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Multilevel Simulation of Physical and Engineering Problems

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Abstract**: *This article discusses peculiar features of simulation of physical and engineering problems, criteria for their efficient simulation in development environment are formulated. Software for simulation of complex dynamic objects is briefly analyzed (as superclass of physical and engineering problems). Provisions of the developed approach to multilevel computer simulation of physical and engineering problems in the frames of multilevel component circuits formalism are described. Peculiar features and capabilities of this approach are exemplified by simulation of forces on polished rod of sucker-rod pump for extraction of petroleum.***

Keywords**: *component circuits method, multilevel simulation, sucker-rod pump, simulation environment.***

I. INTRODUCTION

Physical and engineering problems (PEP) are widely applied in various fields of physics and engineering for researching and educational purposes as well as for functional designing. PEP are comprised of formulation of a certain engineering problem concerning complex dynamic objects which can be solved using knowledge of specialized fields of physics. Complexity of dynamic object [1] is defined as follows:

1) complexity of behavior which implies existence of discrete continuous (hybrid) [2, 3] behavior: combination of discrete and continuous (physical) behavior which can be initiated by numerous reasons [4];

2) complexity of structure which implies existence of constituent components (bodies) connected both by rigid and elastic link;

3) variable set of simulated objects depending on time and states;

4) interaction of objects of various essence (for instance, engineering device with discrete behavior and physical object with continuous behavior).

Such features of PEP present certain requirements to simulation environment:

1) existence of tools for simulation of both continuous and discrete continuous behavior of objects;

2) existence of tools for presentation of geometrical properties of objects;

3) possibility of step-by-step detailing of model;

4) existence of typical units and possibility of their flexible adjustment;

5) existence of ready units (elements) containing models of object domain (allowing representation of physical properties of objects);

6) possibility of decomposition of object behavior into several levels aiming at subdivision of object models and their control systems.

The applied tools of simulation of complex dynamic systems, in total, and PEP, in particular, can be subdivided as follows [5]:

1) universal simulation environments (LabVIEW, Simulink, VisSim, Rand Model Designer [6], ISMA [7]);

2) systems of computer mathematics (Mathcad, Mathematica (Wolfram), Maxima);

3) software implementing numerical methods (Excel, programming languages);

4) field specific packages, including CAD (for instance, SolidWorks for problems of hydraulics).

The following disadvantages of the existing simulation systems were highlighted in [8, 9]:

1) unavailability of efficient simulation of event-driven systems;

2) unavailability of convenient language of planning and computing experiment;

3) unavailability of interfaces between various simulation environments (impossibility to exchange models between packages);

4) unavailability of standardized components in different packages.

Analysis of existing simulation environments considering for highlighted features of PEP reveals the following. Simulation tools of discrete continuous behavior are available in such environments as Simulink, Rand Model Designer, ISMA, however, they are characterized by certain drawbacks, the main of which is that the continuous behavior of model supplementing discrete behavior can be assigned only in symbol form, which constrains researchers, especially in the case of tools of physical simulation: development of models on the basis of structural and functional units corresponding to highlighted elements of system.

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The LabVIEW library contains components for representation of geometrical properties, however, they do not allow to cover overall range of considered problems: the units are intended for geometrical transformations (rotation of axis, conversion into SI, etc.) and solution of basic geometric operations (for instance, computation of center of gravity). Ready units for representation of physical properties are available only in Simulink.

It should be mentioned that the aforementioned environments do not separate the continuous model of object from the model (algorithm) of its control system, however, such separation is the fundamental concept for MARS multilevel simulation system (MARS MSS) [10], which proved itself for solution of problems in various fields [11, 12, 13]. Separation of continuous object model from algorithm of its control system (including scenario of simulated computational experiment) is the most preferable not only for visual representation of model flowchart but also for improvement of its operation efficiency.

II. METHODS

A. General description

MARS MSS is based on the method of multilevel component circuits (MMCC) [14] and characterized by open component library [15]. The models in MARS simulation environment are based on visual (graphical) language [16].

MMCC is referred to the class of universal methods of computer simulation of engineering objects and characterized by the following features:

1) it is an object-oriented language;

2) it is intended for simulation of complex objects and systems characterized by information and energy flows in links;

3) it can be used for simulation of objects and systems of various physical essence (hydraulics, electrical engineering, etc.);

4) it allows to develop both imitation models (in the form of algorithmic designs) and analytical models (in the form of algebraic differential equations).

B. Algorithm

MMCC assumes decomposition of computer model into three levels corresponding to the layers of MARS MSS editor (Fig. 1).

1. Circuit object level [17] where continuous object behavior is described by tools of analytic simulation. This level corresponds to object layer (C layer) of simulation environment at which model is built of components (visual units) and each of them corresponds to certain set of algebraic differential equations. The equations can be presented both in explicit and inexplicit form.

2. Algorithmic level [18] where discrete object behavior is described by tools of simulation technique. This level corresponds to logical layer (L layer) where circuits are developed which describe experiment scenario by simulation, object behavior by state diagrams, simulation result processing, interaction with data sources (databases [19], geoinformation systems [20]), automated recording of simulation results [21], etc. In addition, the L layer also transfers data between C layer and visual layer (V layer) of multilevel computer model.

3. Visual level [22] which is an external (visual) presentation of object behavior and, in fact, is the interface between researcher and model. This level corresponds to V layer which provides interactive interaction with model including graphical components allowing to control model and to visualize simulation results.

C. Flow Chart

Basic concepts of MMCC are component and component circuit. A component is formalized representation of certain element or functional unit of simulated system having its mathematical (mathematical algorithmic) model. Component circuit (CC) is a computer model of considered system comprising the combination of interrelated components. Nominally, CC is the combination of a set of components *K*, branches (links) *B* and nodes *N*.

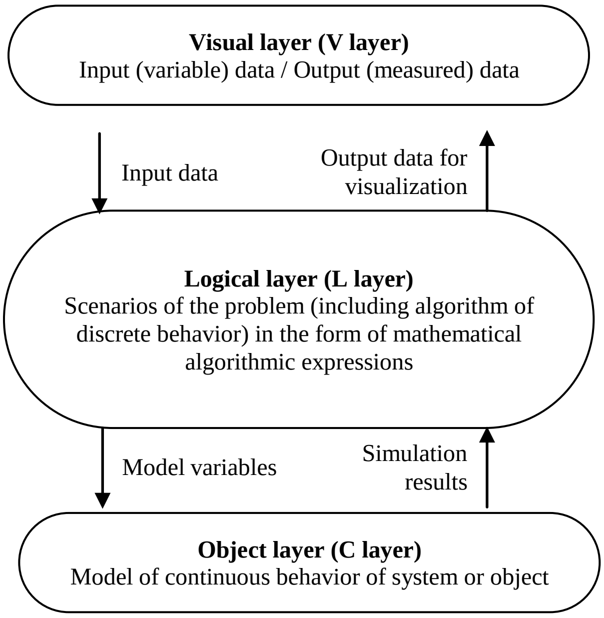


Fig. 1. Multilevel presentation of model

Models on the C layer are component circuits comprised both of ready components (with predefined mathematical model available for parametrization) and of mathematical toolbars (units containing editable mathematical model in symbol form) [23]. Each elemental link B of component C on C layer corresponds to a pair of dual variables: V_n is the potential variable (for instance, velocity, pressure, voltage), and V_b is the stream variable (for instance, force, flow rate, current). In the CC nodes the stream variables are regulated by topological law of summation (sum of similar variables equals to zero), and the potential variables are regulated by the law of equality to each other.

III. RESULTS AND DISCUSSION

A. Simulation of forces on sucker-rod pump rod

PEP (as problems of engineering, artificial object solved by knowledge from specialized fields of physics) can be exemplified by simulation of force on polished rod of sucker-rod pump (SRP), it is schematically illustrated in Fig. 2 [24].

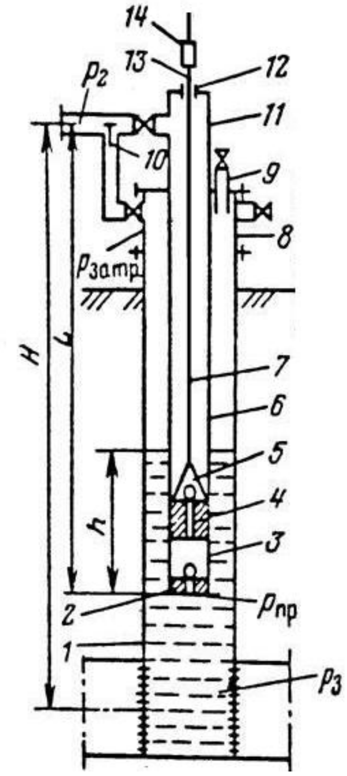


Fig. 2. Schematic view of SRP. 1 – production string; 2 – intake valve; 3 – pump cylinder; 4 – plunger; 5 – injection valve; 6 – oil well tubing; 7 –pump stems; 8 – cross beam; 9 – wellhead tap; 10 – reverse valve for gas bypass; 11 – T-bend; 12 – polished rod packing; 13 – wellhead stem; 14 – cable hanger.

Oil extraction rigs equipped with SRP are the most popular of extracting equipment. Despite low production rate (in comparison with electric centrifugal pumps), these facilities are widely applied for extraction marginal wells and wells characterized by certain difficulties, such as high water contents, sand related problems, high viscosity or temperature of oil well fluid, existence of aromatic hydrocarbons, salt and paraffin formation, that is, in the cases when centrifugal pumps are inefficient [25]. The simplest approach to determine optimum pumping rate of oil well fluid, optimum law of motion of polished rod, detection of various failures of SRP, etc. is the development and analysis of its mathematical model.

While simulating, SRP is presented as a system of consecutively connected elements of plunger pair, stems, rod. Reciprocal motion of stems is described by the differential equation of longitudinal oscillations of uniform rod. Herewith, the preset boundary conditions are motions of polished rod and plunger as well as forces applied in these points [26].

Let us describe formal pattern [27] of the considered problem. The main simulated process is reciprocal motion of stems, hence, the main interacting objects are the polished rod (source of motion), plunger (moving body), pump stems (expansible body). Let us consider the polished rod as the source of motion in the simulated system predicting its motion $S(t)$ by certain harmonic law. Let us assign this object to the Velocity source (Fig. 3), its mathematical model is as follows:

$$B_1 \cdot V_p = S(t) \quad (1),$$

where B_1 is the coefficient (constant or functional parameter), V_n it the potential variable (velocity in our case), $S(t)$ is the functional dependence.

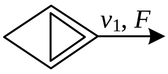


Fig. 3. Velocity source.

Motion is simulated in MMCC using the so-called models of solids (characterized by constant shape, sizes, weight, moments of inertia) based on the laws of motion kinematics and dynamics. However, in the considered case (motion along one coordinate), participation of solids in the model is reduced to inertial link: a point characterized by weight. Let us consider the pump stems and plunger as these objects considering such their parameters as cross section area and material density. Mathematical model of inertial link (Fig. 4) is as follows:

$$A_1 \cdot \frac{dV_n}{dt} + B_2 \cdot V_b = 0 \quad (1),$$

where V_b is the stream variable (sum of forces F acting on the body), V_n is the potential variable (velocity V), A_1 is the model parameter (weight m), B_2 is the model parameter (equaling to 1 in this case), t is the time.

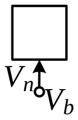


Fig. 4. Inertial link.

Deformation (expansion and compression) of stems during their motions can be simulated by such components as Spring (Fig. 5) characterized (as other considered components) by two elemental links with potential variables v_1, v_2 (velocities) and stream variable F (force). Typical mathematical model of component is as follows:

$$\frac{dF}{dt} = k \cdot (v_1 - v_2) \quad (2),$$

where the coefficient k can be both constant and functional parameter. Expansion of stem in this case can be predicted by the difference between the velocities v_1 and v_2 in the component links.

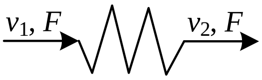


Fig. 5. Spring.

Friction forces acting during motion on rod, stems and plunger can be simulated by Damper component (Fig. 6). Mathematical model of this component is as follows:

$$F = R \cdot (v_1 - v_2) \quad (3),$$

where the coefficient R can also be either constant or functional parameter.

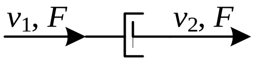


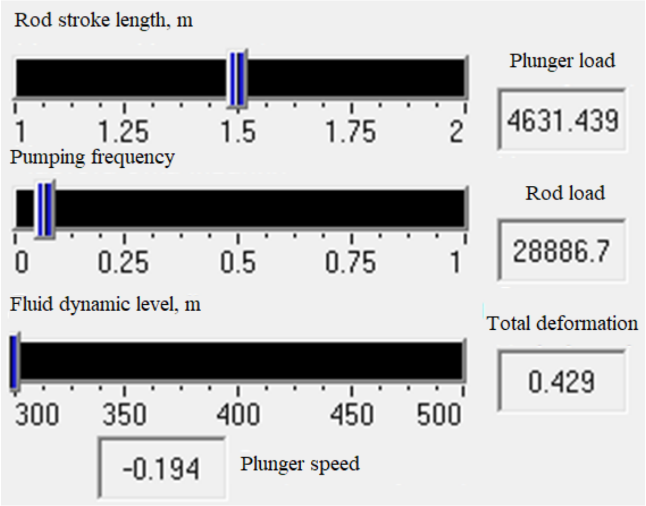
Fig. 6. Damper.

Pressure of oil and gas mixture on plunger can be simulated by Source of stream variable, similar to Velocity source, and described by the following mathematical model:

$$B_2 \cdot V_b = C(t) \quad (4),$$

where B_2 is the coefficient (constant or functional parameter), V_b is the stream variable (force in this case), $C(t)$ is the functional dependence.

Let us develop computer model of the considered problem on the basis of the described components highlighting the points of force application (objects of their action) by formation of topological links of the components using the mentioned topological laws.



Rod stroke length, m

Pumping frequency

Fluid dynamic level, m

Plunger load 4631.439

Rod load 28886.7

Total deformation 0.429

-0.194 Plunger speed

Fig. 7. Model at V layer.

The model L layer (Fig. 8) presents:

1. State diagram (CC Start–Down (rod)–Up (rod)) characterizing plunger motion direction (down or up), which is required for prediction of stem deformation and friction force by means of different expression upon down and up motions as well as for consideration for plunger delay when it moves after stems. The state diagrams are the conceptual model of object in the form of finite state machine characterizing object behavior in the form of sequence of its states changing each other after meeting certain conditions [28]. In this problem, the state diagrams supplement the continuous behavior of system described at the C layer by the discrete behavior, thus forming the hybrid behavior [29]. The work order of state diagrams in MARS MSS is as follows: when *true* is transferred to input, the *Start* component begins to transfer the values at input *in* via output *out*, this continues until the assigned condition (mathematical expression) is true, then its operation is terminated by transferring *true* to output *End*.

2. CC performing parametrization of the main model components: Plunger, Stems, Friction, Deformation, Mixture pressure, which are represented similarly in the C layer. Variables at this layer are transferred consecutively from component to component (after transformations defined by the components, when necessary). When all variables are initiated (data transfer to C layer), computational experiment begins at C layer (solution of algebraic differential equations by computing core), the obtained results at each iteration of model operation are returned back to the L layer and represented, when required, at the V layer by receiving components (plots and components in the form of Digital display).

The model parameters taken as constant (for instance, cross section area of stem, density of stem material, and others) are preset at this layer by means of properties of respective components.

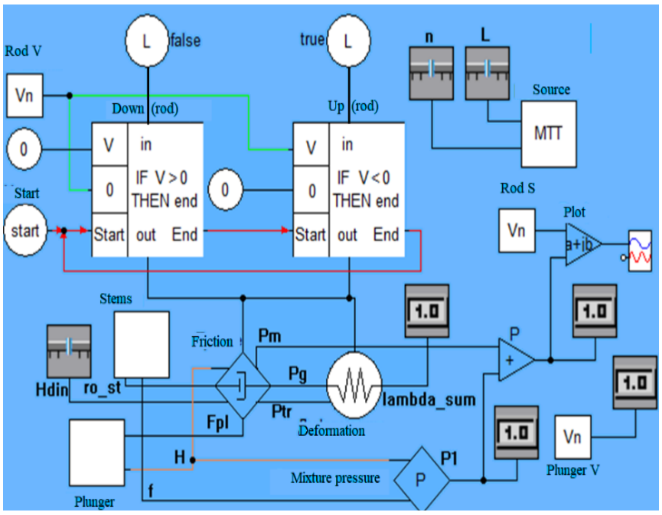


Fig. 8. Model at L layer.

The C layer (Fig. 9) presents the model of continuous behavior of simulated system (visually corresponds to Rod–Stems–Plunger) in CC form comprised of the following components:

1) Plunger, Stems are the components representing models of inertial bodies performing reciprocal motion;

2) Source is the component representing rod model (Velocity source);

3) Friction is the components containing a set of equations for prediction of plunger friction upon downward and upward motions;

4) Deformation (elasticity) is the component for prediction of deformation of stems upon downward and upward motions;

5) Load is the component for prediction of load of oil and gas mixture on plunger;

6) Virtual measurer of potential variables Vn, transferring the values to similar presentations on the l layer;

7) Integrators IN, used for predictions of rod and plunger positions.

Each component (except for virtual measurers and integrators) contains a set of algebraic differential equations, which are solved at each iteration. Predicted velocities of plunger and rod are transferred to the L layer via virtual measurers, other variables are transferred to outputs of respective components as the solution progresses. Topological links of the components determine the order of their request and, as a consequence, the sequence of solution of the set of equations (which are solved when the request is terminated).

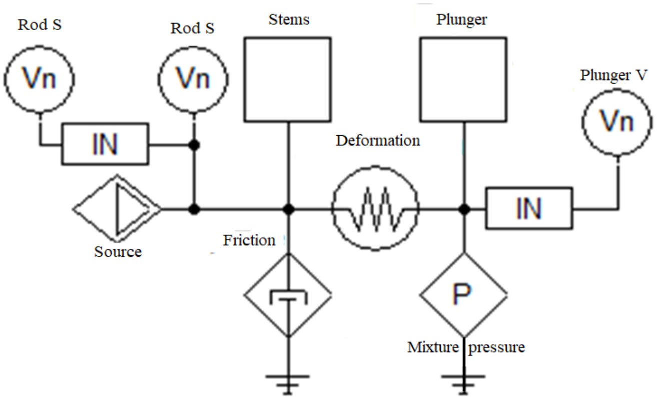


Fig. 9. Model at C layer

Using integrating components in this C layer makes it possible to transfer from basic variables, force *F* and velocity *v*, to work of force and motion. Similarly, differentiating components can be used. In order to measure steam variables, appropriate virtual measurers V_b are used. In this layer, it is also possible to simulate motion of multiphase streams (for instance, petroleum/gas) by means of pump, pipe, and other components using heterogeneous vector links [30] containing several pairs of dual variables (potential and stream).

The results of the developed model are illustrated in Fig. 10.

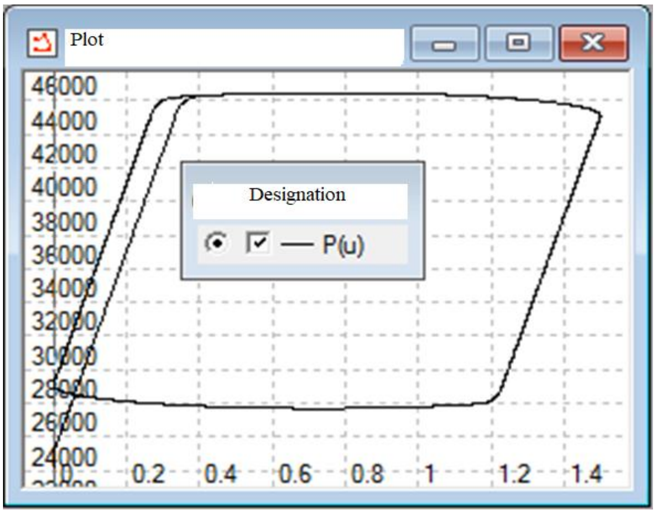


Fig. 10. Load at stem hanging point as a function of motion of this point

IV. CONCLUSION

PEP, widely applied in researching, designing and educational activities, are characterized by certain features (caused mainly by complexity of simulated objects), which decreases simulation efficiency by classical tools. The described approach makes it possible to build model of ready parametrized units while separating the model of continuous object behavior (presented both in unit symbol form and in component form) from the model (algorithm) of its control (implemented by various tools, including state diagrams). Herewith, application of ready units does not decrease versatility of environment due to possible flexible adjustment of the units as well as open library of the components. Separation of variables into dual pair (potential and stream) and possibility of arrangement of heterogeneous vector links between the components make it possible to simulate multiphase power and information streams.

PEP are exemplified by the considered problem of force simulation on SRP polished rod. It is characterized both by structural and by behavioral complexity, which is reflected in its multilevel computer model. The performed formalization permitted to decompose it into three levels: 1) continuous model of motion upon friction and expansion forces considering for structural complexity; 2) discrete model of motion subdivided into cycles considering for behavioral complexity; 3) visual representation of the model operation. Such subdivision would permit to perform further development and adjustment of this model. This problem was solved using application of standard components of one-dimensional mechanics (Velocity source, Spring, Damper) with their correction and parametrization, which confirms the concept of versatility of the developed approach.

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