National Conference with International Participation
ENGINEERING MECHANICS 2007
Svratka, Czech Republic, May 14 – 17, 2007

SOME PROBLEMS OF COMPLEX DRIVE SYSTEM SOLUTION

C. Kratochvíl, P. Heriban, L. Houfek, M. Houfek*

Summary: *Today the drive system is considered mainly as interactive system containing a range of subsystems with different physical nature: mechanical – the basic ones, electrical and hydraulic, pneumatic and also electronic – control ones. Models of those complex systems can then be characterized as so called 'purpose build and partially structured'. The models of those partial subsystems have their typical signs and properties, which can often essentially influence the dynamic properties and global system models behaviour. The aim is to keep so called functional model purpose – in comparison with the real system, which does not necessarily mean that the model must contain all the function and signs. By contrast we suppose that those functions have their carrier, which in limit case can be represented by black box. The control of such systems then more and more often require use of intelligent control algorithms, based for example on genetic algorithms and artificial neural networks.*

1. Introduction

Today requirements on drive systems design essentially differ from requirements usual in past. Firstly the requirements on operating effects appear during the design phase and so called 'complex' modelling, modelling 'in alternatives' with the emphasis on design influence on the environment starts to enforce. Dynamic and stress/strain analysis (even the complex ones) become common routines and provision of operating reliability for the specified period of analyzed structure technical life become the priority.

The contribution shows how to solve mentioned problems during the analysis of particular technical systems with tooth wheels and gears. To model and simulate such system is necessary:

- to create objective and partially structured model of basic mechanical structure,
- to create at least simplified models of meshing conditions, transfer function and kinematical excitation for tooth wheels and gears,
- to create model of surrounding environment,
- to formulate the concept of drive system control and
- to propose the way of integration of drive system structure, surrounding environment and control.

* prof. Ing. Ctirad Kratochvíl, DrSc., Ing. Pavel Heriban, Ing. Lubomír Houfek, Ph.D., Ing. Martin Houfek, Ústav mechaniky těles, biomechaniky a mechatroniky, FSI VUT v Brně, Technická 2, 616 69 Brno, tel.: +420 541 142 853, fax: +420 541 142 876, e-mail: kratochvil@fme.vutbr.cz

Furthermore, the following has to be known:

- models of technological, drive and parasitic effects,
- structured requirements on control from the technology, process, safety, energy requirements or limits (e.g. ecological) point of view,
- model(s) of logical-information connections.

2. System methodology and its use in drive system modelling

It's clear that modelling of particular technical system must respect general recommendations mentioned above and at the same time it has to consider the particularities coming from the given system requirements definitions ant their purpose. In drive system we have to consider that the systems primary purpose is to work as the drive for working machines. Its generalized structural diagram is shown on Figure 1. We can see that the drive as independent structural subsystem is connected with certain other subsystems, which must be considered in corresponding model.

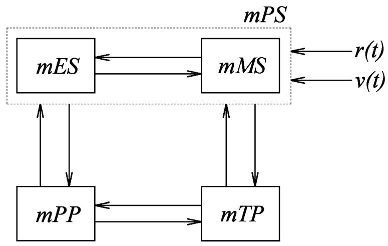

Fig.1. Complex model of drive system

That means that our aim is to create submodels of:

- electrical (hydraulic) parts of the motor – **mES**
- mechanical parts (motor, gearings, ...) – **mMS**
- working environment model – **mPP**
- technological requirements model – **mTP**

First two submodels create the submodel of drive system (**mPS**) with control requirements **v(t)** and perturbations **r(t)** inputs as outer effects (see Fig. 1). Such model will be further called the **complex model**.

That means that we must:

- build equations of motion of particular subsystems of the drive according to their physical principle, that means for mechanical part, electrical part, control, etc.,
- create models of gearing conditions and kinematical excitation for gearing subsystems,
- create model of surrounding environment effects,
- create model of requirements of technology and control and integrate those into control submodel,
- formulate and model driving, parasitic and malfunction effects and finally
- create model of information elements.

3. Use of isomorphism and homomorphism in drive system modelling

Previous section defined requirements for creation of computer models of drive systems. It is clear that not all the models will contain complete set of submodels. Models are considered as **purpose-build and partially structured**. In other words, according to the model purpose its structure can be changed and therefore its properties and usage. The effort in defining appropriate level of structural complexity depends on requirements on the model, working states it models, transmitted energy power course and required information capacity. Therefore we request the functional equality and real difference between technical object and its model system at the same time. This can be considered as certain type of analogy which keeps the isomorphic conditions. For the drive systems and its mathematical models it means that there is unique mapping between variables domains, between initial states and input and output functions. If following drive system is considered with appropriate state equation as mathematical model

$$\dot{x}(t) = f[x(t),t], \quad f : R^{\omega} \to R^{\omega},$$
$$y(t) = g[x(t),t], \tag{1}$$
$$x(t=0) = x_0 .$$

Or for parametric dynamic system in form of

$$\dot{x}(t) = f[x(t),\alpha,t], \quad f : R^{\omega} \to R^{\omega},$$
$$y(t) = g[x(t),\alpha,t], \tag{2}$$
$$x(t=0) = x_0 ,$$
$$\alpha(t=0) = \alpha_0 .$$

Then we must realize the following transformations between real system Sr = S1 and its model system Sm = S2:

- mutual unique mapping F1 between state sets of both systems X1 and X2,
- mutual unique mapping F2 between output sets U1 and U2
- mutual unique mapping F3 between output sets Y1 and Y2

Mentioned transformation are generally valid for isomorphic systems, but in reality we often see that several elements from set X can be assigned to certain element from set Y, that means that unconditional uniqueness is not required. The relations are more liberal, characteristic for homomorphism. Homomorphic system does not have to be identical, feature identity is sufficient. Homomorphic systems can be identical even if one of them (abstract) is simplified in such a way that its elements and linkages, inputs, states or outputs are not perfectly distinguished – which is in an agreement with the conception of purpose-build and partially structured dynamic system and its model.

4. Structural analysis of drive systems [3]

If we summarize the basic matters, mentioned above, we can say that drive systems are represented in simulation experiments by model systems, understood as objective and partially structured dynamic systems:

- defined on real objects on chosen distinguish level,
- understood as sets of mutually linked elements and couplings,
- linked interactively with the environment.

The system embraced this way can be at the same time the element of higher order system, on the contrary the element of the system can be the system of lower order.

The drives can contain (from the structure point of view):

- motor subsystems,
- generally multilevel control subsystems,
- gearing mechanisms,
- technological mechanisms,
- service mechanism.

Not all the models must contain all mentioned subsystems. Contrariwise it's typical for certain drives that a number of substructures is doubled (so called function backup), therefore its models must respect this fact. The structure can essentially differ from the point of view of objective the model is used for. If we narrow the problem onto mechanical subsystems only we can see a number of different model schemes, among them the most common are:

- drives modelled as rigid systems with 1 DOF, loaded with drive and load torque, possibly with absorbing outer torque;
- drives modelled as rigid motor + mechanism with rigid elements;
- discrete model with massless spring and dumping bindings (generally with n-DOF);
- discrete drive model made using FEM;
- drive systems with continuously distributed mass (continually distributed moment of inertia), stiffness and dumping characteristics;
- models of interactive controlled drives containing submodels of subsystems of various physical principle (mechanical, electrical, electronic, hydraulic, ...). Models of mechatronic systems with certain level of intelligent behaviour belong to this group as well.

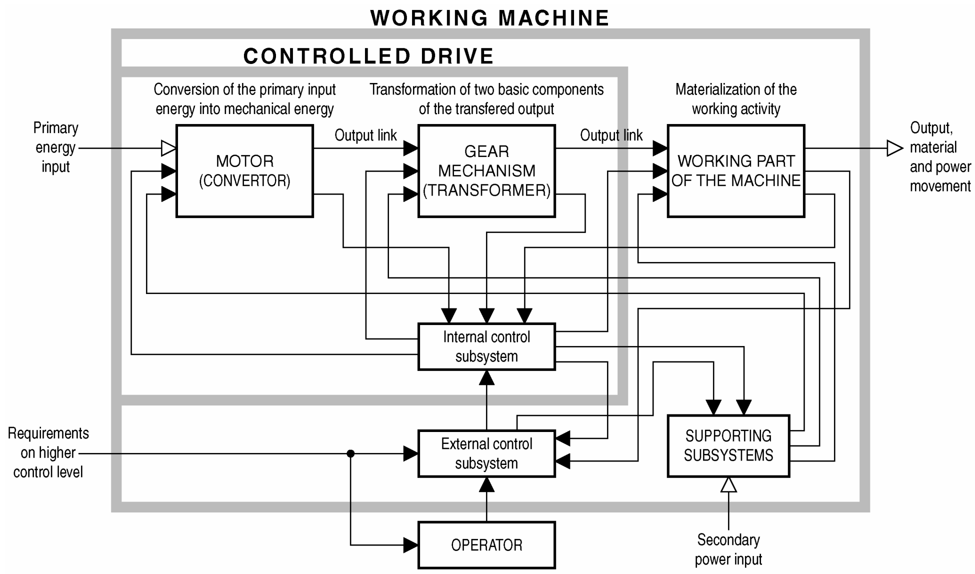

Fig.2. Structure of the drive system

5. Modelling of mechanical parts of drives

Discrete models of real systems

First we must distinguish between physical discretization and discretization in FEM.

Physical discretization represents the isolation of parameters of mass, stiffness and/or dumping, which results in model system made of centralized masses (moments of inertia) with massless spring and dumping bindings. There are no inertial bindings in the system! Model formulated this way is limited regarding Poisson's ratio – for plane tasks the model is valid for μ up to 1/3.

Discretization in finite element method is higher form of model creation, closer to the real system. It enables to remove the absence of inertial bindings, which on contrary brings additional parasitic stiffness of elastic bindings. This results in phase speed of dynamic loading sin waves higher than corresponding speed in continuum. There are no limits for Poisson's ratios. Disperse effects of model system are influenced by the density of the grid in given load. Therefore it is recommended to choose the density in such a way that wave elements of the load have in the frequency area the phase velocity only slightly different from constant wave speeds in continuum. Elements symmetry and homogeneity of triangulation have essential influence on disperse characteristics. We must also keep in mind that element size changes disperse properties of the model and the value of limit frequency.

Diagonalization of mass and dumping matrices

When diagonal mass matrix is used the absence of inertial bindings occurs – with effects mentioned above. When diagonal dumping matrix is used we describe only absolute (outer) dumping, which is highest in lower frequencies. On the other hand the consistent dumping matrix describes material (internal) dumping, which is highest in high frequencies.

6. Toothed gearing – sources of possible parasitic oscillations [8]

The problems connected with toothed gearings and simulations of its dynamical properties and behaviour will be discussed in different contribution [7]. Let us give at least sources of possible parasitic oscillations which can be excited in toothed gearings and which can essentially effect dynamic properties of whole drive – see Fig. 3.

Faulty engagement of toothed wheels can lead to the consequences shown on Fig. 4.

Thermal distortions
Pinion distortion → ↓ **← Wheel distortion**
Gearcase deflection → ↓ **← Gearcase accuracy**
Pinion movement → ↓ **← Wheel movement**
PInion tooth deflection → ↓ **← Wheel tooth deflection**
Pinion profile accuracy → ↓ **← Wheel profile accuracy**
Pinion pitch accuracy → ↓ **← Wheel pitch accuracy**
Pinion helix accuracy → ↓ **← Wheel helix accuracy**
TRANSMISSION ERROR
↓
Gear Masses **Support Stiffnesses** **Combined Damping**
↓
Intemal Dynamic Response
↓
BEARING FORCES
↓
Casing Masses **Casing Stiffnesses** **Casing Damping**
↓
GEARCASE FOOT VIBRATIONS
↓
Antivibration Mounts
↓
TRANSMITTED STRUCTURE VIBRATION
↓
Sound Radiating Panel
↓
AIRBORNE NOISE

Fig.3. Possible sources of parasitic vibration in gear teeth

7. The procedure for designing a control system [7]

The design procedure for designing a control system is an orderly sequence of steps. Good engineering design is interdisciplinary and requires that the engineer first thoroughly understand the customer’s requirements, the defined control system specifications, the environment that the control system will operate in, the available power, the schedule that it must be built in, and the available budget to do the job.

Fig.4. Consequences of faulty tooth design

Other considerations are reliability and maintainability which may dictate the kind of motor to use (i.e., electric motor or hydraulic motor).

Due to the availability of a large number of techniques to solve the great variety of control system problems present, the element of experience is very important to the approach used for the solution of a specific problem. An outline of a logical step-by-step procedure for designing a control system from its conception through the final hardware stage is illustrated in Figure 5 and described as follows:

1. Obtain a complete understanding of the job requirements with respect to
   - a general description of the problem,
   - the overall control-system performance and accuracy with respect to the steady-state and transient phases;
   - identification of the transfer function of the controlled process;
   - miscellaneous requirements as to reliability, schedule, cost, maintainability, size, weight, and available power.
2. Consider several alternative solutions, including electric and hydraulic power servo drives, the use of continuous control or digital control, etc.
3. Choose the most desired approach based on the specifications, requirements, and elements fixed by the customer.
4. Interpret these requirements in terms of such closed-loop design characteristics as frequency and transient response.
5. Establish the approximate open-loop characteristics that will satisfy the closed-loop requirements.
6. Design the system and select the sensors, actuators, amplifier, and stabilization required (analogue or digital) in order to satisfy step 5.
7. Review , refine, and simplify steps 5 and 6.
8. Simulate the system on a computer, including its linear and nonlinear characteristics, to check the design. Make any necessary changes to the design.
9. Build a prototype, and check the design experimentally. Make any necessary changes to the design.
10. Refine the design in order to optimize performance and minimize cost.

Observe from this approach that the procedure is an iterative one, and is itself a feedback process, as illustrated in Figure 5.

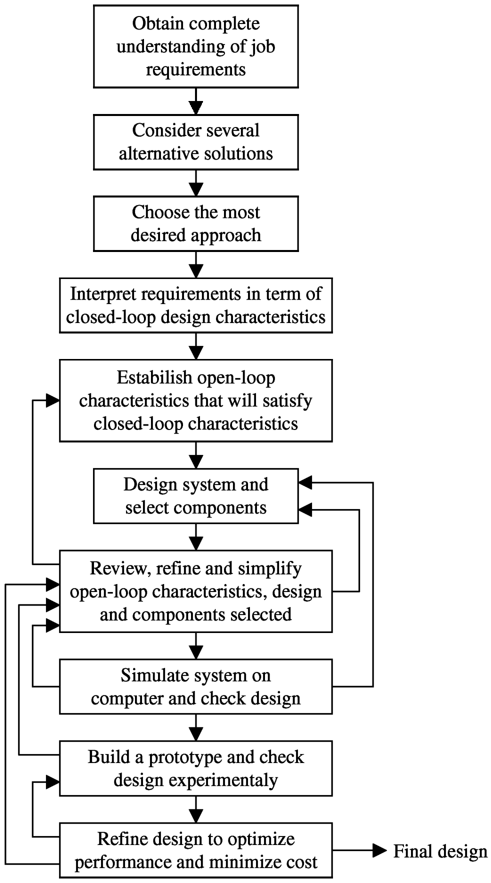

Fig.5. Procedure for designing a control system

8. Example of drive system [1, 2, 5, 6]

The aim of this-example is to reveal application of the multipole modelling on the solution of problems of dynamic of driving system with gears. The gears and first of all gearboxes, constitute one of the basic structural parts of driving systems. Due to their dynamic properties, given most of all by their constructional arrangement and dimensioning, they may influence significantly the behaviour of drives. The epicyclical gearboxes used in off-the-road vehicles (see Fig. 6, modules III and IV), have many steps (5 or 7), contain two or more than two planet units and many spur gears, couplings and brakes. The control of coupling and brakes is hydraulic. Most of such systems are of mixed energy – domain nature. Phenomena in liquid are exploited in them in combination with phenomena coming from other energy domains (like mechanical, electrical, etc). Also thermal phenomena affect the behaviour of there systems. The available control design procedures are based on a rather high degree of system abstraction and idealization. Most of the procedures assume that the controlled systems, controllers, sensor and other components are linear and simple. In practice, however, they are mostly nonlinear, complex and subjected of many constraints.

When dynamic behaviour of these systems is investigated, the systems are usually decomposed into a number of mutually interacting modules. These system modules may be real components from which the system is actually assembled on aggregates of such components. But they may also be just some non-separable parts of the components exhibiting certain dynamic phenomena (fiction, clearances, flexibility of individual gear-teethes, etc). In general, to investigate energetic interactions between a system module and the rest of the system, we have to integrate all the infinitesimal energy flows through a module energetic boundary – a geometrical surface enclosing the module.

Figure 6 shows block diagram of the off-the-road vehicle drive. This drive system is decomposed into following interactive modules: I – motor; II – final drive; III and IV – epicyclical gear – cases; V – starter; VI – servosystems.

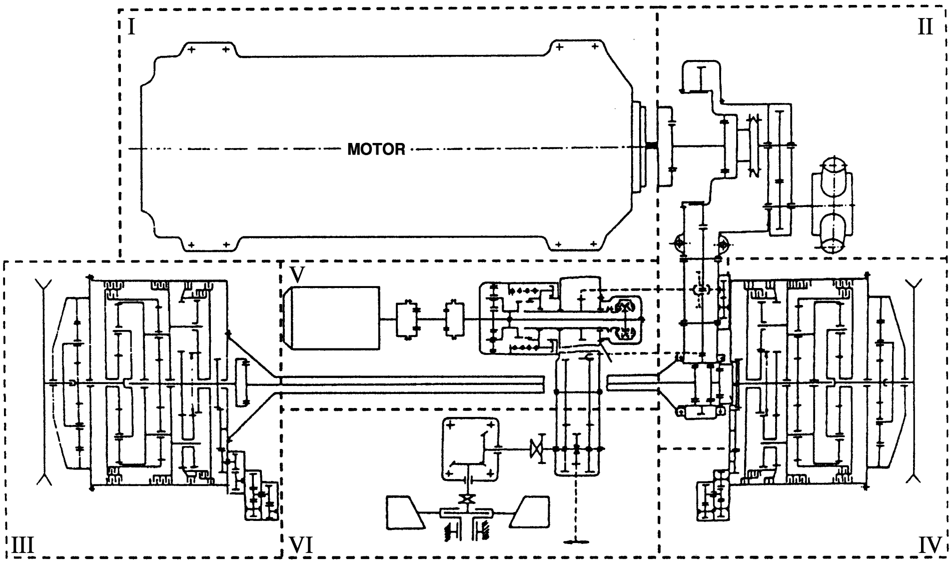

Fig.6

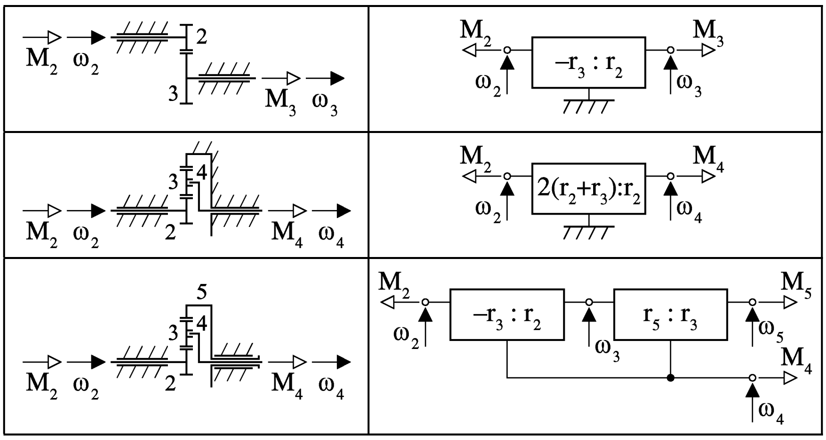

Fig.7

Table in the Figure 7 gives examples of the basic mechanical subsystems (which are used in the scheme on Fig. 6) and their multipole representation.

Fig. 8 shows a graphical representation of a multipole model of the complete drive system.

Following figures show some of output processes. Fig. 9 shows phase portrait in the modal point A – see Fig. 8. The changes of torque moments of the epicyclical gear shafts (modal point 1 and 2 – see Fig. 8) during the gear shifting are seen in Fig. 10. In Fig. 11 the course of maximum and real moments in the fluid coupling S3 (see Fig. 8) are seen. Also, there is evident mutual coupling between the parameters of the mechanical and hydraulic subsystems [2].

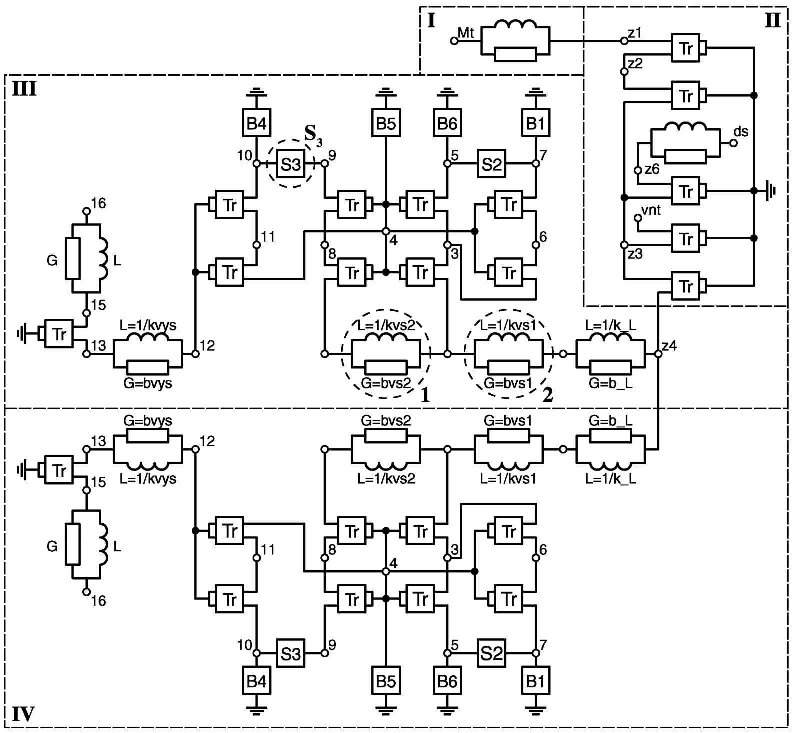

Fig.8

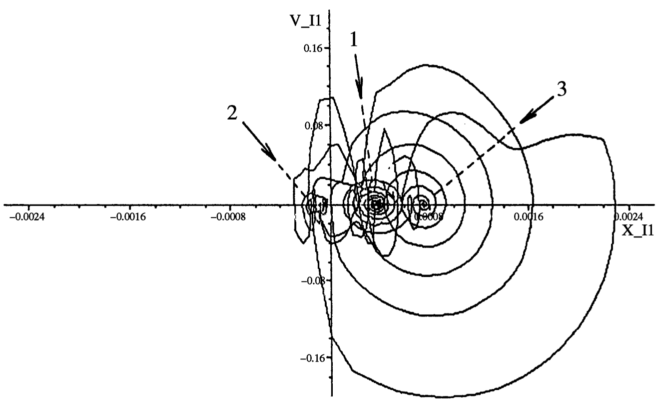

Fig.9

9. Conclusion

Problem of design of dynamic drive system with toothed gearings and simulation of its dynamical properties is extremely broad and complex. Present drives represent interactive systems with elements of subsystems of various physical principles. Therefore we limited the contribution onto selected problems including basic thoughts connected with creation of the model, its function and control.

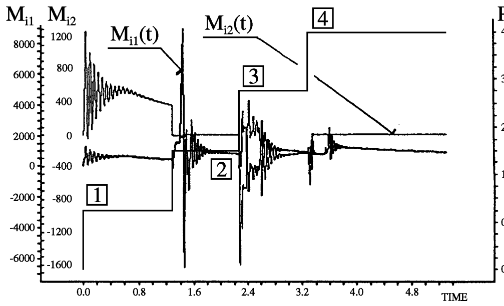

Fig.10

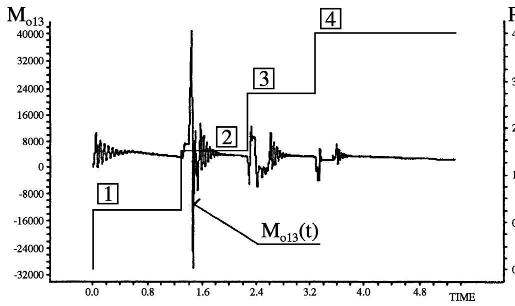

Fig.11

While calculating the kinematical parameters of response and course of elastic moments at particular points of the model, their mean or maximum values, and standard or extreme deviations, we can also calculate the courses, the correlation and spectral density functions. These values, plotted in relation to the changes in selected structure parameters of drive models, can then be used by engineers to give the dimensions of parts of the drives, and after further analysis, to determine optimum variants of the structure. In solving a highly topical technical problem we have tried to demonstrate many advantages of the simulation method in dynamic analysis of machinery drive systems.

10. Acknowledgement

Published results were acquired with the support of the Institute of Thermomechanics AS CR (research plan AVO Z 2076514) and project of the GA CR No. 101/06/0063.

11. References

[1] Havlíček, J & Štyl, P. (1990) *Seznam makromodelů pro SADYS*, zpráva ŽĎAS č. 4 T29561–29576, Žďár nad Sázavou

[2] Heriban, P., Kotek, V. & Kratochvíl, C. (1993) *Modelování interaktivních pohonových soustav*, zpráva z řešení projektu GA ČR číslo 101/93/0297, Brno

[3] Janíček, P. (2001) Systémové metodologie, in: *Sborník TEAMWORK 2001*, VUT v Brně, pp. 5–16, Brno

[4] Kratochvíl, C., Heriban, P. & Šperka, P. (1994) *Modelling of Interaction Drive Systems II*, Research Report No. 101/93/0297, Brno

[5] Kratochvíl, C., Kotek, V. & Heriban, P. (1992) *Analýza dynamických vlastností planetové převodovky*, výzkumná zpráva ÚMT FS VUT v Brně, Brno

[6] Mann, H. (1986) *SADYS – program pro simulaci a analýzu dynamických soustav*, DT ČS VTS, Praha

[7] Shinners, S. M. (1998) *Advanced Modern Control Systems. Theory and Design*, J. Wiley and Sons, Inc., New York

[8] Smith. J.D. (1999) *Gear Noise and Vibration*, Marcel Dekker, Inc., New York