

MECHATRONICS BETWEEN DREAM AND ACTUAL REALITY

Florin IONESCU¹, Ion BOSTAN², Valeriu DULGHERU³, Dragoş AROTĂRIŢEI⁴,
 George CONSTANTIN⁵, Kostadin KOSTADINOV⁶, Florin STRATULAT⁷

Abstract: *The paper presents some achievements in complex modelling and simulation in mechatronics, being underlined some characteristics of the mechatronics field together with applications of the mechatronics design principles. Some aspects of the optimized and integrated design having as main part the modelling and simulation of the system are presented. The facilities of the programs used for kinematic and dynamic simulation of multi-body systems are emphasized. Some mechatronic systems are presented as examples of modelling and simulation in MATLAB/Simulink (MS), SolidDynamics (SD) or MotionInventor (MI) programs with accent on robots for micro and nano manipulations of cells, industrial robots, and precessional drives.*

Key words: *mechatronic systems, design, modelling, simulation, analysis, optimization, micro-nano robots, industrial robots, precessional drives.*

1. INTRODUCTION

The concept of mechatronics appeared in Japan 30 years ago, and is a complex concept in a continuous change. It has had the meaning of a synergistic combination of mechanics and electronics, being related to electromechanics, but differing in the criteria of design. Therefore, mechatronics is a significant interdisciplinary design trend that involves the application of the latest techniques in precision mechanical engineering, controls theory, computer science, and electronics (Fig. 1) to create and bring fast to the market more functional and adaptable products with precise performances. Figure 2 presents the mechanical process and information processing in mechatronic systems.

The concept of mechatronics has a strong influence not only on the product design and development and the competition on the market, but also on the mechanical engineering education and team leaders or engineering managers.

Thus, the mechatronic products have specific characteristics, including the replacement of many mechanical

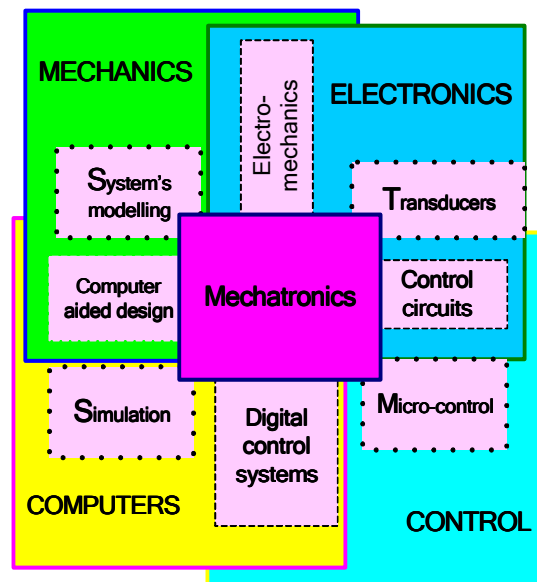


Fig. 1. Fundamental elements of mechatronics.

functions with electronic ones. By applying new controls one expects from a mechanical device to reach new levels of performance.

2. OPTIMIZED AND INTEGRATED DESIGN IN MECHATRONICS

Having permanently in view the achievement of a higher quality-price ratio and also the performances a product of relative high complexity has to satisfy, the application of the simulation on physical models at real or reduced scale, which do not allow flexibility, is not appropriate.

The optimization in closed loop is not possible in those cases. Important stages of the presented cycle can be easily done by using a computer. Thus, one has to use high integrated methods of computer aided design [6]. The advantages of the programs in this domain and their

¹ PhD, Dr. h.c. mult., Prof., University of Applied Sciences Konstanz, Germany, Tel./Fax 0049 7531 206 289, E-mail: ionescu@htwg-konstanz.de

² Acad., PhD, Dr. h.c. mult., Prof., Rector, Technical University of Moldova, Republic of Moldova, E-mail: bostan@mail.utm.md

³ PhD, Assoc. Prof., Head of Theory of Mechanism and Machine Elements Department, Technical University of Moldova, Republic of Moldova, E-mail: dulgheru@mail.utm.md

⁴ PhD, Prof., "Gr. T. Popa" University of Medicine and Pharmacy, Iasi, Medical Bioengineering Faculty, Iasi, Romania, E-mail: darotari@htwg-konstanz.de

⁵ PhD, Prof., University "Politehnica" of Bucharest, Machines and Manufacturing Systems Department, Bucharest, Romania, E-mail: george.constantin@icmas.eu

⁶ PhD, Assoc. Professor, Bulgarian Academy of Sciences – Institute of Mechanics, E-mail: kostadinov@imbm.bas.bg

⁷ PhD, Prof., Assoc. Professor, University "Politehnica" of Bucharest, Automatics and Industrial Informatics Department, E-mail: stratulat@gmail.com

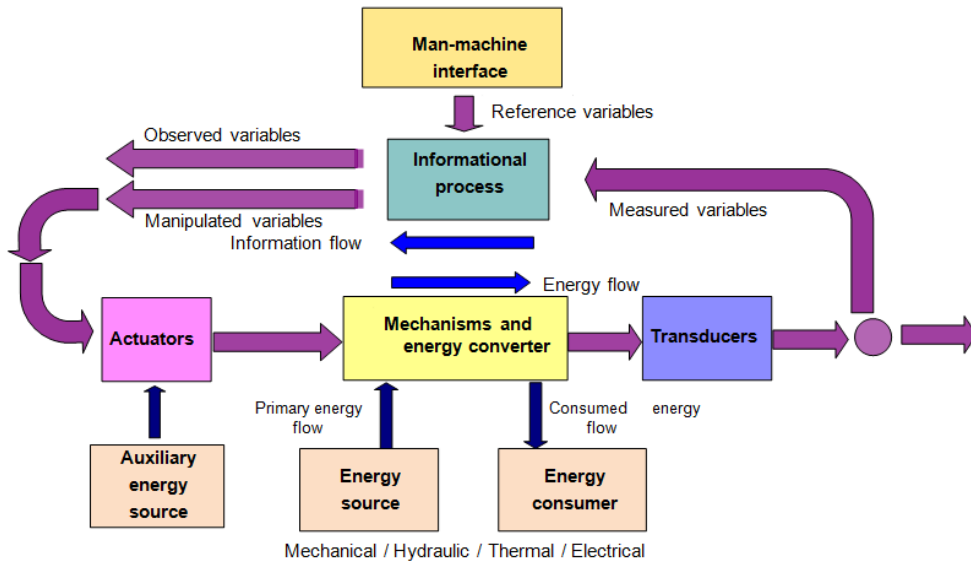


Fig. 2. Mechanical process and information processing in mechatronic systems.

integration that are specialized on 3D geometry generation, kinematic and dynamic simulation, static and dynamic behaviour analysis, are used. In Fig. 3 the diagram of the integration principle is shown starting with the pre-design and ending with the final product [16, 3].

Figure 4 shows the information model with multiple loops which allows the design and optimization at different levels. The stages in their sequence are emphasized: project specification, preliminary draft, project achievement, model building for calculation and analyzing with kinematic and dynamic simulation programs MS or SD, result obtaining, checking the validity, finite element analysis (ANSYS), decision on the analysis results, prototype creation, experimental test, optimization and procedure confirmation. The information transfer is realized in multiple loops, the loops of optimization being of great importance [15].

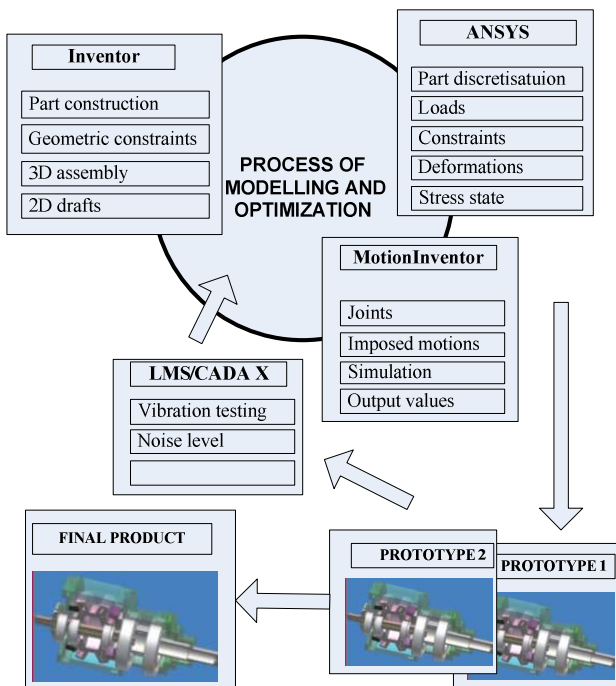


Fig. 3. Integration principle diagram. Process of developing the precessional drive products using CAD-CAE platform.

In SD and ANSYS there are internal optimization loops that work on the basis of pre-established performance criteria (not presented in figure).

After the pre-project realization, the three dimensional representation is achieved consisting of geometrical characteristics. These have parameters that can be specified in the drawing or calculated as part of the analysis. The geometric calculations are associated to the bodies that have mass properties. The analysis can be done on the existing drawing, or on the idealized drawing derived from the real one.

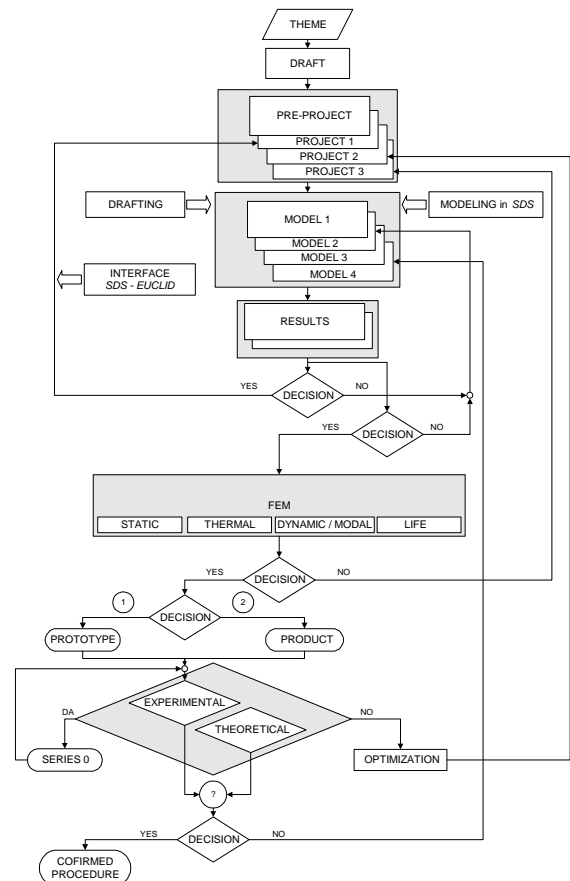


Fig. 4. Information model for the integrated CAE system.

In principle, the analysis can be limited. In this case a unique data set is used, or global, when all interesting parameters are scanned in the reference fields. The experimental simulation produces in its turn multiple sets of data. More than one idealized drawing can be achieved for a single existing drawing.

The analysis is a complex domain, because there are many different types of analysis (static and dynamic, linear and nonlinear, of rigid or elastic bodies, etc.). These depend on the part type and its requirements. Four types of analysis and implications of the modelling information at every level are identified: parameterized drawing, simple calculations on the real project, complex calculations on the idealized project and simulation.

3. MODELING AND SIMULATION OF ROBOTS

3.1. Robot for micro and nano manipulations of cells

The challenge of development of ultra-precise manipulating systems is to combine the unique features of piezo actuators together with appropriate mechanics, sensor and control electronics in order to achieve the requirements of the micro and nano world. This challenge refers also to the scientists and design engineers working in that field.

The robot system with 6 DOF utilizing the teleoperated control approach with impedance scaling is developed as a RoTe MiNa robot for cell micro and nano manipulations as a result of optimized design process. It consists of regional structure with 3 translational joints with a range of 55 (100) mm, repeatability of less than 2 μm, linear sensor resolution of 0.1 μm (Fig. 5). The local robot structure with 3 d.o.f. has been developed in a way to guarantee the precise reference three-dimensional nano motion and control for sample manipulation or injection in sub-micrometer or nanometer range. Two of the joints are rotational around *x* and *y* axes in a range of 30 mrad

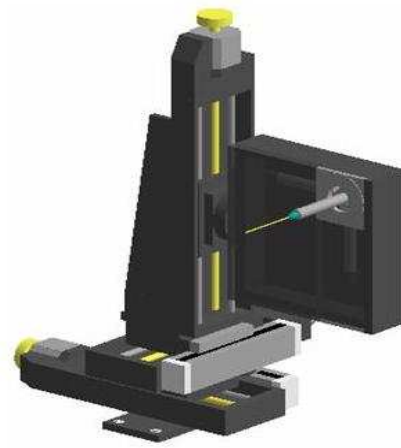


Fig. 5. RoTe MiNa Robot model.

with actuator resolution of $1.6 \cdot 10^{-3}$ arcsec. The last joint is a translational one having a stroke of 65 μm with resolution of 1 nm. The sensors used for the local robot structure are strain gauge sensors integrated in the piezo actuator bodies with resolution of 35 nm. Teleoperation hybrid approach transferring operator motion and manipulation skills for controlling the robot system for cell micro and nano manipulations is developed based on the linear (velocity) or impedance scaling approach (Fig. 6). The time for the operation to be performed is reducing using familiar for the operator dynamics which is the main request especially for the cell manipulations. An approach of impedance scaling has been utilized here in order to give a acceptable and useful preliminary for the operator dynamics of the robot system manipulating in micro and nano range.

The identification of the structure is made in MATLAB using the obtained experimental results for the X, Y and Z-axes for different identification methods and

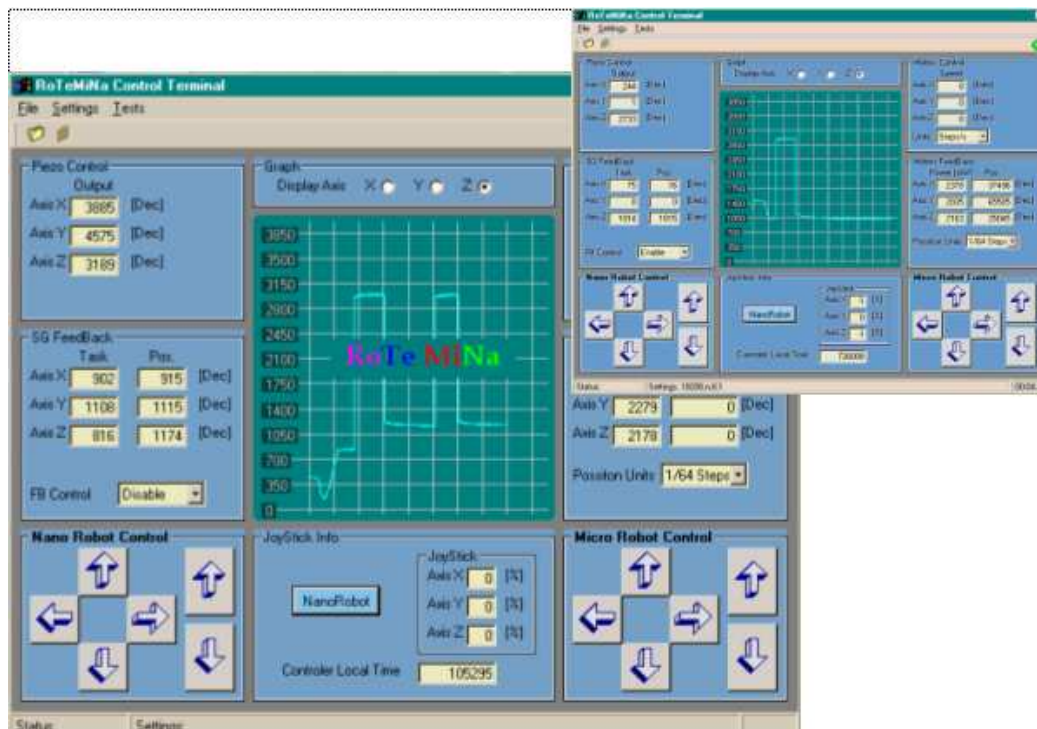


Fig. 6. The control interface RoTeMiNa for hybrid teleoperation and penetration.

two different types of the input signal - sinus and triangle type. The transfer functions of these three axes have been obtained for control research of the piezo actuated micro robot discussed.

The equations of motion of micro-nano robot have been generated based on oriented edges graph with multiple cycles. The concept of matroid, applied to independency of columns, is a novel approach for generating equations of motion.

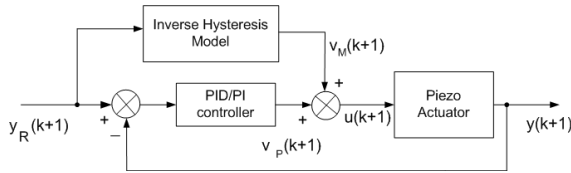


Fig. 7. The proposed control system structure.

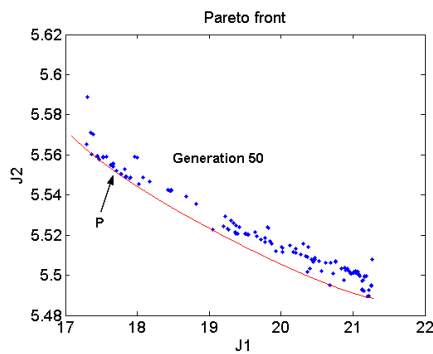


Fig. 8. The PF after 50 generation. The point P indicates the selected individual for PID tuning parameters (TP, TI, and TD).

A control schema was proposed in order to compensate the hysteresis of piezo actuators included in micro/nano robot (Fig. 7). The schema uses a neuro-fuzzy inverse model with PID/PI error mapping compensator. We adopted an originally mixed algorithm in order tune the PID/PID parameters using GEATbx toolbox. The results of simulation proved that our method is very effective, with a very good linearization of the hysteresis curve even in the case of a very sharp upper a lower corner of hysteresis. The MSE was below 0.005 in all the tested cases.

The control schema is based on inverse neuro-fuzzy model in a feed-forward connection. The piezoactuator is modeled by modified mathematical model in order to be simulated and to be tested in a mixed analog-discrete schema. The mapping errors due to dynamic fuzzy model are compensated by PID/PI controllers. The PID/PI parameters are found using genetic algorithms applied to global optimization problem with two objectives. The Pareto front that describes the optimal solutions is found using rank-based selection for local points that describe the Pareto front (Fig. 8). The proposed method improved noticeably the linearization of the hysteresis and the performance of the piezoactuator.

During simulation, the program provides information concerning positions, velocities, accelerations, point trajectories, the forces and moments applied to the articulations, the energies, as well as other data concerning the system, pre-defined by the software or defined by the user [11]. SD simultaneously displays the evolution of the graphs and the 3D animation of the mechanical system (Fig. 9).

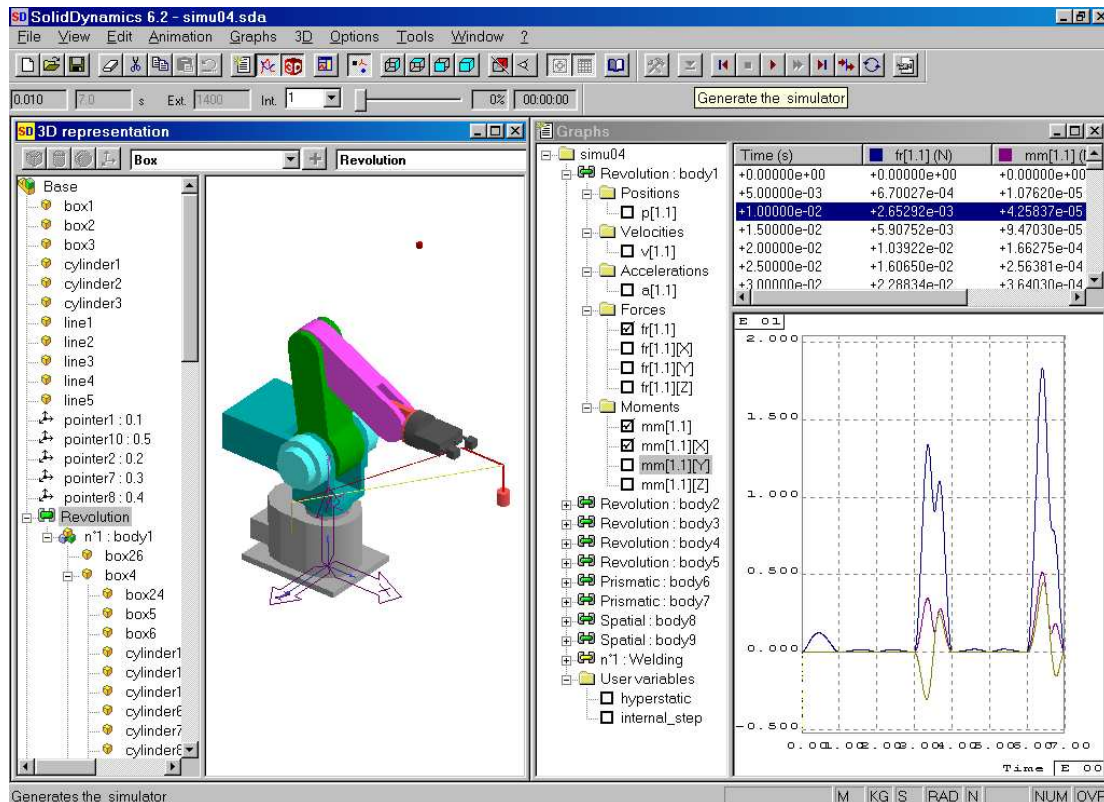


Fig. 9. General screen of the SD program with (from the left to the right) menus, tool bars, tree structure, 3D window accompanied by animation, output variables and Graphs window [4].

3.2. Modeling and simulation of industrial robots

It is generally accepted that a multi-body system is a set of rigid solids linked to each other by joints [5]. A system can further consist of several independent subsystems. A rigid body is a physical body that suffers no stress. There is a permanent contact (joint) between two solids consisting of an articulation and a type of movement. The dynamic system is governed by two kinds of actions: the internal action generated by actuators (engines, brakes, etc.) and the external actions due to environment (gravitation, impacts, perturbations, etc.) [16].

Mathematical model. For instance, a mathematical model has four components:

- A set of names for the object and agents that interact with it, as well as for any parts of the object represented in the model.
- A set of descriptive variables (or descriptors) representing properties of the object.
- Equations of the model, describing its structure and time evolution.
- An interpretation relating the descriptive variables to properties of objects in the reference class of the model.

As regards the mechanical systems, the mathematical model can be given by the Newton–Euler formulation [24]. The following *velocity* and *acceleration* vectors are considered:

- $\dot{\mathbf{p}}_{C_i}$: linear velocity of the overall centre of mass C_i ;
- $\dot{\mathbf{p}}_i$: linear velocity of origin O_i of frame i ;
- $\boldsymbol{\omega}_i$: angular velocity of link i ;
- $\boldsymbol{\omega}_{mi}$: angular velocity of rotor i ;
- $\ddot{\mathbf{p}}_{C_i}$: linear acceleration of overall centre of mass C_i of augmented link i ;
- $\ddot{\mathbf{p}}_i$: linear acceleration of origin of frame i ;
- $\dot{\boldsymbol{\omega}}_i$: angular acceleration of link i ;
- $\dot{\boldsymbol{\omega}}_{mi}$: angular acceleration of rotor i on link $(i-1)$;
- \mathbf{g}_0 : gravity acceleration.

The *forces* and *moments* to be considered are:

- $\mathbf{f}_{i-1,i}$: force exerted by link $(i-1)$ on link i ;
- $\mathbf{f}_{i,i+1}$: force exerted by link $(i+1)$ on link i ;
- $\boldsymbol{\mu}_{i-1,i}$: moment exerted by link $(i-1)$ on link i , with respect to the origin O_{i-1} ;
- $\boldsymbol{\mu}_{i,i+1}$: moment exerted by link $(i+1)$ on link i , with respect to the origin O_i ;
- $m_i \mathbf{g}_0$: gravitational force concentrated at C_i , acting on link i .

The **Newton** equation for translational motion of the overall centre of mass C_i is:

$$\mathbf{f}_{i-1,i} - \mathbf{f}_{i,i+1} + m_i \mathbf{g}_0 = m_i \ddot{\mathbf{p}}_{C_i} \quad (1)$$

The **Newton** equation for rotational motion of the overall centre of mass C_i is:

$$\mathbf{m}_{i-1,i} - \mathbf{m}_{i,i+1} + m_i \mathbf{g}_0 \times \mathbf{r}_{i,C_i} = J_i \ddot{\boldsymbol{\omega}}_C \quad (2)$$

The **Euler** equation for the link rotational motion, referring moments to the overall centre of mass C_i is:

$$\boldsymbol{\mu}_{i-1,i} + \mathbf{f}_{i-1,i} \times \mathbf{r}_{i-1,C_i} - \boldsymbol{\mu}_{i,i+1} - \mathbf{f}_{i,i+1} \times \mathbf{r}_{i,C_i} = \frac{d}{dt} (\bar{\mathbf{I}}_i \boldsymbol{\omega}_i + \mathbf{I}_{mi+1} \boldsymbol{\omega}_{mi+1}) \quad (3)$$

One uses the equation:

$$\boldsymbol{\omega}_{mi+1} = k_{r,i+1} \dot{\mathbf{q}}_{i+1} \mathbf{z}_{mi+1} \quad (4)$$

with $k_{r,i+1}$ gear reduction ratio of the actuating train $(i+1)$ and $\dot{\mathbf{q}}_{i+1} \mathbf{z}_{mi+1}$ the projection of the joint velocity $\dot{\mathbf{q}}_{i+1}$ on the rotation axis \mathbf{z}_{mi+1} of rotor i $(i+1)$.

The axis of rotation of rotor $(i+1)$ being aligned with its principal axis of minimum inertia, \mathbf{z}_{mi+1} , with the inertia tensor \mathbf{I}_{mi+1} of rotor $(i+1)$ having diagonal form, then it is:

$$\mathbf{I}_{mi+1} \mathbf{z}_{mi+1} = I_{mi+1} \mathbf{z}_{mi+1} \quad (5)$$

where, as previously defined, I_{mi+1} is the element $(3, 3)$ of \mathbf{I}_{mi+1} , representing the mass inertia moment of rotor $(i+1)$ about its rotation axis. The final expression of the **Euler** equation results as:

$$\boldsymbol{\mu}_{i-1,i} + \mathbf{f}_{i-1,i} \times \mathbf{r}_{i-1,C_i} - \boldsymbol{\mu}_{i,i+1} - \mathbf{f}_{i,i+1} \times \mathbf{r}_{i,C_i} = \frac{d}{dt} (\bar{\mathbf{I}}_i \boldsymbol{\omega}_i + k_{r,i+1} \dot{\mathbf{q}}_{i+1} I_{mi+1} \mathbf{z}_{mi+1}) \quad (6)$$

From equation (6) it is evident that the gravitational force $m_i \mathbf{g}_0$ does not generate any moment, since it is concentrated at the centre of mass C_i .

In the tree structure of the robot, each body is positioned in relation to the preceding body using the joint positions named $p[i,j]$, where "i" is the number of the body and "j" the number of the DOF of the joint (from 1 to 6). The structures starting from the Base in an open sequence that can be chained (only one branch or with a tree structure).

A closed mechanism structure has at least a kinematic loop (closing joint). This is a structure with closing joints (as an example we consider a parallel robot). One can observe that a kinematic chain starts on the Base and ends also on it.

The next example of modelling a simulation in SD deals with the off-line programming of robots and is a complex one. The programmer creates three dimensional graphic models of the robots and devices and applies inverse kinematic solutions to the models to control the device motion. The robots and devices are then placed in a graphic work cell environment to create an exact representation of a real world work cell. During execution the models simulate the motion of the actual robot or device, allowing the programmer to check for robot work space, possible collisions, motion, and optimization. The ASCII file containing the joint coordinates is generated and used for the real robot control (Fig. 10).

Different types of robot models are presented in Figs. 11, 12, 13, 14, and 15. All are considered including applications for following the trajectory of TCP.

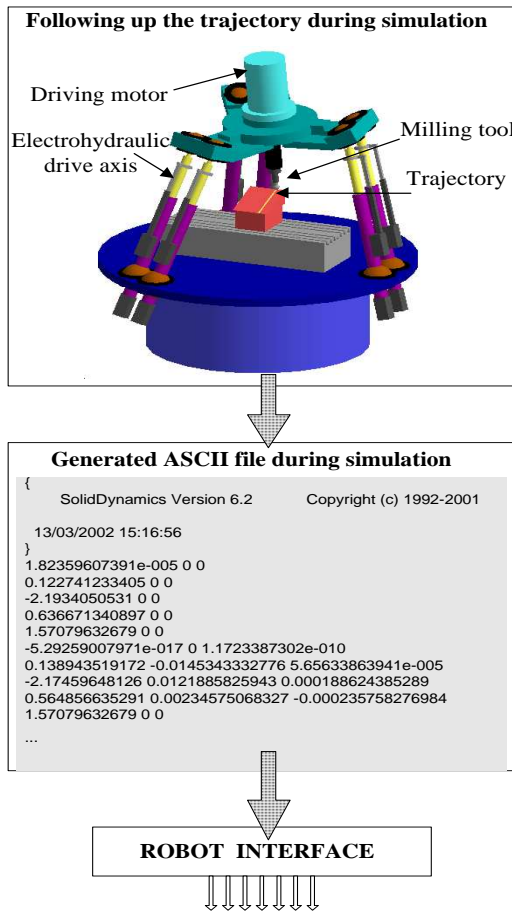


Fig. 10. Off-line control of a six axes parallel robot.

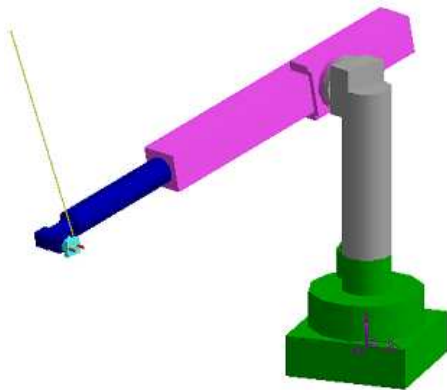


Fig. 11. Model of a spherical robot.

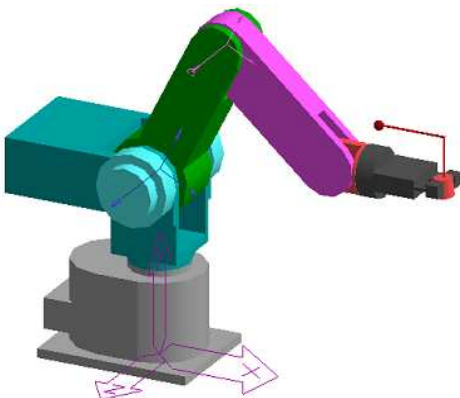


Fig. 12. Model of a revolute robot.

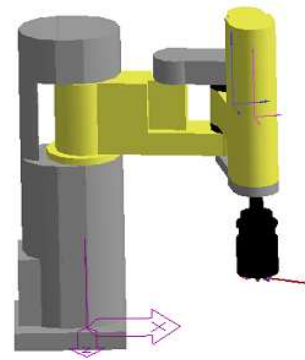


Fig. 13. Model of a SCARA robot.

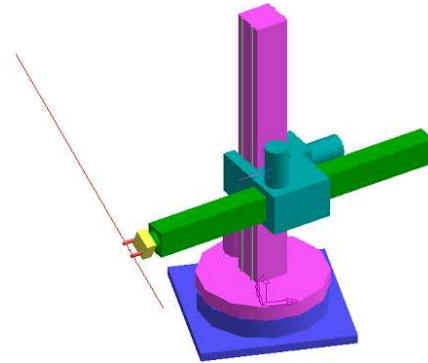


Fig. 14. Model of a cylindrical robot.

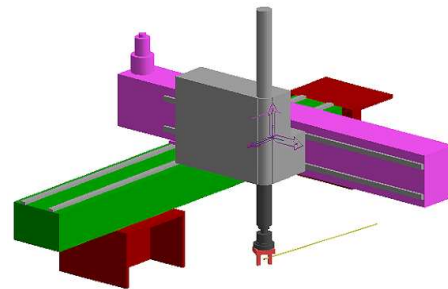


Fig. 15. Model of a Cartesian robot.

4. SIMULATION OF KINEMATIC AND DYNAMIC PARAMETERS OF PLANETARY PRECESSIONAL TRANSMISSION

The next example of modelling and simulation presents some original results of the activity in the frame of a project for developing two types of precessional drives [2] with the characteristics transfer ratio, input speed, output torque respectively:

- $i = 100, n = 1480 \text{ rot/min}; M = 4.690 \text{ Nm};$
- $i = 78, n = 1480 \text{ rot/min}; M = 1.480 \text{ Nm}.$

The calculation [6] of the planetary precessional transmission by simulation was carried out using the simplified 3D model created in program MI 2004+[25, 26] and SD 2004.

The 3D model for calculation is shown in Fig. 16 [5]. The crankshaft 1 is supported by the drive housing through cylindrical roller bearings, which means a connection through a cylindrical joint (R-T), which gives the possibility of satellite self-centring. The block satellite 3 is mounted on the inclined part of the crankshaft by means of two conical roller bearings that require two

joints of Point-Line type (R-R-T). The conical rollers are mounted on small shafts on the block-satellite, which means Revolution joints (R). The contact between the rollers of the block-satellite and the fixed (1) and mobile (2) wheels are modelled through 3D contacts of material couples (steel on steel). The output shaft 5, having at one end the fixed mounted output wheel, is supported by the housing by means of two conical roller bearings, thus it has a revolution motion that leads to Revolution joint (R) in the model. The fixed wheel 2 is attributed to the Base, which is always immobile and accompanied by the main coordinate frame. The model accompanied by the tree regarding the joints is shown in Fig. 16.

The model study was achieved in stages. In the first stage, the kinematic analysis was carried out, which included the following parameter simulations: transfer ratio, absolute angular speed of the block satellite, relative angular speed of the block satellite, angular speed on the output shaft, transfer ratios between different elements of the drive. Some of the results are shown on Fig. 17.

The next stage is the dynamic simulation that allows us to determine the loadings in bearings, forces in the drive, such as: the total force on a satellite roller (Fig. 8a), contact force on the tooth profile (Fig. 8b), contact forces roller-tooth including visualization of force progress (Fig. 19).

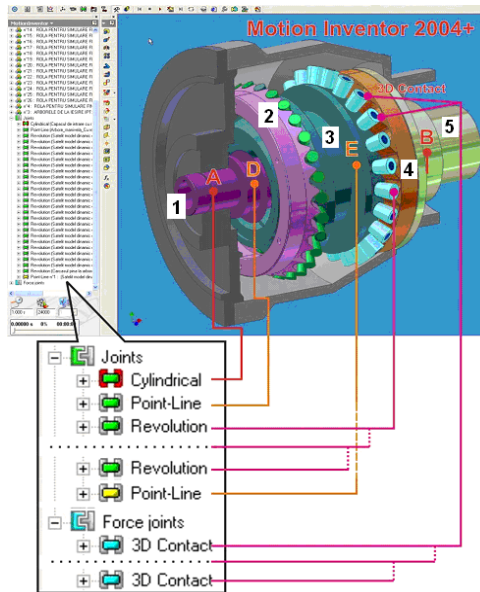


Fig. 16. 3D model of planetary precessional transmission.

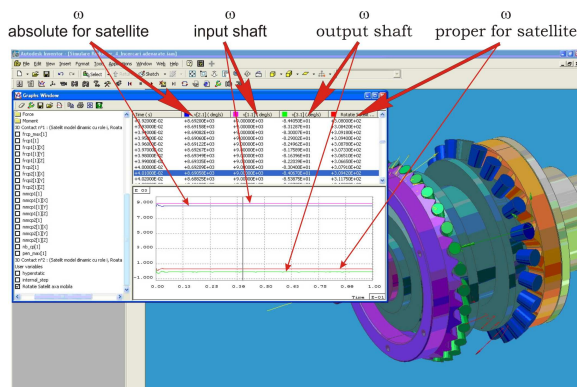


Fig. 17. Kinematic simulation of planetary drive.

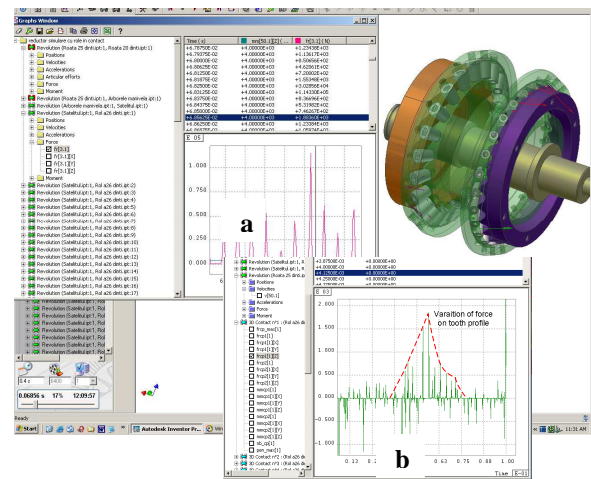


Fig. 18. Dynamic simulation: a - variation of the total force on a roller axis; b - variation of the contact force on the tooth.

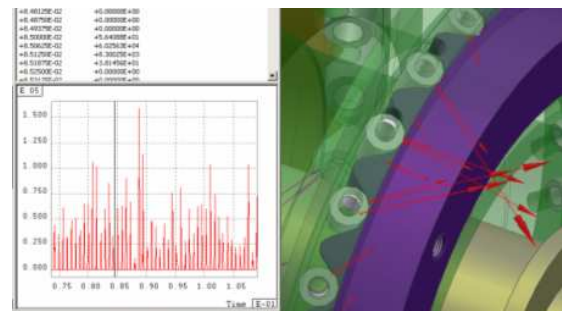


Fig. 19. Contact forces between the crown teeth and satellite rollers.

5. MODELLING AND SIMULATION OF HUMAN BODY

The modelling and simulation of the human moving system are subject of more intensive studies, due mostly to the development of the computer technologies. Most fields of application are the reconstruction of the mechanics of human movements with drive, transmission and control systems. The goal is to achieve a helpful complete model of the human body, which is able to describe with high accuracy its complexity. For now this aim has been not achieved, remaining a major future ambition. In the followings the state of arts and results of our experience towards this goal are presented.

5.1. Goals of the approach

The foreseen goal was to model and simulate the human body by means of classical 3D software like Solid-Dynamics (SD), mostly used for CAE instrument in the design of products, machines and plant. Additional programs (such as ADAMS, DADS and SIMPAK) were used and compared, before the SD was selected. The working way with SD was easier for our research team consisting of non mechanical engineers. Based on SD and according with its evolution, we started to build a Module Library (ML) containing 3D-modules of (partial) systems such as: hand, arm, or parts of them like: bones, cartilages, etc. The achieved results after simulation were validated (as much as the state of art had allowed that) by comparison with experimental results and were further used for research and applications. In the SD environ-

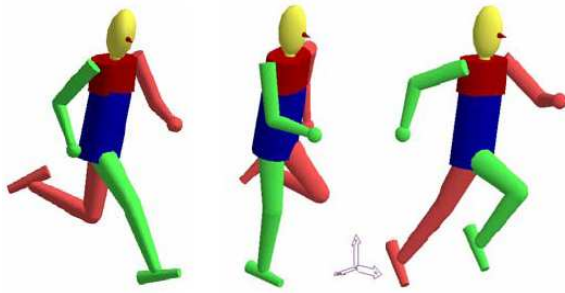


Fig. 20. Simulation of SDS Modell Hanavan after Vieten [22].

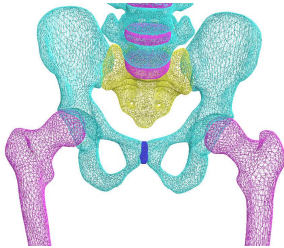


Fig. 21. Modell ANDOR 3D Solid-Dynamics-“Polygon-Soups“.

ment it is possible to build kinematic chains with connected solid bodies, including elastic ones via connection with FEM, in the AIP version. A biomechanical model is quite different from a mechanical one some specific elements being considered: 1. the bodies are non homogeneous; 2. the materials are quite different inside of the body (bones, textures, etc.); 3. many nonlinear laws are defining the materials; 4. the torques and forces are not produced in joints by electro-mechanical driving systems such as stepping motors. They result as action of complex muscle structures with variable characteristics.

The research started from the existing Hanavan model, a simplified model example achieved in SD - *Sprint*, after Vieten [22], built up with simplified primitives like spheres, cylinders, truncated cones, connected by joints (Fig. 20).

Under ANDOR the available standard elements (ball, cylinder, box, cone and joints) having real and important aspects (forms) of the human skeleton are considered, in order to realize realistic a human body model.

The program flexibility (even the source code) makes it possible each necessary extension. However, the use of so mentioned Polygon-Soups (a great number of polygons, which do not have to be subject to a restriction e.g. concerning orientation or surface closing) is intended for the future (example 3D model ANDOR in SD – Fig. 21).

5.2. The method

The method consists of the following steps:

- 3D measuring of a human skeleton by laser scanning;
- optimization of the joints that are built up in the model simulated as a whole;
- optimization of the model with the already available Hanavan model;
- model simulation and experimental researches of human body based on animation programs;
- extension of modelling through more elements, complex joint characteristics, 3D movements aiming the

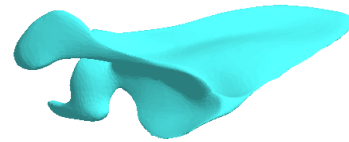


Fig. 22. Example of bone model in SD after elimination of errors.

simulation of complex motions (motion analysis of sportsman and athletes);

- model comparison with the previous simulations in the field of sport science;
- requirements for application relevance in recovering practice and therapy;
- transfer possibilities to orthopaedics, recovering and preventing sports.

The bones were positioned on a thin stick, so all profile elements to be reachable by the laser beam. Figure 22 shows the bone model after scanning and error elimination.

The processed bone models were then exported in STL format into the program SD 6.2. There the structures were arranged to complete the skeleton.

In the available research [23], the markers were recorded with five video cameras and then the films were digitized on the computer. The following programs were used: Ariel Dynamics Performance.

Human Builder, and- Solid Dynamics (SD). The work was divided into four steps: recording, digitization, model building, simulation.

Execution of recording. First the moving body was recorded as a frame with 18 points. Three points are fixed as reference points. During the recording two small lamps served as points of synchronization.

Digitization phase. The digitization was divided into five work procedures: 1. playing the records on computer, 2. synchronization and cutting the records, 3. digitization, 4. transformation of data as 3D data, 5. conversion of data into APA files.

For playing the records on the computer the AVI master 2000 analogical card was used. The film was played in the PAL system on the computer. With each record the characteristics of the capture card must be adjusted. Afterwards playing of records begins on the computer. In the next step all cameras were synchronized and the AVIs cut. The program finds the mark points position in space (Fig. 23).

The digitized data of the individual cameras are computed with one at a time by the software *Transform* and stored as 3D files.

A dialogue box with all cameras, which were digitized before, appears. Each camera is confirmed. The program stores the computed data (the data *.cf format) as 3D file automatically into the file, in which the data were stored.

The conversion of data into APA files is done with the aid of APAS package. The program stores the data *.3D files as *.apa files, which are needed later for the program Human Builder.

Model construction. In model construction, the structure of a biomechanical model is understood by software (Human Builder and SD).

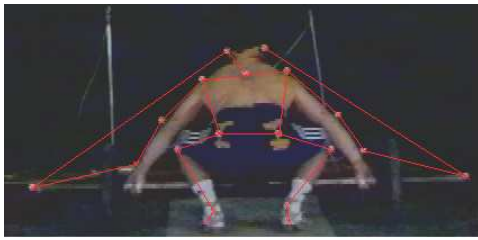


Fig. 23. Marker connection through digitization in APAS-System [22].



Fig. 24. 3D Model ANDOR – Sprint (SD).

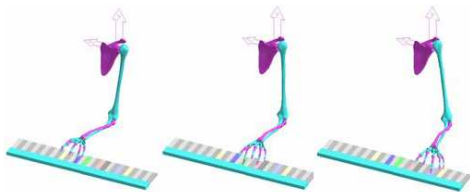


Fig. 25. Piano player hand model (ANDOR) in SD.

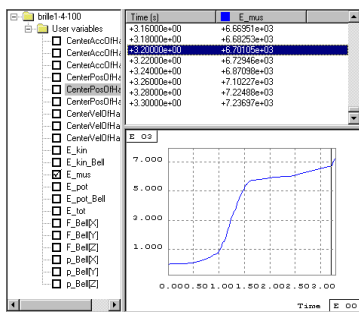


Fig. 26. Diagram of biomechanical variables in SD.

The Human Builder software is a program, with which through the anthropometry characteristics and digitized motion data model can be provided. The model allows the inverse-dynamic variables to be determined directly through the Hanavan model.

An anthropometric measurement is considered for the individual parts of the body, in order to provide a three-dimensional biomechanical model. This measurement plays an important role due to the relationship between body parts and their movements.

By animation file one understands the transfer of APA files in the Human Builder as well as storing as HIF files. In addition, these data have to be calibrated with the marker and joint files.

Simulation phase. In this step, one begins starting from the model provided by Human Builder (Fig. 20) with the help of Hanavan model to simulate the 3D body model (Fig. 24 and 25) [1]. With SD program the motion parameters as biomechanical variables (E_mus, P_mus and CoG) become available (Fig. 26).

6. MATHEMATICAL MODELL GENERATION AND SIMULATION OF HYBRID SYSTEMS

HYPAS is an object oriented and multitasking software that uses Windows facilities [17, 19]. 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 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 data base. Different types of diagrams assist the user to better understand the modelling and operation of the installation.

6.1. Mathematical Modelling in HYPAS

Mathematical Modelling in HYPAS occurs upon an own mathematical description called:

Systemic Model. Description (SMD) [7, 8]. 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 Fig. 27. 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.

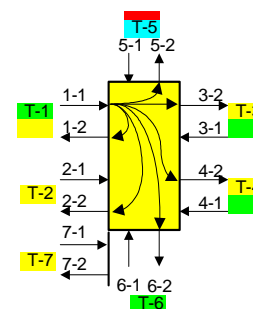


Fig. 27. Generalised block presentation of an element in HYPAS, as multiport.

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.

If one consider the installation in the Fig. 28, one may see, that contents (simplified) then elements: two pumps with variable displacement, two actuators, three servovalves and two pressure valves. Each of them is described by at least a differential equation of second order, without mentioning 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 than that, the graphical association of these equations into analogical-block-diagrams and the overview on the phenomena became more and more difficult with the growth of the number of equations and necessitates scientist's appropriate experience.

Figure 29 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 and deposited, were graphically transported as diagrams from the data base of modules, and put 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 are means of different graphs, as: transient, space of state and frequency representations the achieved results can be visualized.

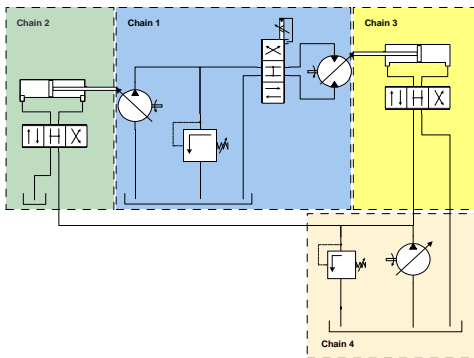


Fig. 28. Manually achieved diagram of a system to be modeled.

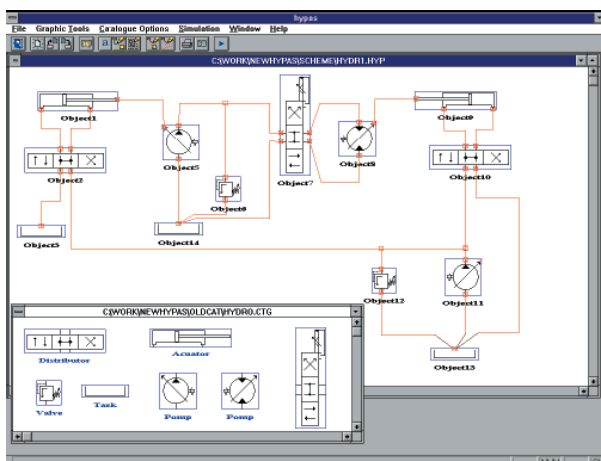


Fig. 29. Simulation diagram of the installation in Fig. 28 generated with HYPAS.

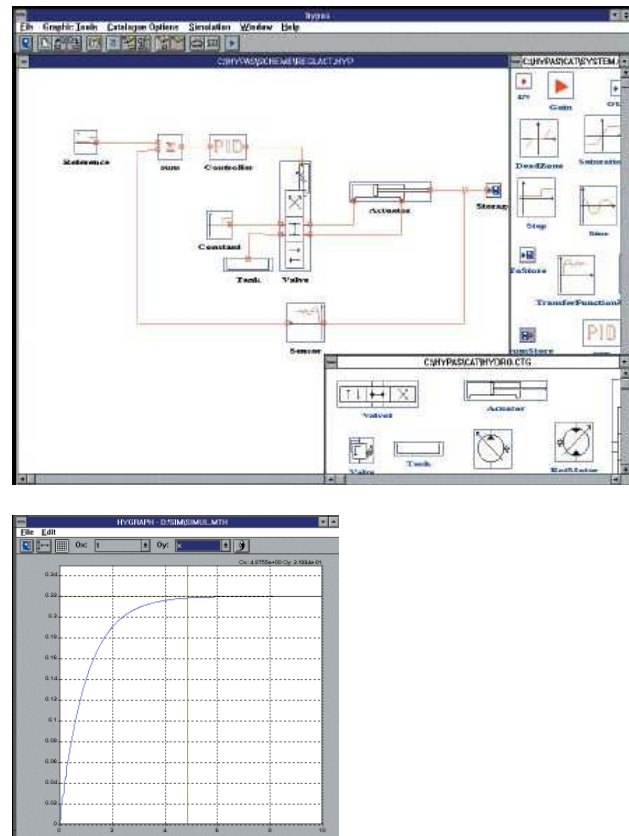


Fig. 30. HYPAS bloc diagram of an electro-hydraulic axis and result of a simulation.

Figure 30 presents the diagram of an electro-hydraulic axis automatically generated with HYPAS and simulated [14, 17, and 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 approx. 5.8 s after a monotone evolution.

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

Hydraulic and pneumatic installations have several particularities:

- They are characterised by many static and dynamic nonlinearities.
- Are involved in installations together with mechanic and electric components and are interfaced with process control.
- Are working with plenty of variables who are of different physical nature whose administration and evaluation could be difficult, if no organised approach is involved.

These are enough to conclude, that the Mathematical Modelling (MM) of an H & P-Installation necessitates high level knowledge and abilities. This is mostly reserved to the scientists: To overcome this situation and

let engineers (& scientists) an open door to MM, several technologies are commercially available: AMESIM (2006), DSh+(2005).

As presented [14 and 19] a alternative platform, called HYPAS, was developed. It allows to automatic model and simulate any (linear, nonlinear, partial or full) H-, P- and Hybrid installation and to simulate it in: steady-state, transient and frequency domains.

6.2 Main targets of HYPAS and examples of solutions

The following main targets are accomplished by HYPAS [17, 18, and 19]:

1. 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.

2. HYPAS requires no programming knowledge.

3. It opens for further developments by adding new modules.

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

5. 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.

6. By using smart algorithms HYPAS corrects false defined parameters or structure variables (Fig. 31). They refer also to all structure parameters and can be activated immediately after the definition, or later, by manually defining their domain of definition.

7. permit to achieve graphic documents protocols for writing down reports.

8. HYPAS assists flexibly the user during the model building to achieve a simulation and for the graphical data representation. As example to this family of facilities, Fig. 32 present the way of setting of the degree grade of denominator (DEGDEN) and nominator (DEGNO) and the gain of transfer functions. A smart debugger will help to keep DEGDN \neq DEGNO.

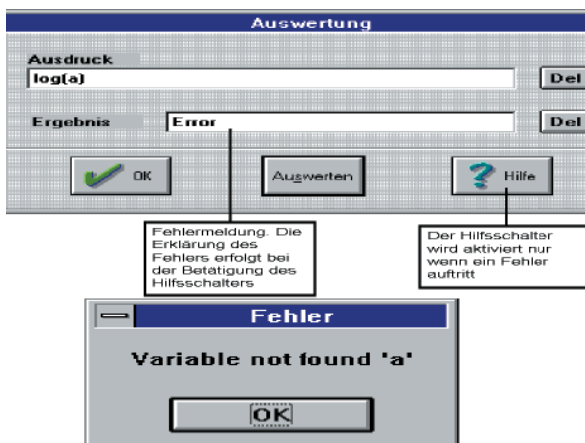


Fig. 31. Result of a smart self debugging function in HYPAS.

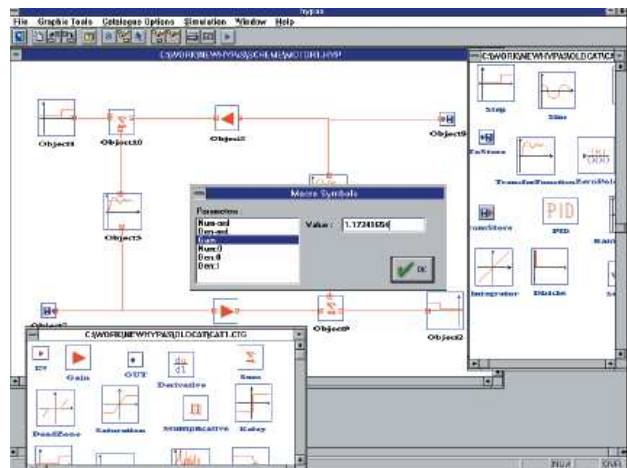


Fig. 32. Setting of transfer functions in HYPAS.

6.3. Main Menu

The main menu of HYPAS, presented in Fig. 33, 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 contains the MM of these elements. The numerical files contents the assigned data sets.

2. *To access the design editor.* The graphical editor will be called and its windows open after the appropriate command occurs.

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 data bases 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. Drawn diagrams can be directly printed, after having set the environment.

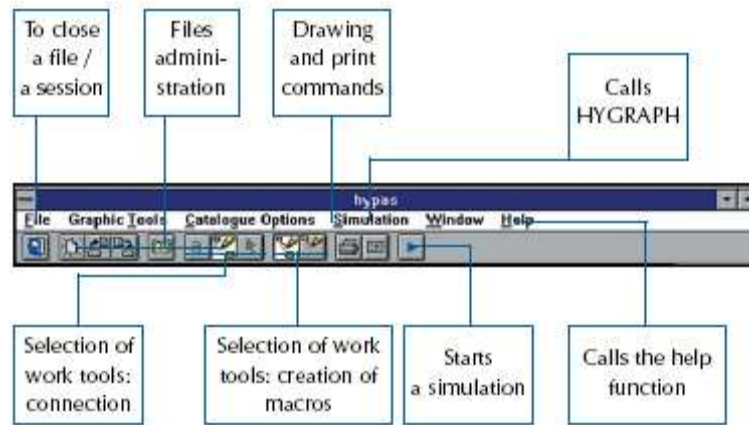


Fig. 33. Main menu of HYPAS - Modelling and Simulation Program.

6.4. 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 data bases. 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 drawn. 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 Fig. 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.

6.5. 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 foresees 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 [22].

- 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 [19].

6.6. Main procedures in HYPAS

Three possibilities can be envisaged by the user:

- To generate the MM of an own simulation diagram.* The 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 data base to the executing file. After that all inputs and outputs 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;
- To simulate a predesigned simulation diagram.* In this case the user has the task to choose the appropriate symbols of modules from data base 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;
- 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.

6.7. 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. 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 components field of functional point of view as "object-folder"- definition. 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; *f.* Changing the assigned graphical symbols of the modules; *g.* Creation and modification of new folders completion of the data base.

7. DYNAMIC EVALUATION OF A LINEAR AXIS IN MILLING USING MODELLING AND SIMULATION ENVIRONMENT

The constant trend in the evolution of machine tools is the increasing of speed and acceleration [16]. The flexibility regarding the structure elements has to be taken in consideration for the study of dynamic behaviour of machine tools. That is why the dynamic model of the axes or of entire machine tool plays a very important role for part dimensioning and also for control design (Fig. 34).

The first task for determining system parameters to prevent self-excited structural vibrations is to model a linear axis, consisting of a driving motor (linear or rotary) that moves a slide as Fig. 35 shows. The model is achieved considering the following components:

- m_1 the mass of the motor that can be linear or rotary motor in kg;
- m_2 is the mass of the slide in kg;
- c_1 is the damping in the linear and rotary bearings;
- c_2 is the damping in the actuator-carriage coupling and the carriage structure (c_1 and c_2 in Ns/m);
- k_2 is the stiffness of the actuator and actuator-carriage-tool structural loop in N/m;

For the step response, the system model (SolidDynamics [16, 10]) is excited with a constant driving force that generates the cutting speed of process, in our case $F = 2 \text{ N}$. The system reaches the constant speed $v_2 = 3.38 \text{ mm/s}$ equivalent to 202.8 mm/min , which means a stable system functioning (Fig. 36) [21]. The system parameter values are presented in Table 1.

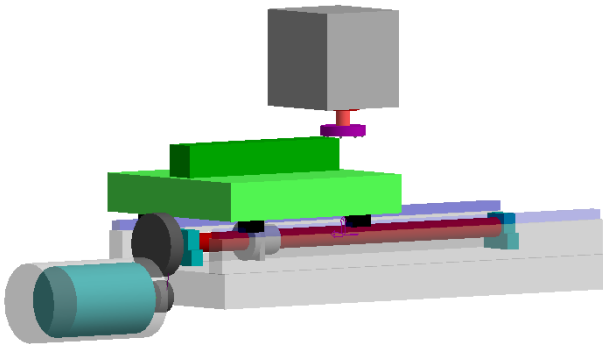


Fig. 34. Feed kinematic chain of a milling machine.

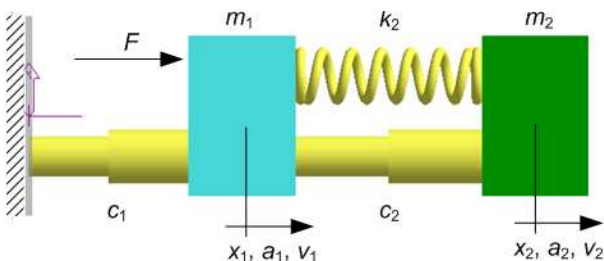


Fig. 35. System model with driving motor and slide.

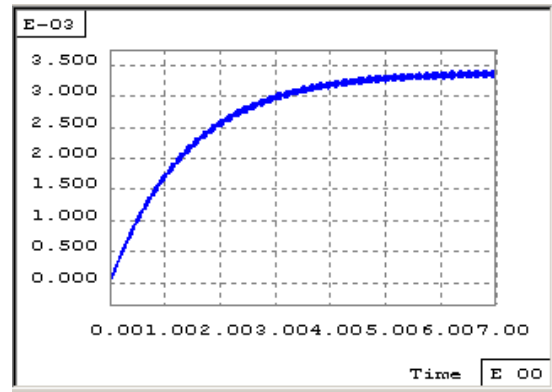


Fig. 36. Model simulation for $F = 1.2 \text{ N}$ (resulting constant speed $v_2 = 3.38 \text{ mm/s}$).

Table 1
Simulation parameters of the model

Actuator	m_1	m_2	c_1	c_2	k_2
Ball screw	50	450	355	19	3.925×10^8

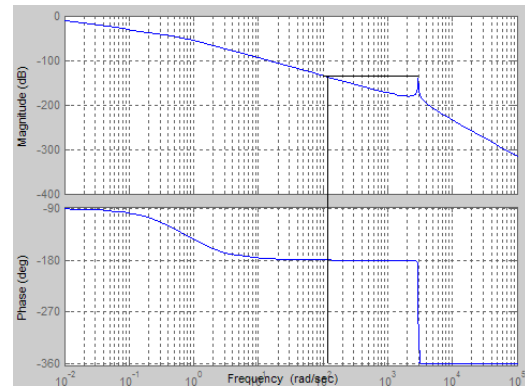


Fig. 37. Response of the driven slide (Bode diagram).

The equations of motion have the form:

$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} \begin{bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{bmatrix} + \begin{bmatrix} c_1 + c_2 & -c_2 \\ -c_2 & c_2 \end{bmatrix} \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} + \begin{bmatrix} k_2 & -k_2 \\ -k_2 & k_2 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} F(t) \\ 0 \end{bmatrix} \quad (2)$$

By considering $\dot{x}_1 = v_1$, $\dot{x}_2 = v_2$, $\ddot{x}_1 = \dot{v}_1$, and $\ddot{x}_2 = \dot{v}_2$ one can reformulate the system in a matricial form:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{v}_1 \\ \dot{x}_2 \\ \dot{v}_2 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ -\frac{k_2}{m_1} & \frac{k_2}{m_1} & -\frac{c_1 + c_2}{m_1} & \frac{c_2}{m_1} \\ 0 & 0 & 0 & 1 \\ \frac{k_2}{m_2} & -\frac{k_2}{m_2} & \frac{c_2}{m_2} & -\frac{c_2}{m_2} \end{bmatrix} \begin{bmatrix} x_1 \\ v_1 \\ x_2 \\ v_2 \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix} \cdot F \quad (3)$$

The transfer function x_2/F – dynamic response of the slide – has the form

$$\frac{x_2}{F} = \frac{k_2 + c_2 s}{c_1 s (k_2 + c_2 s + m_2 s^2) + (m_1 + m_2) s^2 (k_2 + c_2 s) + m_1 m_2 s^4} \quad (4)$$

As a general rule, the drive bandwidth of the system is limited by the drive system running without exciting the structural modes. The frequency can be found by

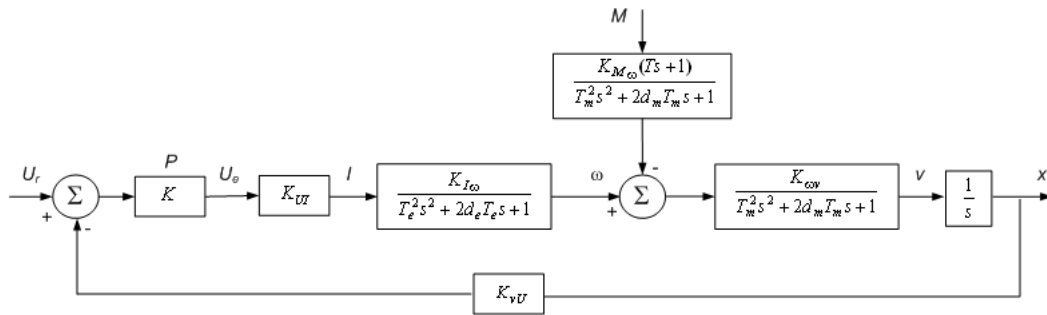


Fig. 38. Complete dynamic model of the axis including the controller.

drawing a horizontal line 3 dB above the resonant peak to intersect the response curve in the diagram shown in Fig. 37. The frequency can be no higher than this value without special control techniques.

7.1. System model without considering disturbance

For system parameters evaluation and optimization a complete dynamic modelling and simulation including the controller is required. The dynamic model control scheme is proposed in Fig. 38. The dynamic model has a proportional regulator of P type. This is also a position feedback control system. The subsystems are transfer-functions of second order. The system coefficients are: K_P – amplification coefficient of the regulator; K_{UU} , $K_{I\omega}$, $K_{M\omega}$, $K_{\omega v}$, K_{vU} – amplification factors (value transfer or adaptation); T_e , T , T_m – time constants; d_e , d_m – damping coefficients [20].

From the structure of the root locus (RL), obtained for the variable parameter K (Fig. 39), one can observe that 2 of the 5 branches of the RL are going through the right semiplan C^+ for relative small values of K (the system becoming instable). It results from here that the possibilities of choosing of a regulator which has a proportional component K are limited:

- for $K = 14$, the repartition of the system poles in closed circuit (automatic control system) is: $(-4.9495 + 8.7477i)$, $(-4.9495 - 8.7477i)$, $(-0.0029 + 0.9901i)$, $(-0.0029 - 0.9901i)$, (-0.0952) .

- for $K = 15$, the repartition of the system poles in closed circuit is: $(-4.9495 + 8.7477i)$, $(-4.9495 - 8.7477i)$, $(0.0005 + 0.9901i)$, $(0.0005 - 0.9901i)$, (-0.1020) .

One ascertains that for $K = 14$ the automatic control system (ACS) is internal asymptotic stable because it has all poles with the real part negative (placed in C^-) while for $K = 15$ the ACS is instable having two poles placed in the right semi-plan C^+ : $(0.0005 + 0.9901i)$, $(0.0005 - 0.9901i)$.

Consequence. ACS is stable only for $K \in (0, 14]$.

For the system to be internal asymptotic stable, we propose a regulator of the type proportional P, having $K = 1$ (used also for simulations).

The characteristics amplitude-frequency and phase-frequency of the transfer function for $K = 1$ are shown in Fig. 40. One can observe that for the frequency $\omega = 100$ Hz the system is near a resonance frequency!

The Nyquist diagram (hodograf) of the transfer function is shown in Fig. 41 for $K = 1$.

The system response at unitary step input $u(t) = 1(t)$, for $K = 1$ is given in Fig. 42.

After obtaining the equivalent system from the given one as an automatic control system with rigid reaction, the transfer function is:

$$H(s) = \frac{6.12e^{-4}}{10^{-10}s^5 + 101 \cdot 10^{-9}s^4 + 102 \cdot 10^{-6}s^3 + 0.002s^2 + s + 0.6732} \quad (5)$$

For simulation with Matlab-Simulink, the sampling-time $t = 0.01$ s was used.

7.2. System with disturbance

The transfer function a disturbance H_{Mx} has the form:

$$H_{Mx}(s) = \frac{r(s)}{p_1(s) \cdot p_2(s)} \quad (6)$$

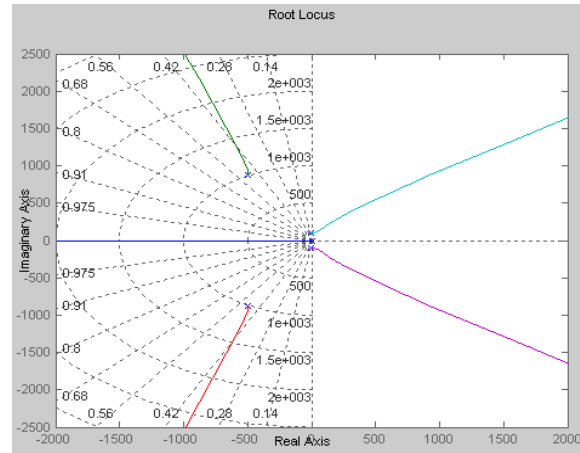


Fig. 39. Root Locus of the transfer function.

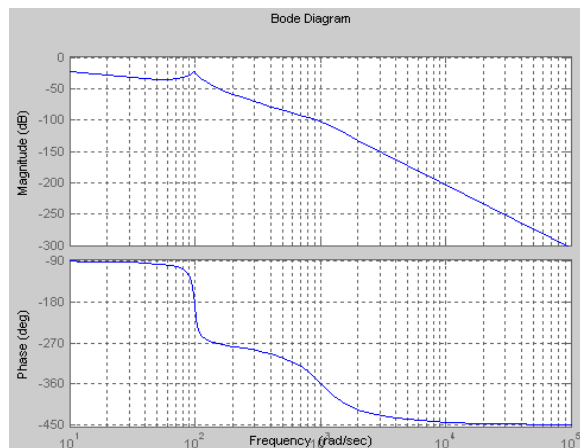


Fig. 40. Amplitude-frequency and phase-frequency diagrams.

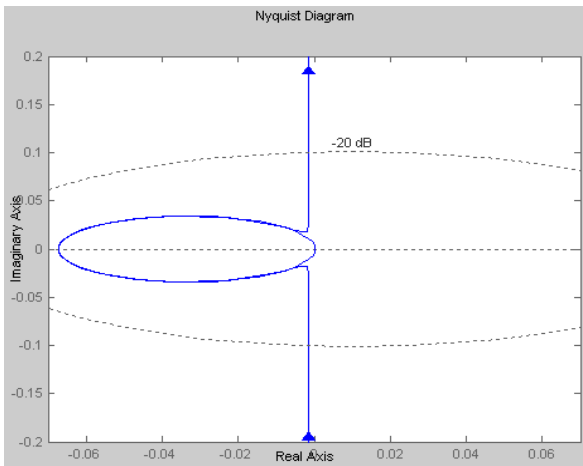


Fig. 41. The Nyquist diagram.

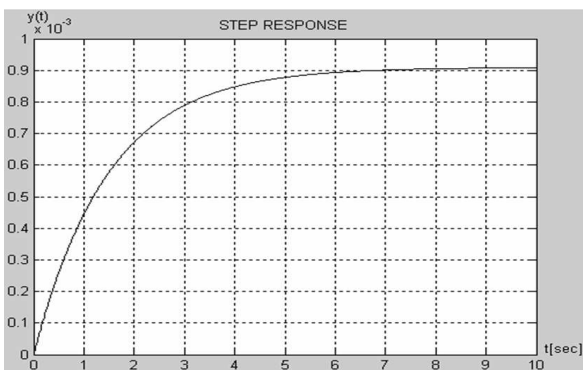


Fig. 42. System response at unitary step input.

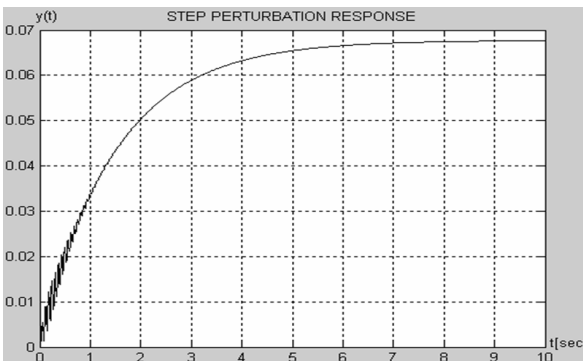


Fig. 43. System response at unitary step input (with disturbances).

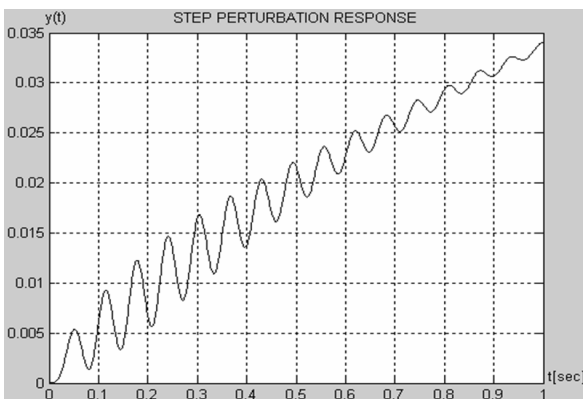


Fig. 44. Oscillations at the beginning of system response (with disturbances).

where

$$r(s) = 912 \cdot 10^{-12} s^3 + 958 \cdot 10^{-9} s^2 + 957 \cdot 10^{-7} s + 457 \cdot 10^{-4},$$

$$p_1(s) = 0.0001 s^2 + 0.001 s + 1,$$

$$p_2(s) = 10^{-10} s^5 + 101 \cdot 10^{-9} s^4 + 102 \cdot 10^{-6} s^3 + 0.002 s^2 + s + 0.6732.$$

The answer of the position feedback control system (Fig. 43) at disturbance $(u(t) = 1(t))$, for $K = 1$ has at the beginning of the transitory regime some oscillations (Fig. 44) generated by the derivative component placed at the numerator of the transfer function of disturbance.

7. CONCLUSIONS

As a consequence of the presented features and of the authors experience in modelling and simulation with technologies with the SD and MI programs, one can conclude that these technique is a very powerful and useful tool, both for visualization with the improvement of user's capacity of representation, as well as for important gain of technological information in the design and optimization phases products. The presented examples underline that mechanic systems independently of their complexity and dimensions can be easy modeled, their behavior can be simulated, analyzed, and optimized with good results.

REFERENCES

- [1] D. Andreescu, M. Vieten, Fl. Ionescu, and H. Riehle (), *Modellierung & Simulation des menschlichen Körpers unter besonderer Berücksichtigung des Knochenskeletts*, Scientific Symposium "40th Anniversary" of University-Konstanz, Germany, 2005.
- [2] I. Bostan, V. Dulgheru, and Ș. Grigoraș, *Planetary, precessional and harmonic transmissions*, București-Chișinău, 1997.
- [3] I. Bostan, L. Cantemir, Fl. Ionescu, and V. Dulgheru, *Some Aspects of Creativity and Process and Product*, ARA-Journal, Vol. 2000–2002, No. 25–26, pp. 136–138,
- [4] I. Bostan, Fl. Ionescu, V. Dulgheru, and A. Sochireanu, *Kinetostatic Analysis of the Sphere – Spatial Mechanisms by using 3D Models and Simulations*, Meridian Ingineresc, Issue Nr. 2, pp. 59–61, 2004.
- [5] I. Bostan, Fl. Ionescu, V. Dulgheru, G. Constantin and A. Sochireanu, *Integrated CAE Development of Precessional Drives Using Autodesk Inventor Platform*, Proceedings of International Conference of Manufacturing Systems – ICMaS, Edit. Academiei Române, Bucharest, pp. 21–28, 2006.
- [6] G. Copani, L. Molinari Tosatti, G. Lay, M. Schroeter, *Rikardo Bueno3New Business Models diffusion and trends in European machine tool industry*, <http://www.nextproject.eu/publications/>, accessed: 2007–09–25.
- [7] Fl. Ionescu, Fl. Haszler, A. Ciomaga, "HYPAS"-Software Simulation Package for Electro-Hydraulic Drive Installations, Proceed. of EUROSIM'95-Session "Software Tools and Produkts", Argesim Report No.2, 1995, pp. 1–4.
- [8] Fl. Ionescu, *Logiciel HYPAS pour la conception des servo-systèmes hydrauliques*, 1st Vol., Journées d'études SMB-FIMOP-BVW, 18–19.10.1995 Brussels, pp. 25–37.
- [9] Fl. Ionescu, G. Constantin, and Fl. Haszler, *High Integrated Approaches of Computer Aided Design and Optimization in Machine Design, TCMM*, Nr. 15, 1996, EDIT, Tehnică, Bucharest, pp. 213–220.

- [10] Fl. Ionescu, G. Constantin, V. Platagea. *Some Examples of Comparative Simulation of Nonlinear Solid Body Systems with MATLAB/SIMULINK and SDS Simulation Programs*, Proceedings of the 2nd World Congress of Nonlinear Analysts (WCNA), Vol. 30, Part 4, Pergamon Press, pp. 1969–1976, July 10–17, 1996, Athens, Greece.
- [11] Fl. Ionescu, and G. Constantin, *Examples of Modeling and Simulation of Solid Body Systems with SDS Program*, SYROM'97. The 7th IFToMM Intern. Symposium on Linkages and Comp. Aided Methods, Edit. Tehnică, Bucharest, pp. 171–178, 1997.
- [12] Fl. Ionescu, *Model Generation, Simulation and Control of Hydraulic and Pneumatic Drive Systems with HYPAS*, ISCFP'99, Sixth Scandinavian International Fluid Power Conference, 26–28 May, 1999, Tampere, Finland. Vol. II, pp. 947–961.
- [13] Fl. Ionescu, *Intelligent Solutions for Mechatronics*, ISS-SPIE '99, International Conference on Smart Materials, Structures and Systems, 7–10 July, 1999, Bangalore, India, pp. 614–623.
- [14] Fl. Ionescu, *Neural Network and Neuro-Fuzzy Intelligent Solutions for Non-linear Systems*, Presented at KES'99, Third International Conference on Knowledge-Based Intelligent Information Engineering Systems, 31 August – 01 September 1999, Adelaide, Australia, pp.501–504.
- [15] Fl. Ionescu, *Simulation Technologies - CAE IV*, University of Applied Sciences, Konstanz, 2002.
- [16] Fl. Ionescu, F. Choynowski, G. Constantin, *Virtual Reality in Mechanical Engineering. Modelling and Simulation with Solid Dynamics*, ARA Journal, Vol. 2000-2002. No. 25–27, 2003, Edited by ARA (American Romanian Academy for Arts and Sciences) pp. 150–157, Montreal, Canada.
- [17] Fl. Ionescu, *Model Generation, Simulation and Control of Hydraulic and Pneumatic Drive Systems with HYPAS*, Proceedings of ARA'25 Annual Congress, Silver Anniversary, 12–14 July 2000, Cleveland Ohio, USA, pp. 245–248.
- [18] Fl. Ionescu, C. Vlad, D. Arotaritei, *Advanced Control of an Electro-Hydraulic Axis* (Handbook of Mechatronics, Edit. Bishop, TU Texas). CRC-Press, Florida, 2001, USA.
- [19] Fl. Ionescu, *Structured Mathematical Model Generation, Simulation and Control of Hydraulic and Pneumatic Drive Systems*. Intern. Symp. on Impact of the Modern technologies on the Continuous Development, 11–13 February 2002, Chisinev, Moldavien, 1st Volume 2002, Meridian Engineeringin, pp. 36–47.
- [20] Fl. Stratulat, *Teoria sistemelor. Analiza asistată de calculator a sistemelor liniare* (System theory. Computer aided analysis of linear systems), Edit. Matrixrom, Bucharest. 2000.
- [21] Fl. Stratulat, Fl. Ionescu, G. Constantin, *Dynamic evaluation of a linear axis in milling using modelling and simulation environment*, Proceedings of the International Conference on Manufacturing Systems, ICMA8 2007, Edit. Academiei Române, pp.73–76, 2007.
- [22] M. Vieten, *Virtual Biomechanics and its Physics*, PhD Thesis, University Konstanz, 2004.
- [23] K. Zahran, M. Vieten, H. Riehle, *Quantification of Technical Skills in Weightlifting*, XXth Intern. Symposium on Biomechanics in Sport, Gianikellis, 2002, pp. 478.
- [24] *** *SDS Training Course and Modules*, SolidDynamics, www.solid-dynamics.com, 2002.
- [25] *** *Autodesk Inventor*, Autodesk, www.autodesk.com, 2002.
- [26] *** *MotionInventor. Powerful 3D Mechanical Simulation Software*, Solid Dynamics SA, France, www.solid-dynamics.com, 2004.