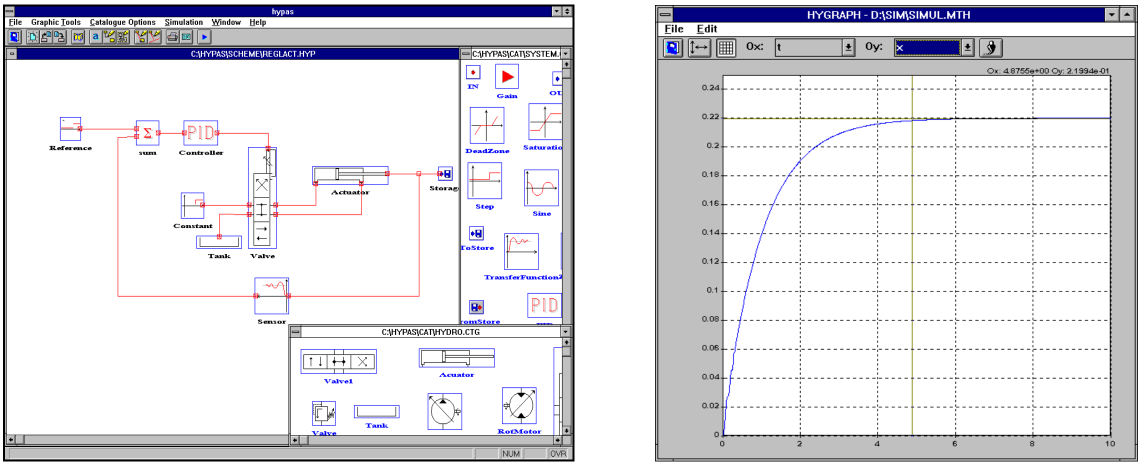


Figure 3,a. Manually achieved diagram of a system to be modelled.

Figure 3,b. Simulation diagram of the installation in figure 3,a generated with HYPAS.

2.3. Example of modelling and simulation of an electro-hydraulic

Figure 4 presents the diagram of an electro-hydraulic axis automatically generated with HYPAS and simulated [14, ... , 18]. To generate the diagram, the following three data bases (DB) were used: the DB of modules, for: servovalve, actuator and transducer; the DB with tools, for the PID controller and the DB with layer properties, for summation, the input variable (in this case a step input) and terminal for the output variable. A displacement of 0,22 [m] is obtained in ca. 5,8 [s] after a monotone evolution.



a. b.

Figure 4. HYPAS bloc diagram of an electro-hydraulic axis and result of a simulation.

After having set the desired integration procedure and the integration data, the integration is achieved. The HYGRAPH module assist the user to represent the desired variables [20]. The scaling can be interactively set by the user self. Data from other programs as EXCEL, SDS, Matlab/SIMULINK can be used, for further representations.

3. CONTROLLERS OF HYPAS

The following types of controllers were implemented: P, PI, PD, PID, Kalman, Observer, self adaptive, Fuzzy, Neuro-Fuzzy and Neural [7, ... , 21]. The PID controller, the observer and some data about the neuro-fuzzy controller will be presented in this section. The used numerical data of the axis correspond to a real electrohydraulic device presented before [5]. This axis and the control algorithms are involved in the control of: position, velocity, pressure and force. The simulation results were achieved for the position control of the servoactuator`s rod. The dynamic behaviour of the mounting was not considered.

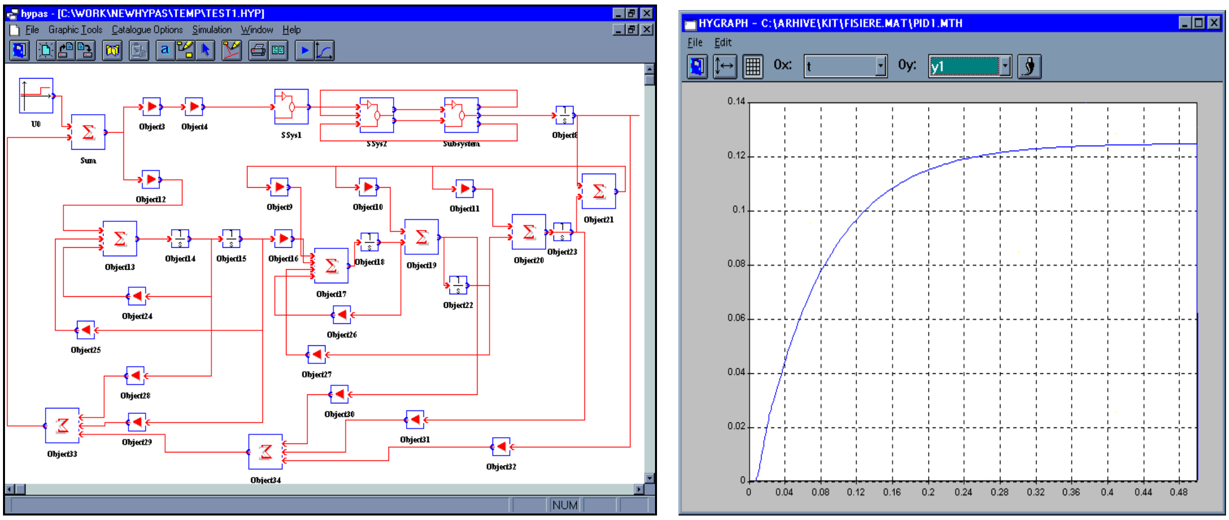
3.1. The PID controller

The optimised achieved PID regulator were defined as: $K_r\ (\ 1\ +\ T_d\ s\ +\ T_i\ /s\ )$ [7, 15, 16 219, 21]. The simulation occur with the analogue-block-diagram whose actuators object can be observed in figure 4,a. The position control, presented in figure 4,b, was obtained with the following set of parameters: $K_r = 1$; $T_i = 0.0028$ **[s]**; $T_d = 0.0005$ **[s]** and a reference input tension $U_{ref} = 2$ **[V],** corresponding to a stroke of **0,1 [m]**.

3.2 The observer

For the proposed axis a (n-m-1) order structure of the observer is adopted, where n = 5 represents the order of the system and m = 1 is the number of outputs [7, ..., 21]. The model is described by five state variables: two for the second order model of the servovalve and three for the third order linear motor/actuator.

The complete system contains: the non-linear axis, with the known static and dynamic non-linearities [6, 20], a parallel second order model for the servovalve, a third order actuator, a linear third order observer for the actuator, a reconstruction model for the servovalve and a controller with five loops for the five state variables. The used observer with inverse reconstruction matrix has the third order and is matched on the actuator, while for the servovalve a parallel model was achieved. The HYPAS analogue-block diagram of the plant with the observer and a simulation result are depicted in figure 6. [7, 20]. A five order observer and a non-linear observer are also available in the data base.



a. **b.**

Figure 6. Flow-chart-diagram of the axis with observer and simulation result in HYPAS.

3.3 FUZZY, Neuro-Fuzzy and Neural Network Controllers

Structures of these controllers, which are implemented in HYPAS and results of simulation are presented in [7, 8, 9, 10, 12, … , 21]. They shown important advantages, but the classical controllers remained implemented in HYPAS. Two phases in designing of the controller were used: the control and the adaptation. In the control phase, the plant output and the reference signal determine a control command *u(k).*

The plant input becomes the sum of the $u(k)$ and $u_p(k)$. In the adaptation phase, the inverse model which has as inputs $y(k+1)$ and $y(k)$ produces as output the signal $\hat{u}(k)$. This signal is used to compute the error $e_u(k)$ which determines

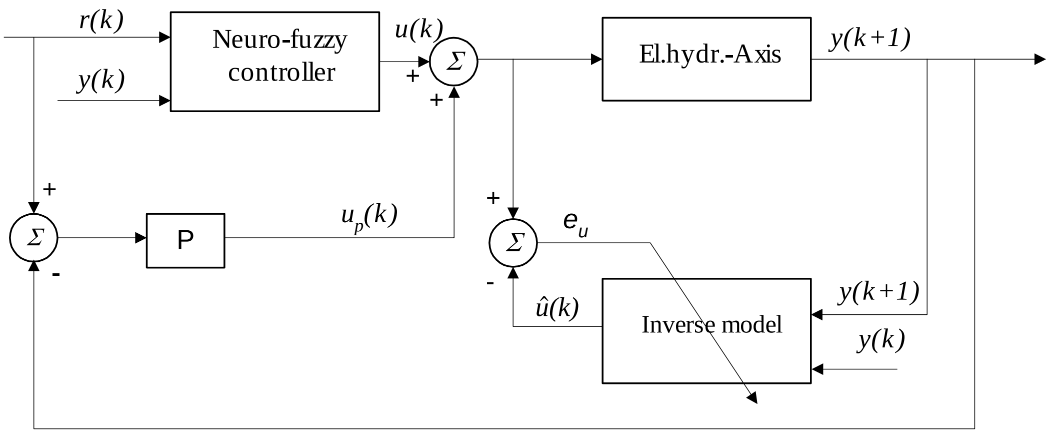


Figure 7. Block diagram for the inverse learning method.

the value of the cost function *J(k)* that has to be minimised:

$$J(k)=\frac{1}{2}\cdot e_u^2(k)=\frac{1}{2}\cdot(u(k)-\hat{u}(k))^2$$

In this example the plant is an electro-hydraulic axis. It is composed of a pressure source, a servovalve as interface element between the control and the actuator, an actuator and a position transducer. The axis has a strong a non-linear structure. The simulation implemented model of axis is depicted in figure 4. This axis is part of a cartesian robot endowed with three similar axes.

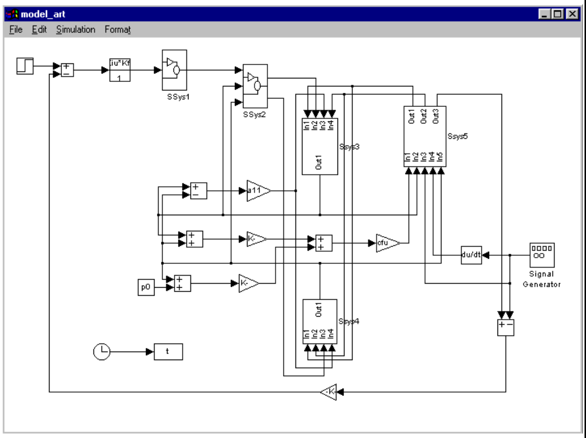


Figure 8. Simulation model of the electro-hydraulic.

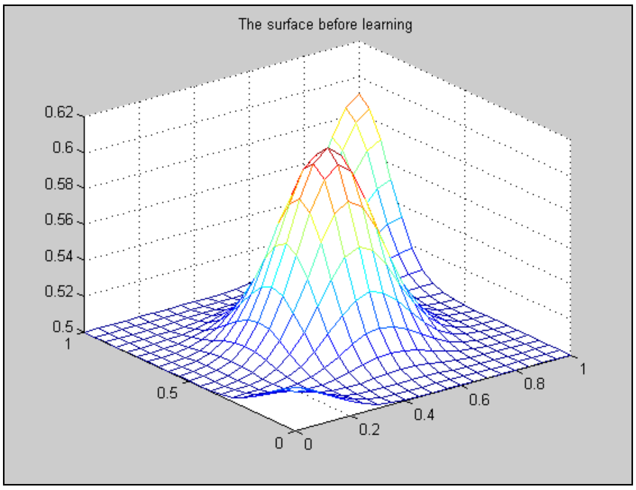
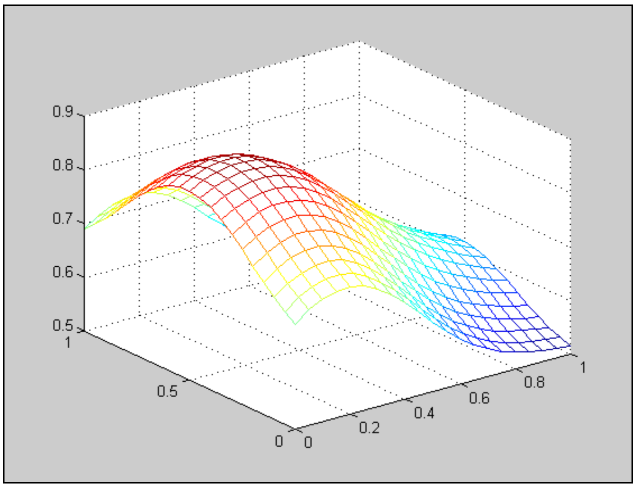


Figure 9. The surface after the first iteration



Figigure 10. Surface obtained after learning.

4. MORE ABOUT MODELLING AND SIMULATION WITH HYPAS

4.1. Main targets of HYPAS and examples of solutions

The following main targets are accomplished by HYPAS 16, 17, 21]:

i. It interactively assist the user by developing own MM of small or large scale installations. The adopted solution in HYPAS uses different types of catalogues with modules or layer properties. The user may accept and, eventually, can change the MM who was put by the computer to its disposal. Installations and other components of artificial and expert intelligence are incorporated.

ii. HYPAS requires no programming knowledge.

iii. It open for further developments by adding new modules.

iv. It allows the study of steady-state, transient and stationary behaviour and permit any graphical representation with means easy to manipulate.

v. HYPAS allows the easy change of structure data, in particularly those data which are present at many places in the MM, such the Bulk-modulus β. This is realised by using a formal mathematical description.

Figure 11. Result of a smart self debugging function in HYPAS.

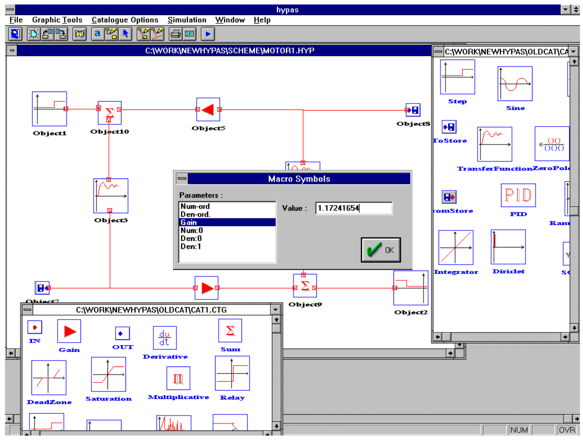


Figure 12. Setting of transfer functions in HYPAS.

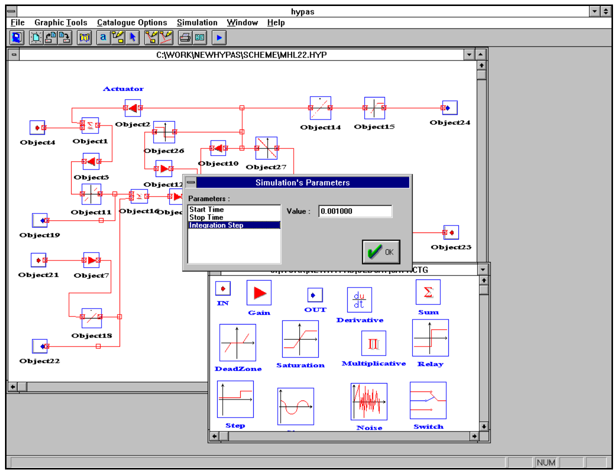


Figure 13. Setting board for operation data by the numerical integration in HYPAS.

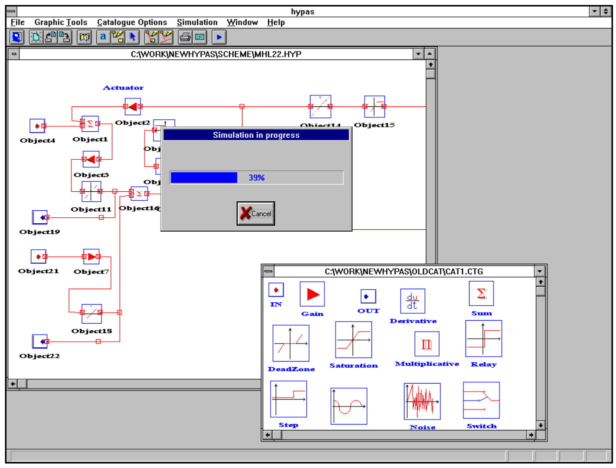


Figure 14. Information on the stand of numerical solution of the analysis

4.2. Main Men

The main menu of HYPAS, presented in figure 15, interactively allows the operations to be achieved. The following operations are assisted:

1. *Management of files*. Files with graphical, logical and numerical data/information will be managed. The graphical one refers to the graphical representation of modules and layer properties. The logical are subroutines assigned to the modules and layer properties and contain the MM of these elements. The numerical files contents the assigned data sets.

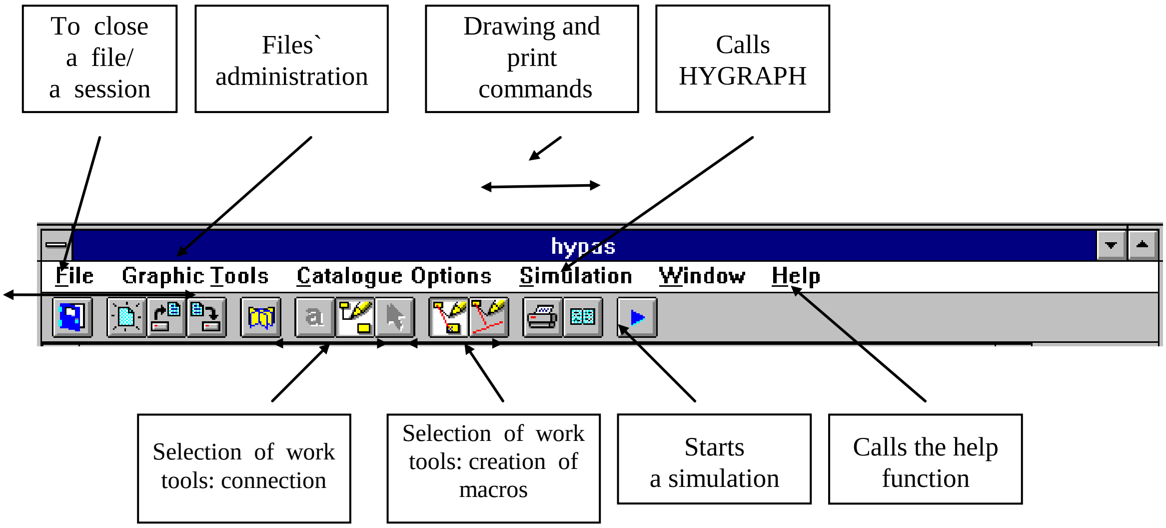


Figure 15. Main menu of HYPAS - Modelling and Simulation Program.

2. *To access the design editor*. The graphical editor will be called and its windows opend after the appropriate command occurs (See also § 4.4).

3. *To construct and/or modify a simulation diagram*. This action consists of building or changing the desired standard diagram, and by this mean, the MM of it. To this purpose, the involved databases with modules will be opened and the icons of the desired modules will be translated be means of the "drag-and-drop" action on the construction window. Afterwards the inputs and outputs of modules will be appropriately connected by using the connection function. This action requires normal engineer knowledge.

4. *To set the numerical data of modules/installations*. By opening of a module, three types of further accesses are created: ***i.*** the graphical data bases with: the analogue-block-diagram, the block-diagram with energy transfer and the block-diagram with information-transfer; *ii*. the listing of the assigned routines, written in ***C++;*** ***iii.*** the data set. These can be manually changed, smart solutions are helping this action.

5. *To build macros*. Macros can be build by using the special facility on the main menu. Each macro will be named and can be separately simulated, stored or called. All the contented individual modules/files will be "added" and assigned to each macro.

6. *To start and/or stop a simulation*. After a simulation diagram was designed, stored and a set of data was assigned, the simulation can start.

7. *To draw the simulation and other computed results*. It occurs with the HYGRAPH Module of HYPAS. Drown diagrams can be directly printed, after having set the environment.

4.3. Data Bases of HYPAS

Four databases are created and are available in HYPAS. They refer to: the graphical symbols/icons of modules; the mathematical models of all modules, as ***C++*** subroutines; the analogue-bloc-diagrams; the bloc-diagrams with energy and information transfer; the numerical data sets. ***i***. *Data base with standard graphical symbols of modules*. This is oriented on functional elements, such as hydraulic, pneumatic and mechanic components for: ***a***. *Hydraulic components*, such as: pumps, rotary motors, actuators, limited angle rotary motors, directional valves, throttle valves, pressure valves, proportional valves, servovalves, lines, accumulators, filters, tanks; ***b***. *Pneumatic components*, such as: rotary motors; actuators, directional valves, throttle valves, pressure valves;

proportional valves, servovalves, lines; ***c***. *Mechanic components*, such as: gear boxes, screw mechanism; ***ii***. *Data base with mathematical*

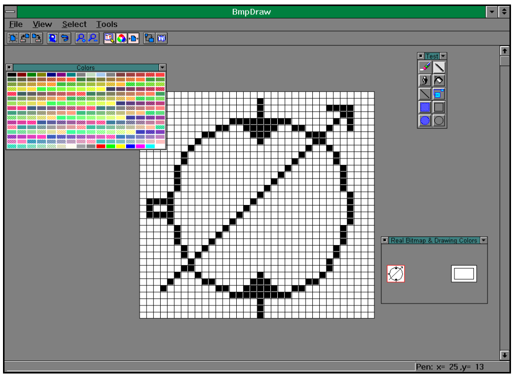


Figure 16. Menu of graphical editor with a diagram of a pump.

models contains the routines of achieved modules, installations and of all layer properties are available in HYPAS. of layer properties which contains integration are written for: Euler-Cauchy, RK-II, RK-IV, HEUN, HEUN-Modified, PL algorithms; ***iii***. *Data base layer properties.* The later refer to: mathematical operations of all kind, input and output functions, usual non-linearities, such as: dead zone, jump in origin, relay, double slope, hysteresis, viscous and dry friction, hysteretic friction, different operations with variables, variables at power different of one. These models are mathematically described and implemented as ***C++*** routines, together with their appropriate symbol in the catalogues. Compared studies were performed with MATLAB/SIMULINK [26] simulation program; ***iv.*** *Database with block-diagrams.* Some block-diagrams are presented in figures 6,a, 7 & 9. There are two types of block-diagrams available: with energy- and information transfer; ***v.*** *Database with analogue-block-diagrams.* To each layer property and to each module a MM was analytically inferred. To each of them a standard or usual known graphical symbol was drawn and/or designed and attached. They are stored in a appropriate data base of mathematical models. (See figures 10, 14 & 15); ***vi***. *Database with numerical data sets.* Structure data of the modules were stored as default data sets and can be used as they are. They were conceived in agreement with the common experimental results of some products on the market. They can be accepted and/or changed before the simulation starts and again stored as variable sets of the default numerical data.

4.4. The design module

This function operates interactively in HYPAS by means of a drawing editor. It can be called by making use of its assigned ICON on the main menu. The design module serves to the creation of the graphical databases. It can be also used to complete and to change the diagram of any module or layer property. There is not limitation of figures' forms that can be drown. The achieved drawings (diagrams, symbols) will be stored as *.bmp-files. The same name will be given to the assigned mathematical model. The drawing window and the symbol of a variable displacement rotary motor are presented in figure 9. The editor works as independent module. The editor-module was developed as *Single Document Interface (SDI)* and can draw only individual symbols with different dimensions. The colours of window are those of the installed Windows. The used tools correspond to the usual for the *Bitmap-Drawing* including 256 colours, which can be chosen for all drawn actions. *Drawing commands.* Usual drawing tools are available as a *Tools-Menu* or as a *Tools- window.* The following actions can be ordered: ***a***. Drawing of geometrical figures such as: square, ellipse, circle s (full or empty); ***b***. Drawing of an outline; Filling up of an outline; ***c***. Erasing of a figure or of a part of it; ***d***. Spray dose; ***e***. Creation of connections in the diagrams.

4.5. Simulation module

Since to every MM a simulation diagram will be assigned. By opening of a simulation session a simulation program with *"empty"* content will be created. Any drag-and-drop action with respect to any *module* and *layer property* will select and put successively on the simulation page of program the assigned subroutine of the above chosen element. The logical connection between the modules and properties occurs only by the connection through lines of an output point with the input. A set of numerical data is attached by default to any simulation model. After assigning a set of data, the executable model can be interpreted or executed step-by-step. Two methods can be applied:

- the first one foreseen the use of a single type of integration. Seven algorithms were developed such as: Euler-Cauchy, RKII, RKIV, RKVI, Heun, Heun-Modified with adapted step, Predictor-Corrector [17, 18, 21].

- The second one uses a dynamic allocation of integration. Before any simulation starts, a classification procedure starts the automatic selection of the algorithms, with respect to the integrations behaviour by non-linearities. They are proposed and can be changed at any moment by the user [17, 18, 21].

4.6 Main procedures in HYPAS

Three possibilities can be envisaged by the user: ***i***. *To generate the MM of an own simulation diagram*. T user has to build the analogue-block-diagram assigned to his mathematical model by using the catalogue of layer properties and the drag-and-drop technique. The MM of the chosen layer properties will be "transferred" from the database to the executing file. After that all inputs and output of the elements are to be graphically connected. To this act corresponds the logical connection of the routines on the executable program. The model can be simulated, after the data sets were assigned; ***ii***. *To simulate a predesigned simulation diagram*. In this case the user has the task to choose the appropriate symbols of modules from database of symbols and to drop and drag them on the work window. HYPAS will take care of the creation of the execution mathematical models of this standard diagram. The user may open the MM given in form of the analogue-block-diagram and the routine; ***iii***. *To simulate a predesigned installation & diagram*. An expert module is foreseen to classify already realised diagrams. They are stored and managed by an expert module, which can find out and suggest an appropriate diagram able to carry out the desired functions. The user may accept or change and simulate it.

4.7. HYGRAPH-Module for graphical drawing

For drawing the obtained numerical results, the HYGRAPH specialised drawing module, was created. Transient and stationary evolutions in real formalisation, such as Bode-Diagrams or in complex formalisation, such as Nyquist-Diagrams, can be represented. Some details about HYGRAPH are presented in figure 4 and 16. [15, 16, 22].

4.8. Macro definitions

Two or more modules as well as any layer properties can be grouped as macros or objects. A special function and an assigned icon on the main menu can be called to this purpose (figure 10). Definitions of type macro (MD) were chosen as general form of ***composite*** representation of element connection. By means of MD one facilitate the design of diagrams independently from their complexity. On this way the MD of a complex installation is an association of the MD of the components.

4.9. Description of some object oriented functions in HYPAS

Any layer property and/or component is defined as objects. They are classified of functional point of view as *"object-folder"*-definition which is grouping the objects with the same function but which is differently conceived. Some other functions are available: ***a***. Moving of objects on the working window; ***b***. Resizing the objects; ***c***. Changing the position of the objects and of the connections; ***d***. Suspending of a connection line between two objects; ***e***. Erasing out of an object;

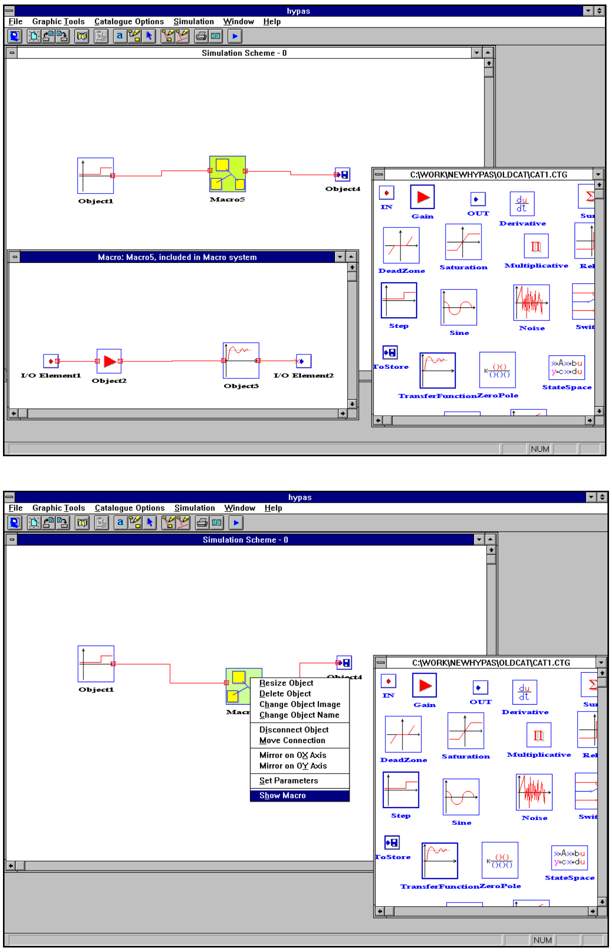


Figure 17. Macro definition and functions for macros handling. Some layer properties in HYPAS.

f. Changing the assigned graphical symbols of the modules; ***g.*** Creation and modification of new *folders* completion of the data base.

5. MODELLING STRUCTURE AND TYPES OF DIAGRAMS

5.1. Description of used object oriented functions

The MM of any module is decomposed down to the elementary layer. The informational hierarchy, presented in figure 15 contains the following six levels: layer properties: forces /torque and flow; group balance equations; half module/module of: pumps, motors, valves {taken completely or only a half of them}; half chain/chain, a succession of (half) modules respectively modules and installation; chain; installation an assembly of minimum two chains.

5.2. Types of Diagrams

According to the point of view of HYPAS, each module contains maximum seven gates, while each gate operates with maximum 2 variables. Graphical symbols were developed in HYPAS. Those four types of diagrams (figures 3, 6, 13 19) assists the graphical formalisation in HYPAS: i. ***Functional-Standard-Diagram***; it represents the first stage in the design process. By means of these symbols, an installation can be standard designed; ii. ***Energetic-Block- Diagram.***. iii. ***Information-Block-Diagram***; iv. ***Analogue-Block-Diagram.*** They are both in linear (rised) and nonlinear form. Five levels of structuration are used in HYPAS. They refer to: layer, group, half module, module, chain and installation.

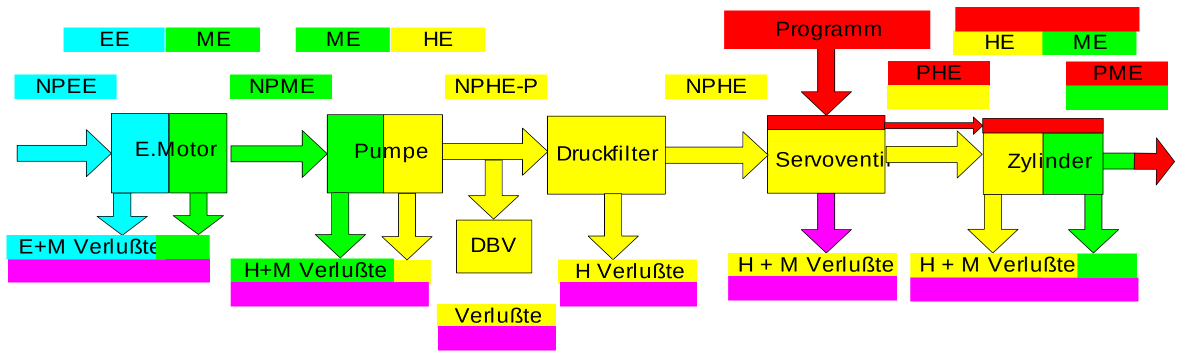


Figure 18,a. Structures hierarchy of the modular-structured mathematical modelling by HYPAS.

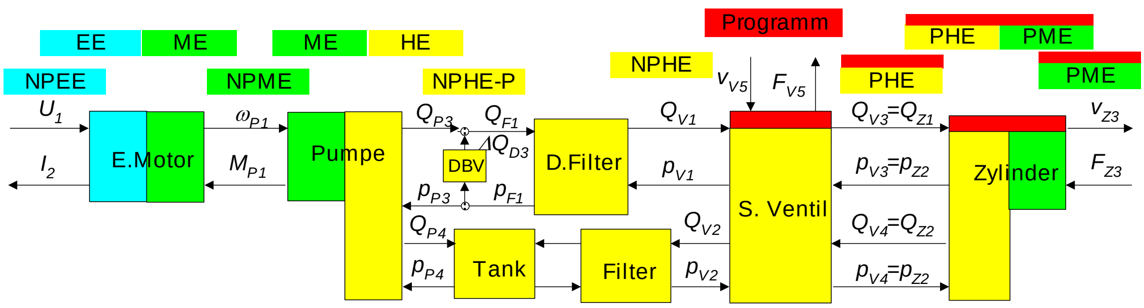
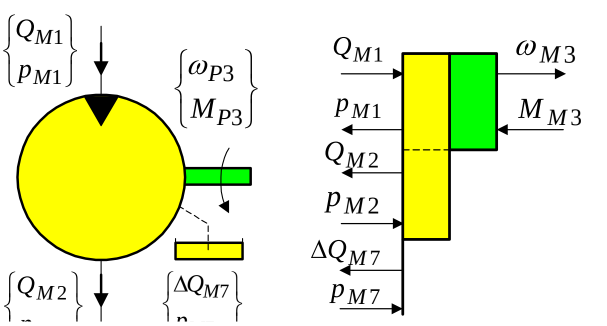


Figure 18,b. Block-Diagram with information transmission as is organised in HYPAS .



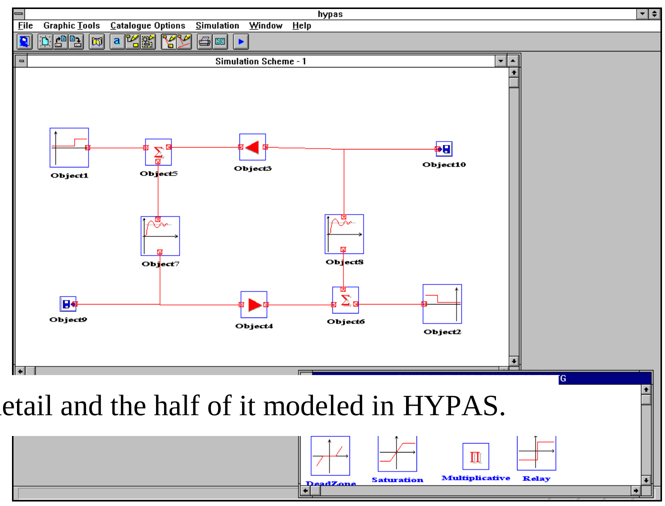


Figure 19. Block-Diagram of the rotary motor in detail and the half of it modeled in HYPAS.

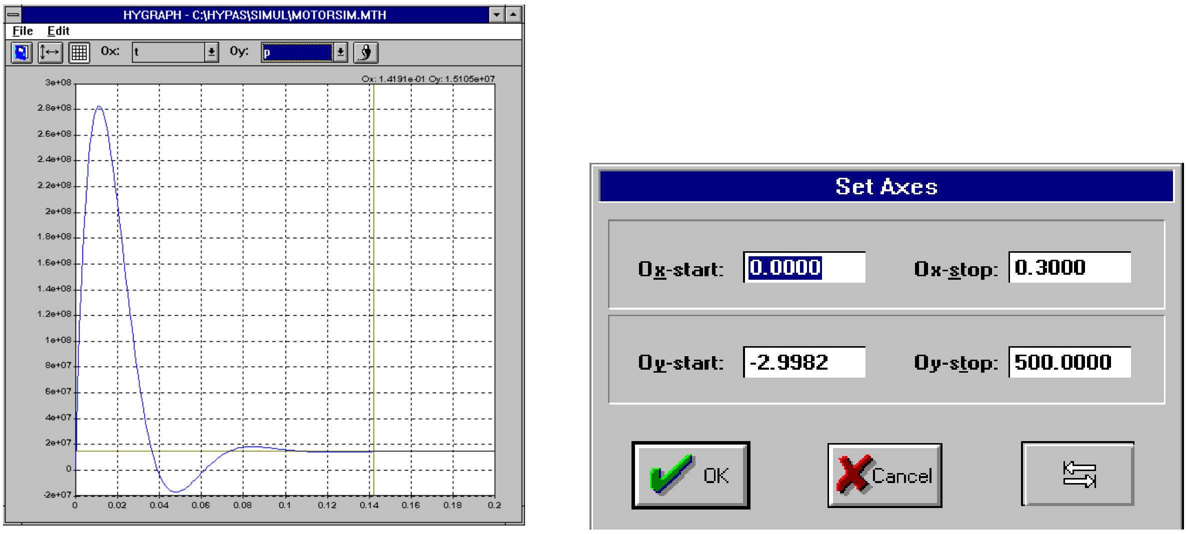


Figure 20. Simulation result of the Rotary motor presented in figure 19 with scaling setting window in HYPAS.

6. CONCLUSIONS

The paper present the achieved results on the field of structured mathematical and object oriented modelling, simulation and control of hydraulic & pneumatic drive systems by means of HYPAS approach and software. Information about this approach and its philosophy, the architecture of the software and its operation mode, tools and databases of HYPAS are presented.

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