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DESIGN SCIENCE FOR MATHEMATICAL MODELLING OF GEAR SYSTEMS

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1. Introduction

Any technical system (TS) is defined by the set of its properties. For a specific class of TS it is also possible to define the specific properties. The designers, using experience acquired throghout many years of study and practice in a certain branch, deal with those properties which they consider to be important within the lower levels of the design process. This experience is almost impossible to communicate and its consistency and integrity are not guaranteed. This is due to the fact that the experience was obtained in a specific branch depending on the type of the professional career of each individual designers.
Consequently, in the design process the TS properties are not defined and analysed and as a result the demands made on them are not specified. If the properties are not defined, there their mutual relations and links cannot be known. In this way the necessary multicriterial optimizations and evaluations of propounded solutions guaranteeing the minimal time, minimal costs and maximal utility values are practically impossible. It is impossible or at leas very difficult to keep the required and attained properties in harmony under these conditions.

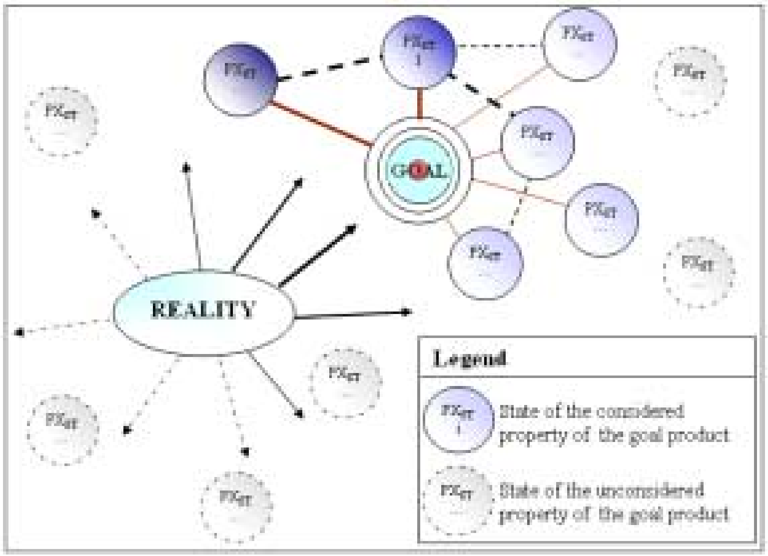

Figure 1. Achievement of property states of a designed product using the prevailing approaches [2]

If the designers influence a certain property in the required manner using only their own experience, then other properties may start to behave in unfamiliar way due to ignorance of their mutual dependence. Properties considered to be insignificant can become important and vice versa by this intervention.

Their further modifications may affect the whole system in an undefined way. Achievement of the desired parameters of the specified properties by a process of "trial and error" is uncertain and to a great degree dependent on chance if the we cannot make the changes cannot be made over and over again ad infinitum (Fig. 1).

From what has been said above it follows unambiguously that it is esential to operate with sets of TS properties, and specify thoroughly and completely both the properties in themselves and the demands made on them preferably as early as the initial phase of the design task solution. It is not easy to develop and use the necessary complex and consistent system of all classes of a complete set of the existing properties of technical products. However, this approach would better to achieve the needed target states of the properties, and at the same time to achieve a better balance between target states in the design of new technical products. This situation is shown in Fig. 2, where, for the sake of clarity, all properties are included in the three highest classes.

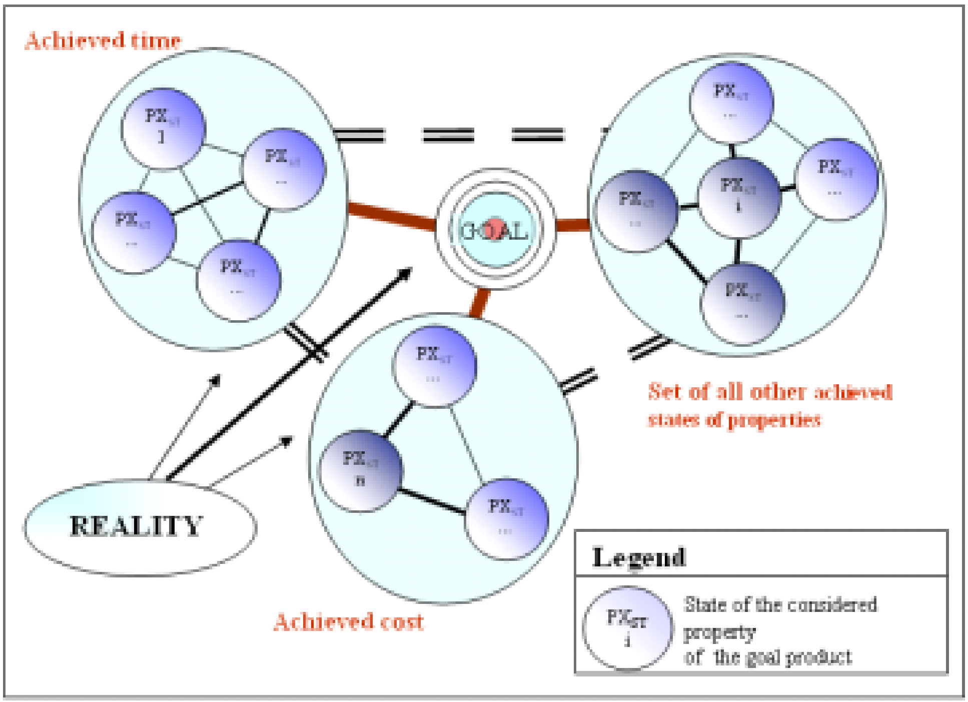

Figure 2. Achievement of property states of a designed product using engineering methods at a newly defined level III [2]

2. Hierarchical levels of the use of engineering design knowledge

These levels could be structured very roughly as follows [2]:

I. ("Intuitive approaches" based mainly on previously acquired knowledge and experience.

II. "Methodical-empirical approaches" based mostly on prescriptive or normative instructions. These are usually in the form of previously acquired summarized general knowledge, special theories and the practical experience of their authors, arranged differently.

III. "Systematic approaches" based mainly on a framework of structured knowledge - Design Science (DS) - obtained by scientific "mapping" of both theory and practice.

Each subsequent higher hierarchical level includes the previous lower level(s), and the real situation is in any case rather vague.

3. Procedural and Auxiliary Basic Operations of the design process

3.1 Four cyclic Procedural Basic Operations are as follows:

- State the problem (for a given task/operation)
- Search for solutions (for a given task/operation)
- Evaluate (the variants of proposed solutions) and Decide (on the best/optimal variant)
- Communicate the solution (the best/optimal or at least the nearest)

3.2 Three Auxiliary Basic Operations are as follows:

- Preparation and Elaboration of information/knowledge
- Verification and Checking
- Representation

4. Applied systematic structure of engineering design knowledge

In order to be able to model the above mentioned gear systems (GS) effectively and then to optimize them according to their dynamic behaviour, it was necessary to make the best use of the possibilities offered by "The third hierarchical level of knowledge use" (see Chap. 2). In this way it was possible to solve any serious problems arising out of the transfer and use of knowledge obtained from highly specialized scientific disciplines in all the basic operations (see Chap. 3) in the GS design process.

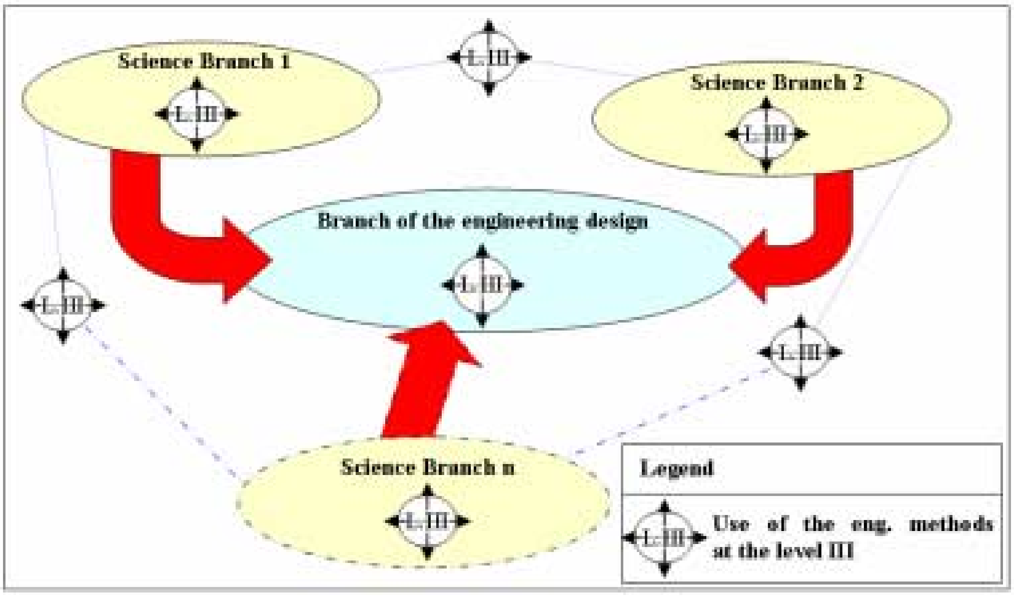

Figure 3. Systematic/scientific support of the use of engineering methods in different scientific disciplines and engineering design including their mutual links

5. Process of optimization of gear systems

The process of GS optimization was divided into three basic steps from the point of view of the dynamic properties of GS. To facilitate the solutions in every individual phase, subsidiary modules were created in the MATLAB language, enabling the simulation of the dynamic behaviour of gear systems.

5.1 Detection of the motion instability of GS

The instability of the motion of shaft systems with gears is inherent to the given system and does not depend on internal and external excitation generators.

The range of instability is given by the function of the gearing rigidity k (ξ) = f (εγ, …) and by the damping b, which considerably inhibits the instability of the motion (Fig. 4).
From the above mentioned it follows that parametric resonance can occur in exceptional cases only and can be anticipated effectively by the appropriate selection of the parameters of the shaft type assembly system (STA).

Table 1. Functional parameters of the gearing of the horizontal boring machine

W180B NC-SKODA	Gear: 2		Speed: II		
Functional parameters FP	Eigenfrequency of system Ω [rad s-1]	Ranges of the tooth frequency $\omega_z \left[rads^{-1}\right]$ and tuning η			
		$\omega_{z_{min}}$	η_1	$\omega_{z_{max}}$	η_2
	1.6971e+005	1330	1.2760e+002	6653	2.5509e+001

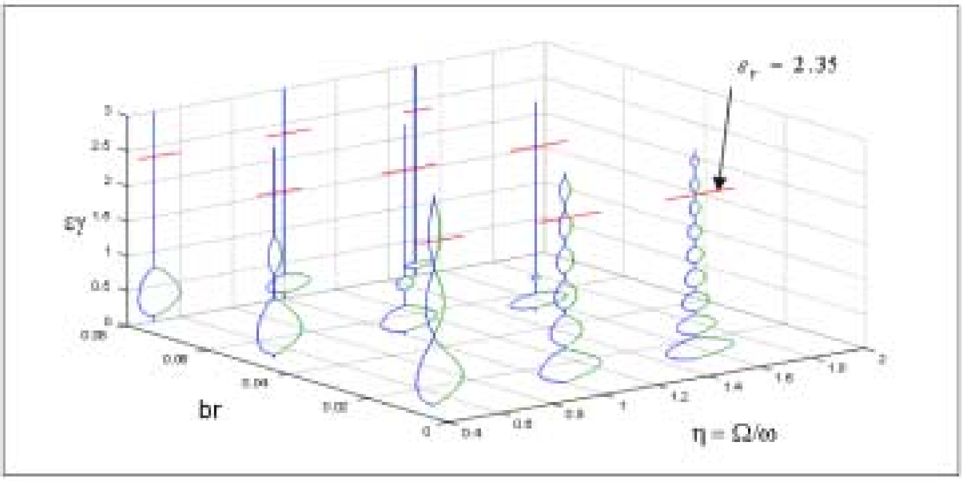

Figure 4. Instability ranges (W180B NC-SKODA)

5.2 Analysis of the vibration of a shaft type assembly system

5.2.1 Structure of the computation module for the analysis of the vibration of STA

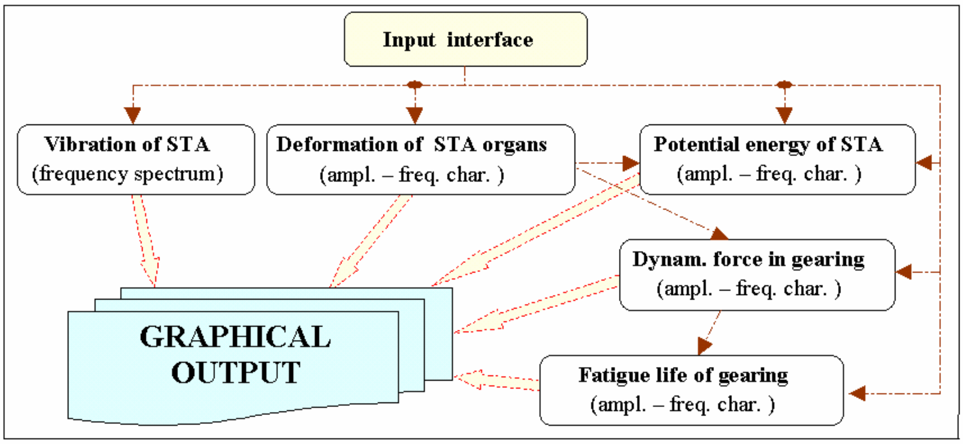

Figure 5. Structure of the computation module created in MATLAB

5.2.2 Mathematical model of STA

STA was broken down into shaft assembly groups (STG). STG were modelled by FME as 1-D continua and were coupled by linear and time invariable tooth couplings [5]. The model STA, thus created, was attached to the frame by bearing couplings with radial clearances. Each STA is composed of machine elements and its organ structure is shown in Fig. 6.

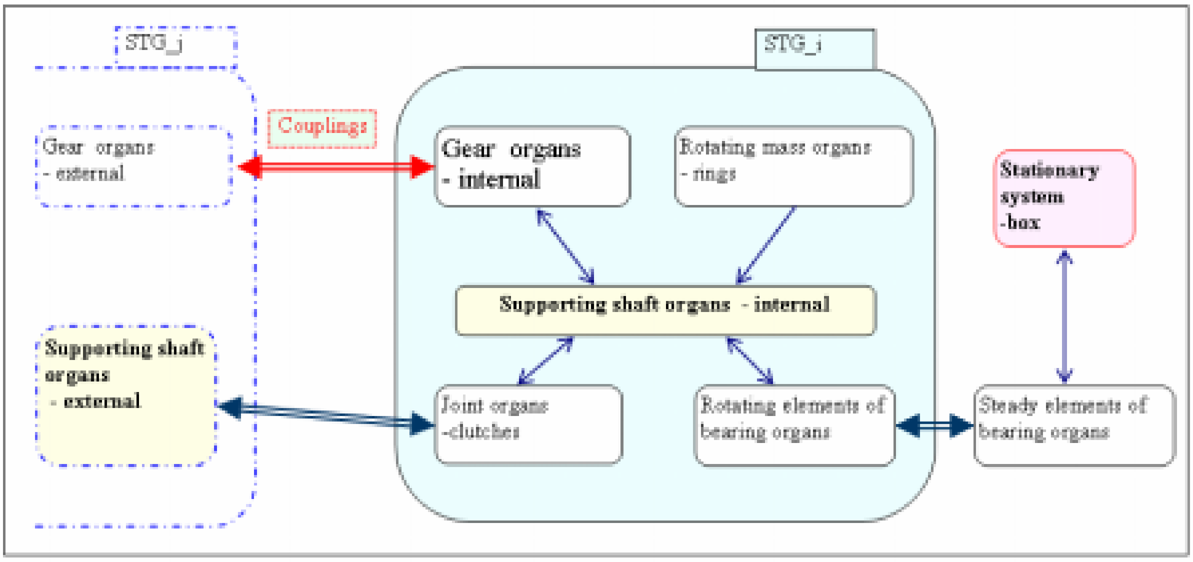

Figure 6. Organ structure of STA

5.3 Evaluation of the dynamic behaviour of STA and design of improved GS variants

The modules of the computational system (CS) mentioned above were designed especially with regard to their simple utilization in practice without presuming that the designers had any special knowledge of the dynamics of technical systems. The outputs from CS have to be well-arranged, intelligible to the designer and most exhaustive. Examples of the graphical outputs are in Figs. 4 and 7.

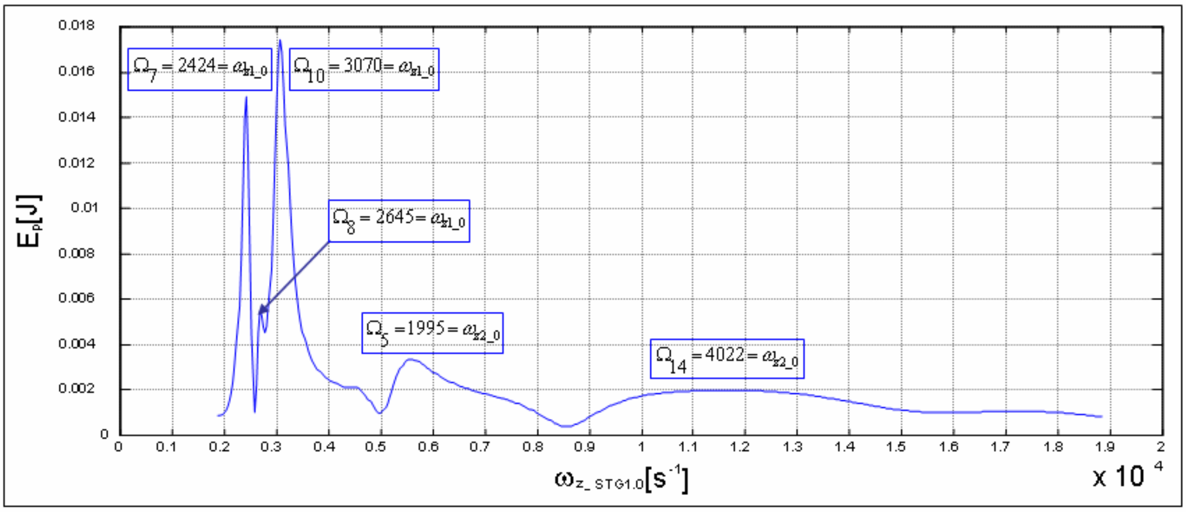

Figure 7. Amplitude characteristics of the stress state

Since the optimization of the STA is especially difficult with nonstationary gears in which tooth frequency varies in a wide frequency band and the resonant states cannot be eliminated from the operating state of GS, the computational system was added to the module of the parameters of GS

properties. The function „fgoalattain“, which is part of the optimization toolbox in MATLAB, was used.
The input parameters of the function were:

- The vector of the goal values

$$\mathbf{F}^* = \begin{bmatrix} \Omega_1^* & \Omega_2^* & \cdots & \Omega_n^* \end{bmatrix}^T \tag{1}$$

where the vector of elements corresponds to the required eigenfrequencies of STA

- Multicriterial function

$$\mathbf{F}(\mathbf{x}) = \begin{bmatrix} \Omega_1(\mathbf{x}) & \Omega_2(\mathbf{x}) & \cdots & \Omega_n(\mathbf{x}) \end{bmatrix}^T \tag{2}$$

where the calculated eigenfrequencies of STA are the function elements depending on the matrix of the tuning parameters (TP) **x**. The elementary – dimensional design properties of the shaft and the stiffness of the bearing organs were selected as the tuning parameters. In this way the designer can effectively affect the value of TP and the range of their changes.

6. Conclusion

In spite of the fact that the complex solution of the optimization of mathematical modelling is difficult and the internal dynamics of the gearing is one of the most complicated gearing problems, a very large computational system was created. This system makes it possible to design optimal gearing systems on the basis of the simulation of their dynamic behaviour, which is necessary for a quick evaluation of the suitability of proposed solutions with respect to the desired criteria. The use of the mathematical simulation of the dynamic behaviour of gearing systems in seeking the optimal solution makes it possible to design and compare the proposed GS variants from the point of view of the monitored parameters and is thus of great benefit to the designers. Compared to the formerly used approach, when it was necessary to produce the proposed variant of the solution and then check the results, the above mentioned methods and means have undoubtedly greater possibilities. Though mathematical simulation has evidently its own problems due the simplification and omission of some facts, in designing a certain variant (using the same method) it is possible to deduce whether any improvement of the monitored properties of the new GS variant has been achieved in comparison with the original solution variant.

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