INSTITUTE OF FLUID-FLOW MACHINERY
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TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

109

Selected papers from the National Seminar devoted to 60th birthday anniversary of Professor Jarosław Mikielewicz, Gdańsk, Poland, April 10th, 2001

WYDAWNICTWO IMP PAN

GDAŃSK 2001

EDITORIAL AND PUBLISHING OFFICE

IFFM Publishers (Wydawnictwo IMP), Institute of Fluid Flow Machinery, Fiszera 14, 80-952 Gdańsk, Poland, Tel.: +48(58)3411271 ext. 141, Fax: +48(58)3416144, E-mail: esli@imp.gda.pl

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Financial support of publication of this journal is provided by the State Committee for Scientific Research, Warsaw, Poland

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ISSN 0079-3205

TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY
Appears since 1960

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TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY
No. 109, 2001, 23-44

JAN KICIŃSKI[1]

State-of-the-art investigations and contemporary challenges in machine construction and exploitation

In the paper presented has been authors subjective opinion regarding contemporary trends in development of machine construction and exploitation. These remarks are particularly referring to integration tendencies in the area of applied research tools as well as in the area of traditionally used exploration tools such as: diagnostics, tribology or safety and reliability. Development of integrated computer systems CAD/CAM/CAE as well as of the concepts of widely understood concurrent design and mechatronics requires a different focus on the issue of machine construction and exploitation. In such context there is an increasing role of machine exploitation as a reflection of the product maintenance starting from its design stage through manufacturing up to its decommissioning.

1. Introductory remarks

A rapid development of computer systems in machine construction and exploitation forced the author of the present work to ask a question whether it is possible to outline the development tendencies of widely understood computerisation in that branch of knowledge or, in other words, which direction are we aiming at with a continuous development of hardware and software? Will that fact influence the integration of traditional scientific disciplines and the way of thinking about the final product? This task is extremely difficult because computerisation in machine construction and exploitation refers to the design and solid modelling systems (CAD), manufacturing and technology (CAM) and also calculations and optimisation (CAE). This is additionally supplemented by integrated software packages for complex manufacturing computerisation (industrial databases, process-tracing systems, visualisation software) and specific software connected with object exploitation according to their state (for example expert systems).

Presented in the work opinions are a result of authors subjective reflections and obviously are subject to argument.

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2. Integration and compatibility of CAD/CAM/CAE systems

For some time now foreign companies offer on our market different systems connected with design, production and engineering analysis. Tracing their development we can observe tendencies of combination of various functions such as design (CAD) with the manufacturing and technology function (CAM) and engineering analysis (CAE). In such way realised is a principle of virtual design:

design ⟶ analyse ⟶correct⟶manufacture

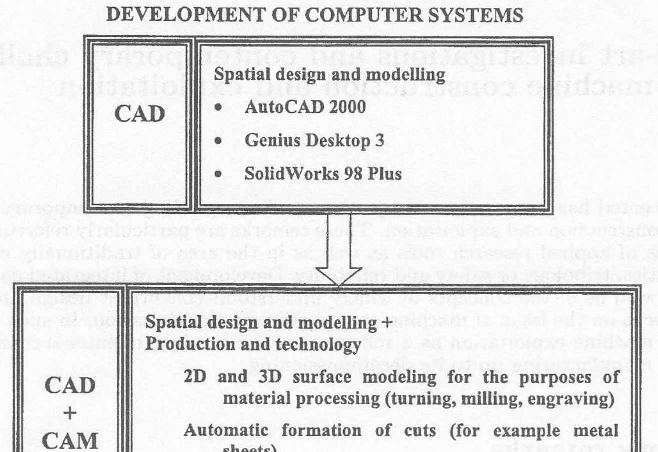


Fig. 1. Integration tendencies in CAD/CAM/CAE systems in machine construction and exploitation.

There is observed an increased role of computer simulation (Simulation Driven Design), and particularly of kinematic, dynamic and thermal analysis in the design process.

In Fig. 1 schematically are presented integration tendencies of computer systems and tabulated are companies regarded as world leaders in that area.

Lets return to the problems connected with engineering analysis (CAE). In Fig. 2 presented are directions of possible development of such systems in the near future. Precisely speaking, presented here tendencies could be observed earlier. It is characteristic, that the systems of CAE type are more and more oriented on the object exploitation according to their state, particularly on the systems with automatic feedback.

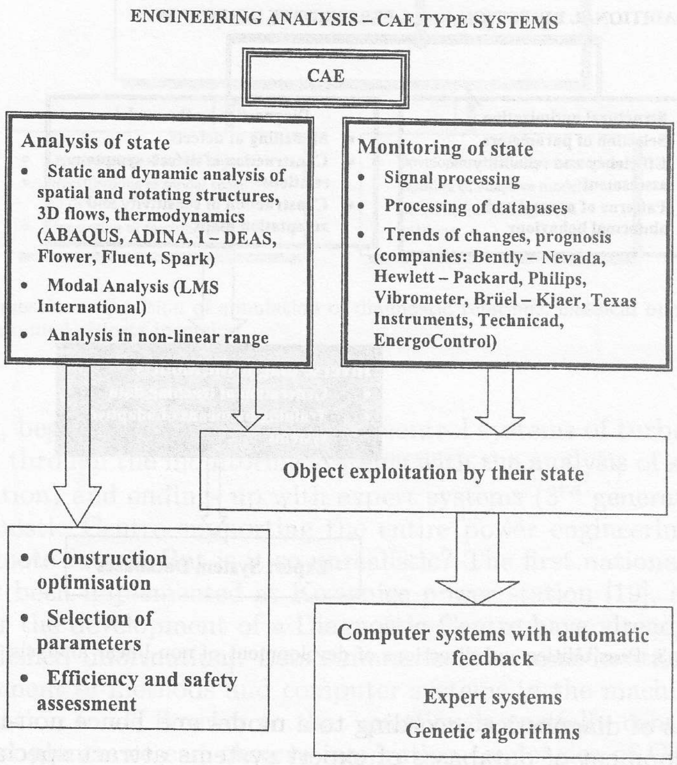


Fig. 2. Directions for the development of systems concerned with engineering analysis.

Traditional tools such as static and dynamic analysis of spatial constructions, modal analysis or non-linear analysis, which up to now have been primarily used in the machine construction and design, are more and more applied in machine, object and process exploitation. That remark regards primarily the non-linear analysis.

3. Non-linear analysis

A relatively new area of application of non-linear analysis is the diagnostics by the model. Possibilities of generation of vibration spectra as well as non-elliptic trajectories containing symptoms of imposed defects makes them very useful in development of relations of the type: defect – symptom. In Fig. 3 presented are capabilities of non-linear analysis along with the directions of its development.

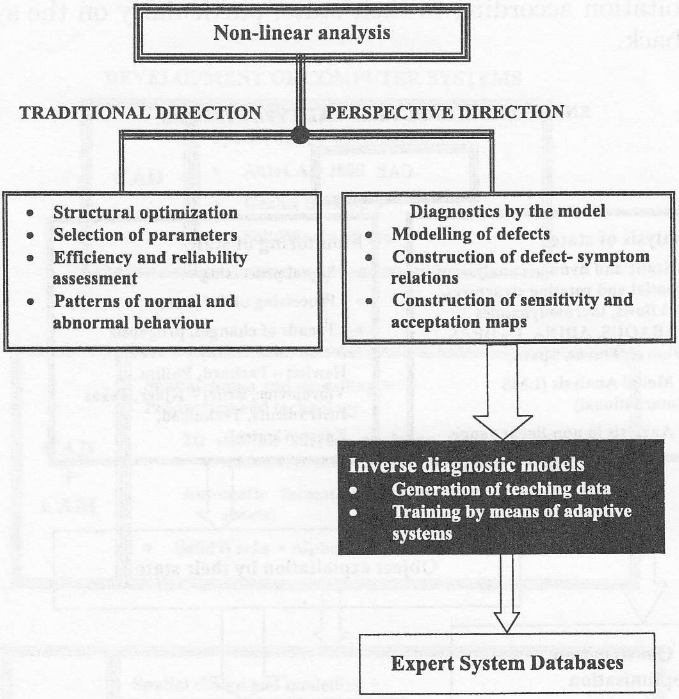


Fig. 3. Possibilities and directions of development of non-linear analysis.

Applications of diagnostics according to a model and hence non-linear analysis in the development of databases of expert systems attract special attention. Simulation knowledge can excellently supplement the knowledge of operation engineers as well as practical knowledge and form a precious chain-link amongst the methods of acquisition of diagnostic knowledge. Particularly useful in this light are the information acquisition techniques by means of inversion of the models of the objects, see Fig. 4 [18].

An opinion might be expressed that in the near future a particular progress in the development amongst systems with automatic feedback or in other words 'with artificial intelligence', commonly named expert systems, will be observed. In Fig. 5 presented is a development of exploitation control systems in power

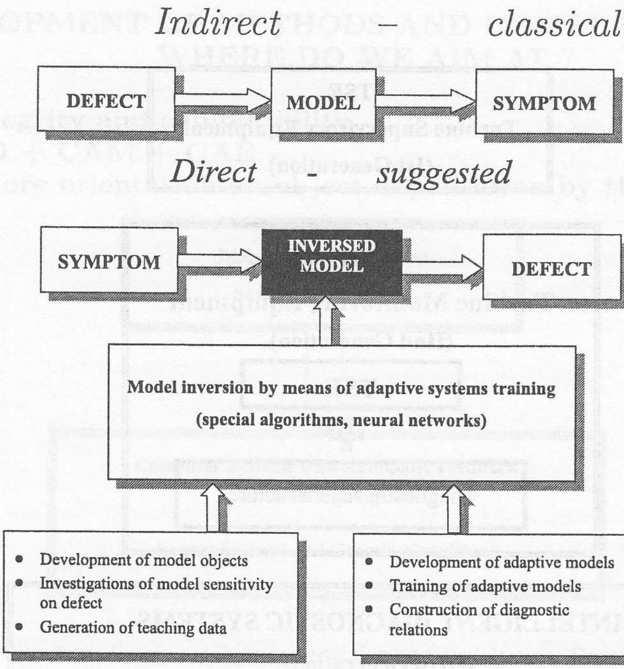


Fig. 4. Techniques for acquisition of simulation of diagnostic relations: classical ones and based on methodology of assumed objects inversion.

engineering, beginning with simple direct control systems of turbogenerators (1^{st} generation) through the monitoring systems with the analysis of state and trends (2^{nd} generation) and ending- up with expert systems (3^{rd} generation).

A Diagnostic Centre supporting the entire power engineering sector is still rather a remote future. But is it so unrealistic? The first national expert system has already been implemented at Kozienice power station [19], and preliminary concepts for the development of a Diagnostic Centre have already been elaborated [unpublished information]. Lets summarise our considerations. Where does the development of methods and computer systems in the machine construction and exploitation tend? Answer to that question is partially contained in Fig. 6.

At a first glance we can observe integration tendencies of CAD/CAM/CAE systems and their mutual compatibility. A role of engineering analysis and simulation investigations in the design process is increasing.

Secondly, we can conclude the tendency of further orientation of computer systems on object exploitation by their state. This can only mean further intensive development of diagnostics by the model, safety and reliability science but primarily of expert systems.

In Fig. 7 these tendencies are schematically outlined. Whereas earlier a much greater effort has been concentrated on the machine construction and building, then in future we can expect rather different proportions.

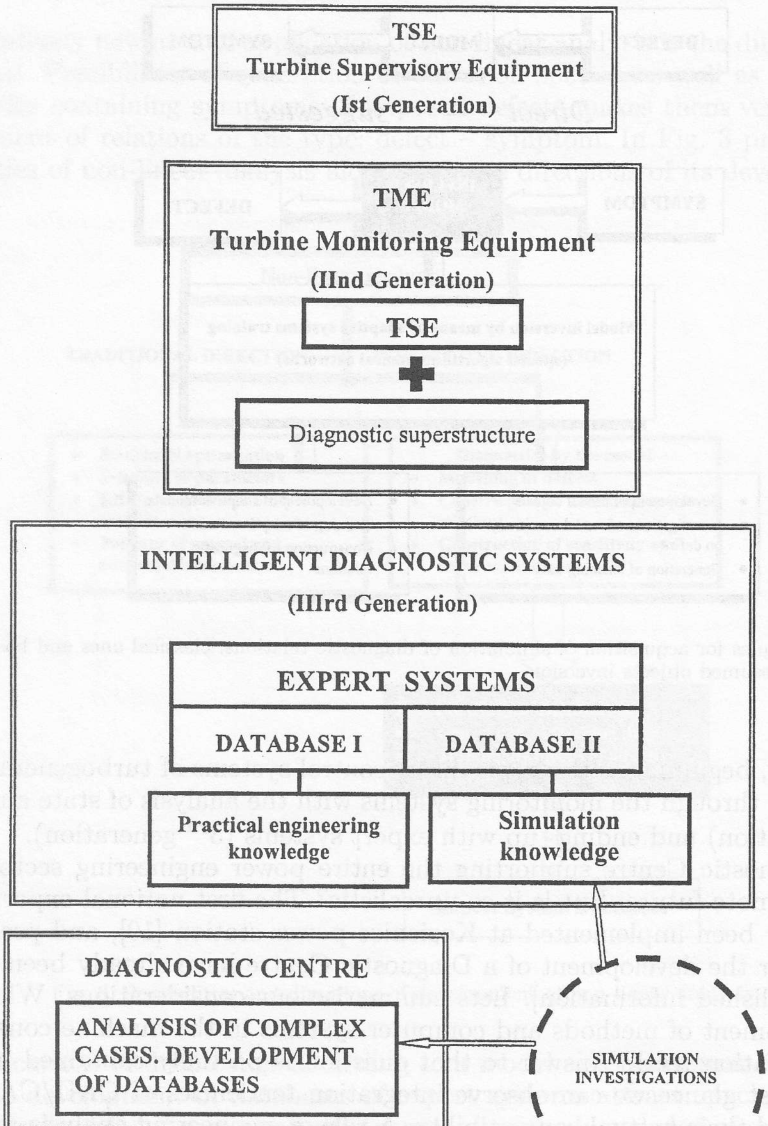


Fig. 5. Development of exploitation systems control of turbosets as an example of the possibility of application of advanced computer analysis in machine exploitation.

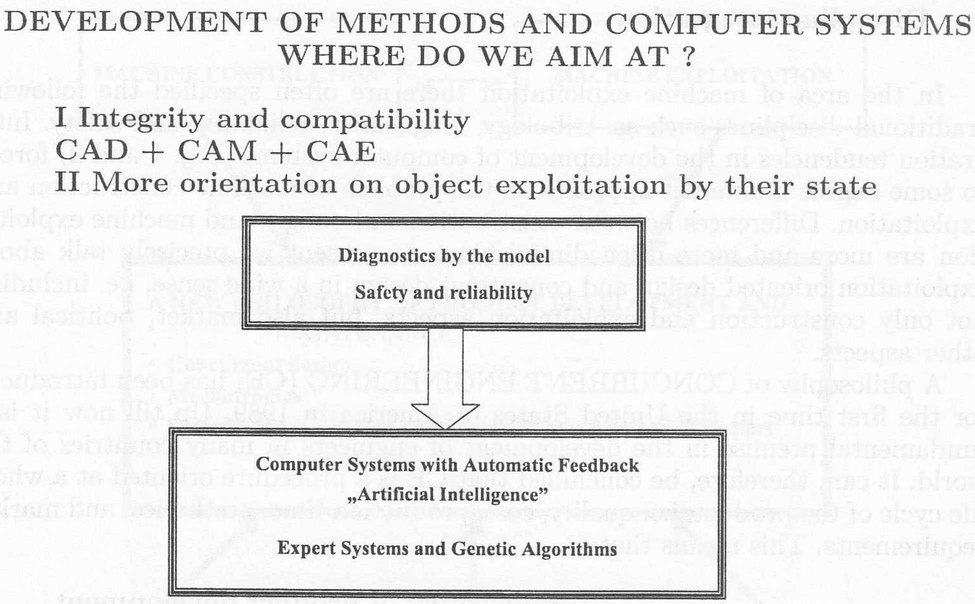


Fig. 6. Computerisation in machine construction and exploitation. Development tendencies.

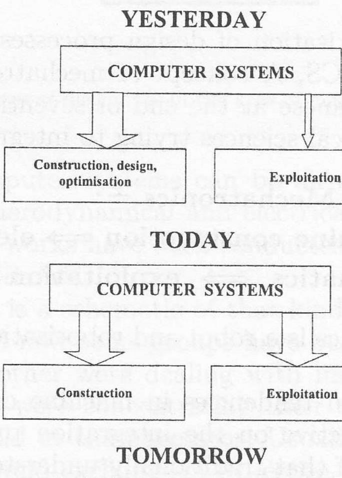


Fig. 7. Increasing role of exploitation in the share of computing and mathematical potential.

4. Discipline integration

In the area of machine exploitation there are often specified the following traditional disciplines such as: tribology, diagnostics, reliability and safety. Integration tendencies in the development of computer systems (Fig. 1 and 2) forced to some degree a different approach to the problem of machine construction and exploitation. Differences between construction and design, and machine exploitation are more and more often diminishing. At present we precisely talk about exploitation oriented design and concurrent design in a wide sense, i.e. including not only construction and exploitation aspects, but also market, political and other aspects.

A philosophy of CONCURRENT ENGINEERING (CE) has been introduced for the first time in the United States of America in 1989. Up till now it is a fundamental premise in the development of engineers in many countries of the world. It can, therefore, be concluded that CE is a procedure oriented at a whole life cycle of the product, i.e. quality, cost, production time, aesthetics, and market requirements. This means that:

$$\textbf{CE} = \textbf{CAD/CAM/CA E}+ \left\{ \begin{array}{l} \textbf{philosophy of product development,} \\ \textbf{ecology, market analysis, financial} \\ \textbf{analysis, product exploitation systems.} \end{array} \right.$$

Another effect of computerisation of design processes and its exploitational orientation is MECHATRONICS, A concept of mechatronics has, for the first time, been introduced by Japanese at the end of seventies. Mechatronics is an interdisciplinary area of technical sciences trying to integrate:

$$\begin{array}{c} \textbf{Mechatronics} = \\ \textbf{mechanics} \Longleftrightarrow \textbf{machine construction} \Longleftrightarrow \textbf{electronics} \Longleftrightarrow \\ \textbf{informatics} \Longleftrightarrow \textbf{exploitation} \end{array}$$

A classical effect of mechatronics is a robot and robotisation of technological and exploitational processes.

Presented above integration tendencies in machine construction and exploitation does not remain ineffective on the integration processes in the area of exploitation itself, especially of that traditionally understood. We talk more and more about the diagnostics of tribological nodes or prognostic-reliability models. This means obviously a common platform of thinking in tribology, diagnostics and reliability. In future that kind of tendencies will be a commonly existing standard at least due to the fact of pending unification and standarisation processes of software tools and investigation methodology. Systems of exploitation and control, which base on the methods of artificial intelligence, so called systems of new generation (expert systems), can serve here as an undisputed example, see Fig. 5 and Fig. 8. An example of action following the philosophy of integration

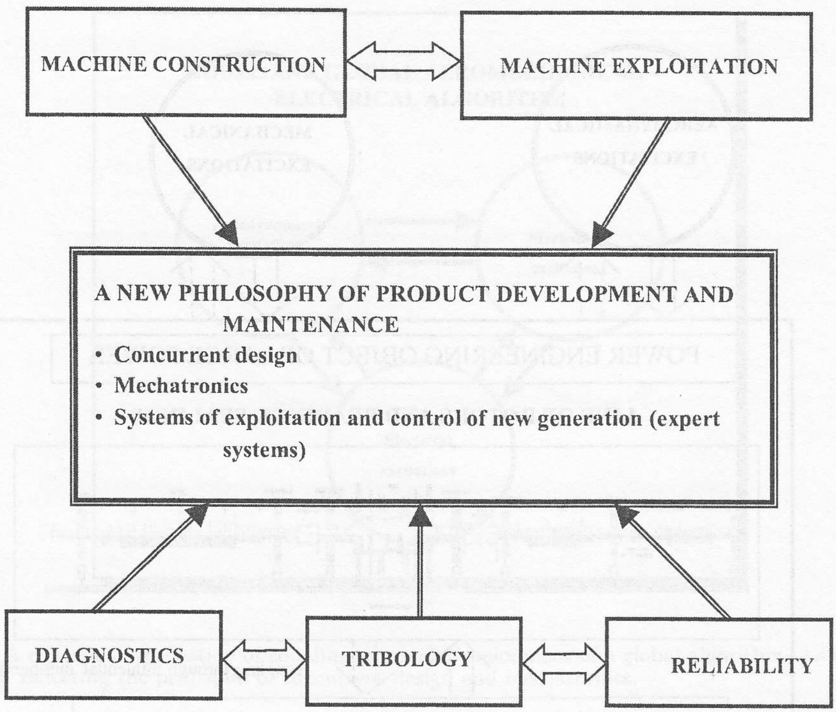


Fig. 8. Integration processes of disciplines in the area of machine construction and exploitation.

of disciplines and computer systems can be an attempt to develop a complex model of mechanical, aerodynamical and electrical interactions in a large power engineering unit. Such works have been conducted at the Institute of Fluid-Flow Machinery, PASci in Gdańsk.

In Fig. 9 presented is a schematic of that kind of excitations in a turboset of 200 MW power. Up till now some groups have been involved in investigations of object aerodynamics, other were dealing with mechanical problems (dynamics, vibrations) and others were concentrating their efforts on investigating the influence of electrical field in the generator. Usually, between these groups there were no close contacts and exchange of expertise, but one has to remember that the object of investigations is one, and is common to all investigators. The issues connected with exploitation of that kind of objects require another approach to the problems of design and state analysis. An appropriate approach here is a development of a global model, where aeromechanical and electrical problems are analysed simultaneously with account of mutual interactions, see Fig. 10.

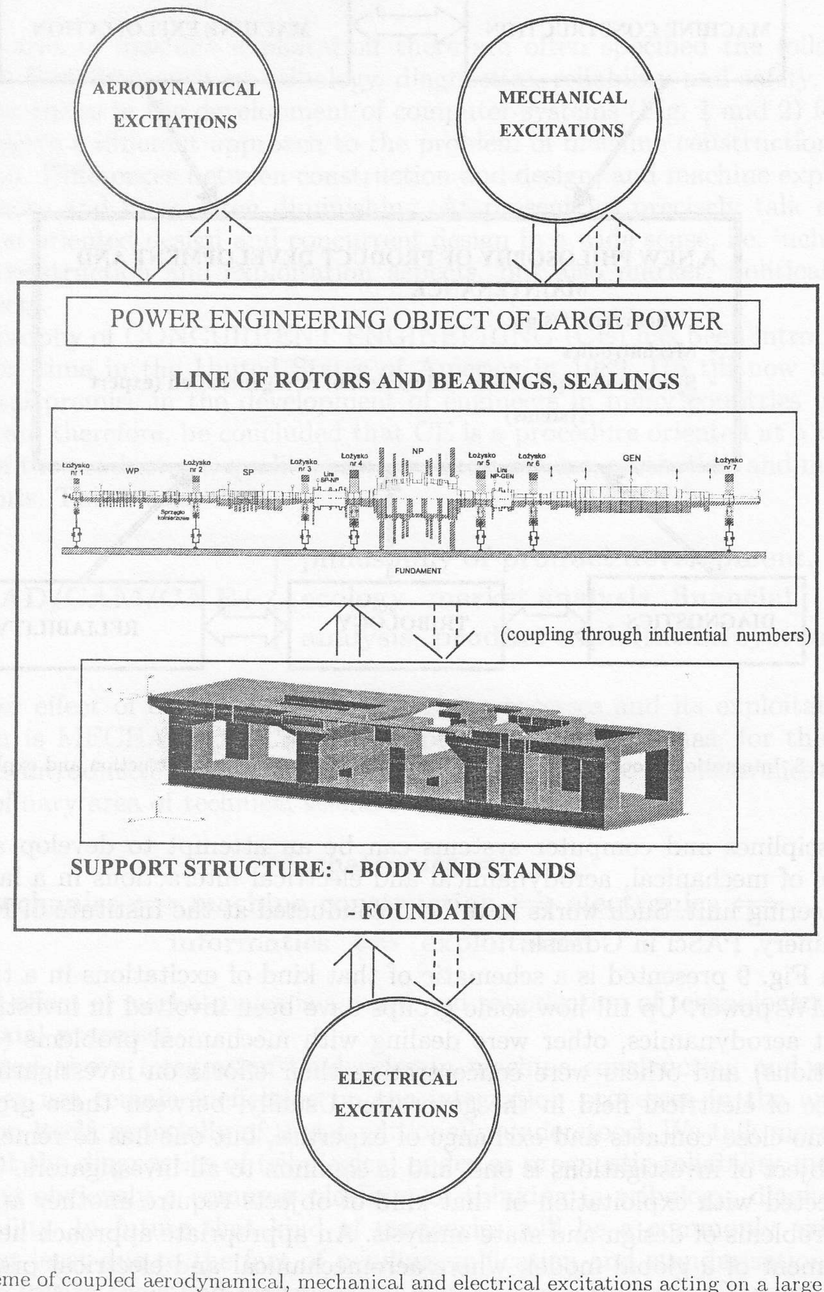


Fig. 9. A scheme of coupled aerodynamical, mechanical and electrical excitations acting on a large power engineering object. An example of interactions integrity in a complex technical object.

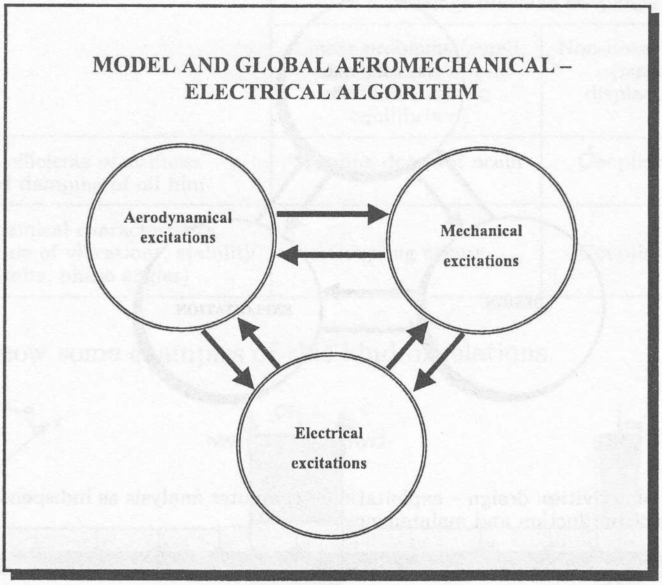


Fig. 10. A concept of realisation of couplings through development of a global algorithm. An example of approach reflecting the principles of concurrent design and mechatronics.

5. Exploitationally oriented design

From conducted analysis results, that nowadays it is difficult to talk about the machine design without account of widely understood aspects of its future exploitation. These demanding exploitation requirements impose the necessity of another glance at a design process and complex analysis of links, which occur between particular sub-systems of a designed machine. The system bearings-machine can serve here as an example.

Lets show, that the analysis of properties of bearings themselves, remotely from the machine and its exploitation parameters, can even lead to qualitative errors in the assessment of for example dynamical state of the object.

In each case we will have to deal with the following, mutually coupled process, see Fig. 11.

Obviously, the process presented in Fig. 11 forms some part of a wider activities in the process of product production and maintenance, see Fig. 8.

Lets illustrate above mentioned processes on some examples. Lets begin with the simplest relations, namely the relations of the bearings – machine type. The influence of bearings properties (construction) on the level of vibrations of selected nodes of the entire machine (exploitation) is here very pronounced.

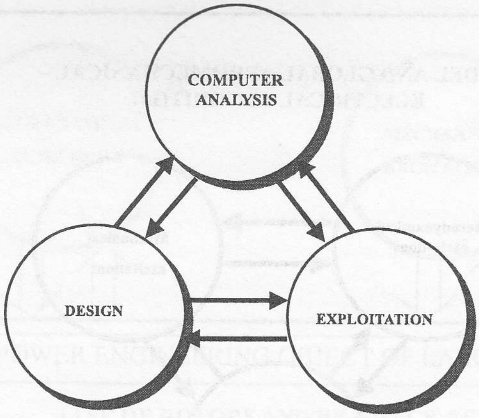


Fig. 11. Integration of activities: design – exploitation – computer analysis as indispensable minimum in the process of product production and maintenance.

5.1. Bearings-machine system. Small rotating machine

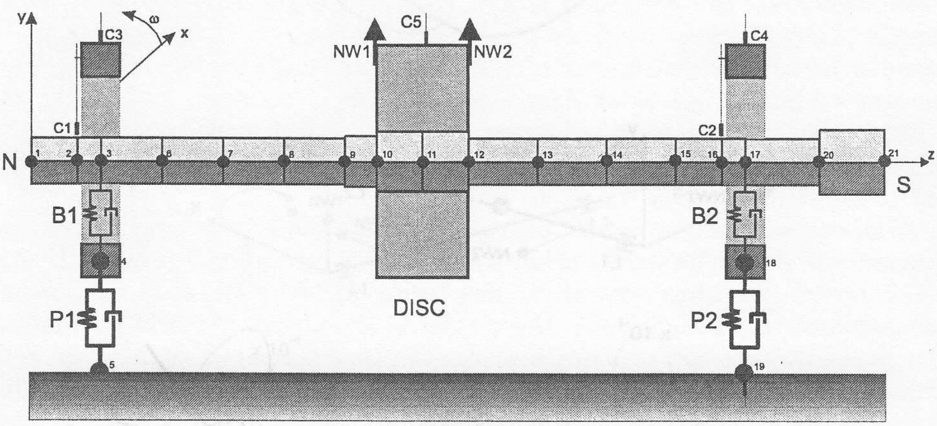
In the case of dynamics there takes place the coupling between the bearings properties with properties of the entire machine. This regards, for example, such systems as: bearings-rotor-foundation, in the case of rotating machine or the bearings-assembly of crank shafts-body, in the case of combustion engines.

It is also worth noting that the degree of above coupling is dependent on the kind of dynamical characteristics, which are taken into account. If we are interested in such parameters as vibration amplitudes, angles of phase retardation or the limit of stability, then in each case (small or large displacements) we must know, apart from the bearing itself, the fundamental data of the entire machine. If, however, we limit our interest to the knowledge of solely the stiffness coefficients and damping of the lubrication film, then in the case of small pin displacements, hence in the case when the linear description is justified, then possible is the analysis of elastic and damping properties of the oil film independent from the rest of machine. In such case bearings can be regarded as isolated system. However, in the case of large pin displacements (non-linear analysis), then even elastic and damping properties of oil film in the form of stiffness and damping coefficients will be dependent on the properties of bearings machine and conditions of its exploitation. Hence, in the case of large pin displacements, where the non-linear description is appropriate, there takes place a full coupling between bearings properties and machine properties. From the above coupling there result important consequences, not always perceived by many operators and investigators.

The table below presents the summary of our considerations in the area of mutual couplings in the bearings-machine system.

	Bearings-machine couplings	
	Linear problems (small displacement of pin around the static equilibrium)	Non-linear problems (large pin displacements)
Coefficients of stiffness and damping of oil film	Coupling does not occur	Coupling occurs
Dynamical characteristics (amplitude of vibrations, stability limits, phase angles)	Coupling occurs	Coupling occurs

Lets present now some examples of this kind of relations.



B1, B2 – bearings no. 1 and 2
P1, P2 – supports no. 1 and 2
S – coupling
N – propeller
C1, C2 – sensors for measurements of relative vibrations of pins
C3,C4 – sensors for measurements of absolute vibrations of bushes
C5 – sensor for measurements of disc absolute vibrations
NW1, NW2 – imbalance masses

Fig. 12. Scheme of assumed for the analysis of rotor-bearings system (stand in the vibro- acoustic laboratory at IFFM PAS).

Lets assume in our considerations a two-support rotor-bearings system (Fig. 12) with pin diameter $d = 0.1$ m, diameter of rotor disc $d = 0.1$ m, diameter of rotor disc $D = 0.4$ m and support span $L = 1.4$ m. Lets assume two bearings with a relative width $l/d = 0.5$ with axial clearance of the value $\Delta R \cong 80\text{x}10^{-6}$ m (for the bearing no. 1) and $\Delta R \cong 90\text{x}10^{-6}$ m (for the bearing no. 2).

Lets assume now, that the system is loaded by two excitation forces (for example imbalance forces) NW1 and NW2, which are equal to each other but applied to the system at different locations and different angle to the horizontal axis. Considerations will be conducted for one only rotational velocity, namely $n = 2973$ rev/min (velocity which falls in the resonance region). Results of calculations for such system are somewhat surprising (see Fig. 13 and 14).

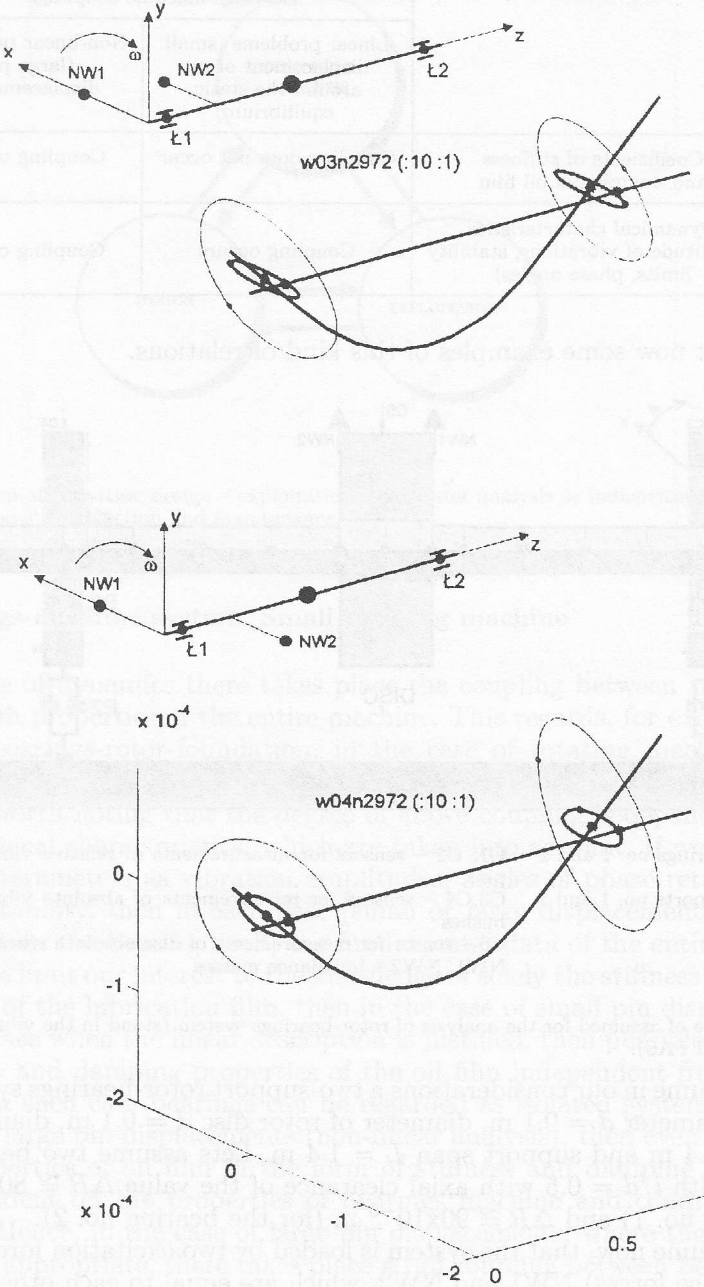


Fig. 13. Illustration of relations between bearings and machine. Accumulation of loads NW1 and NW2 at the bearing B1. Consistent phases – upper graph and opposite phases – lower graph, – thin line – relative vibrations of pin and bush; – thick line – absolute vibrations of bush.

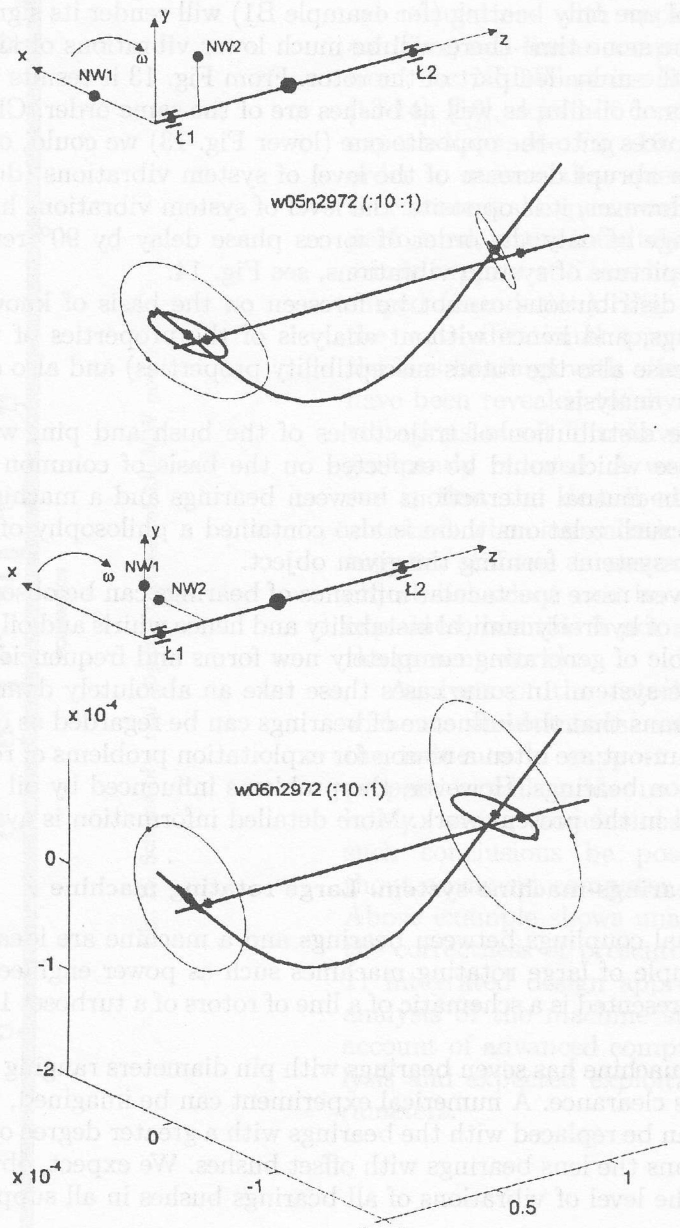


Fig. 14. Illustration of relations between bearings and machine. Change of the order of excitation phases NW1, NW2. Notation as in Fig. 13.

It could be thought, that congregation of both forces NW1 and NW2 in the vicinity of one only bearing (for example B1) will render its significant vibrations and at the same time there will be much lower vibrations of another bearing located at the unloaded part of the rotor. From Fig. 13 it results that both relative vibrations of oil film as well as bushes are of the same order. Changing the phase of both forces onto the opposite one (lower Fig. 13) we could, on the other hand, expect an abrupt decrease of the level of system vibrations (due to balancing of forces). However, it is opposite: the level of system vibrations has even increased. The change of only the order of forces phase delay by 90^o rendered absolutely different picture of system vibrations, see Fig. 14.

Such distributions cannot be foreseen on the basis of known characteristics of bearings, and hence without analysis of the properties of the whole system (in that case also the rotors susceptibility properties) and also obviously without computer analysis.

In the distribution of trajectories of the bush and pin, which are different from those which could be expected on the basis of common knowledge, there are hidden mutual interactions between bearings and a machine operating with them. In such relations there is also contained a philosophy of complex analysis of all sub-systems forming the given object.

Even more spectacular influence of bearings can be observed in the case of existence of hydrodynamical instability and hence whirls and oil run-out. Bearings are capable of generating completely new forms and frequencies of vibrations for the entire system. In some cases these take an absolutely dominating character, which means that the influence of bearings can be regarded as qualitative. Whirls and oil run-out are often a reason for exploitation problems of rotating machinery founded on bearings. However, the problems influenced by oil whirls will not be discussed in the present work. More detailed information is available in [6÷14].

5.2. Bearings-machine system. Large rotating machine

Mutual couplings between bearings and a machine are ideally perceptible on the example of large rotating machines such as power engineering turbosets. In Fig. 15 presented is a schematic of a line of rotors of a turboset 13K215 of 230 MW power.

The machine has seven bearings with pin diameters ranging from 0.35÷0.45 m with lens clearance. A numerical experiment can be imagined, where the lens bearings can be replaced with the bearings with a greater degree of "anti-vibration", that means the lens bearings with offset bushes. We expect, obviously, the reduction of the level of vibrations of all bearings bushes in all supports.

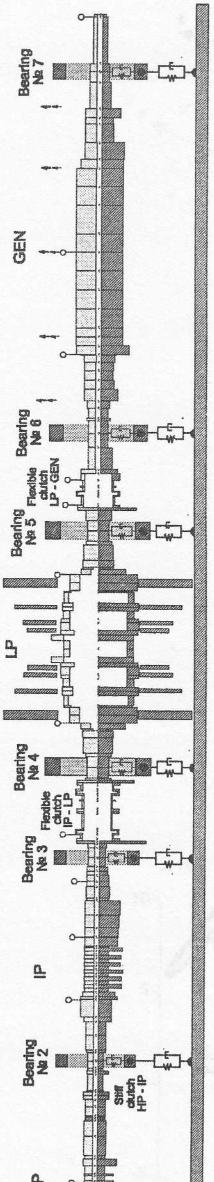


Fig. 15. Scheme of a real object – turboset of 230 MW power.

Surprisingly, the result of numerical calculations with application of complex, non-linear computer codes from the NLDW series NLDW [7], [13-14], [16], does not confirm these expectations, see Fig. 16. Why? In order to answer that question another numerical experiment has been performed, where infinitely large bearings support stiffness has been assumed (foundation) Fig. 17. Now, the anti-vibrational properties of the lens bearings with offset bushed have been revealed totally. Relative vibrations of oil film have been significantly reduced. A worrying issue is that the described effect is obtained when unrealistically large support stiffness is assumed (such object behaviour can be obviously explained, but this is not a merit of the present work).

Analysis of the rotorline itself without simultaneous analysis of the influence of support structure properties will guide us to absolutely wrong conclusions. Would such conclusions be possible without advanced computer analysis? Above example shows unanimously the correctness of presented in Fig. 11 integrated design approach and analysis of the machine state with account of advanced computer analysis and expected exploitation parameters.

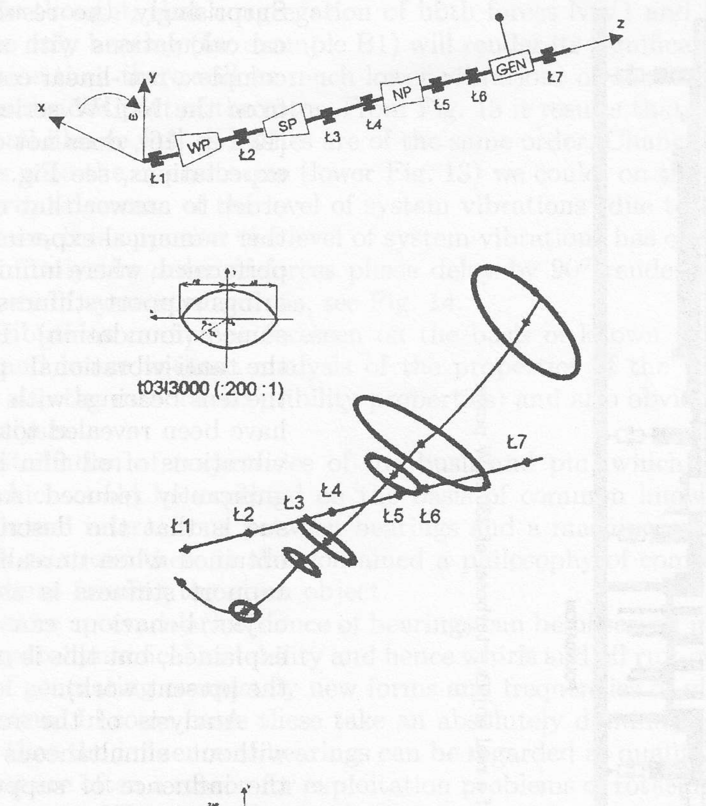


Fig. 16. Absolute vibrations of bushes and relative vibrations of oil film of a turboset from Fig. 15 after change of lens bearings (upper graph) onto anti-vibrational bearings (lower graph). Assumed are real dynamical support stiffness. No visible effect of exchange.

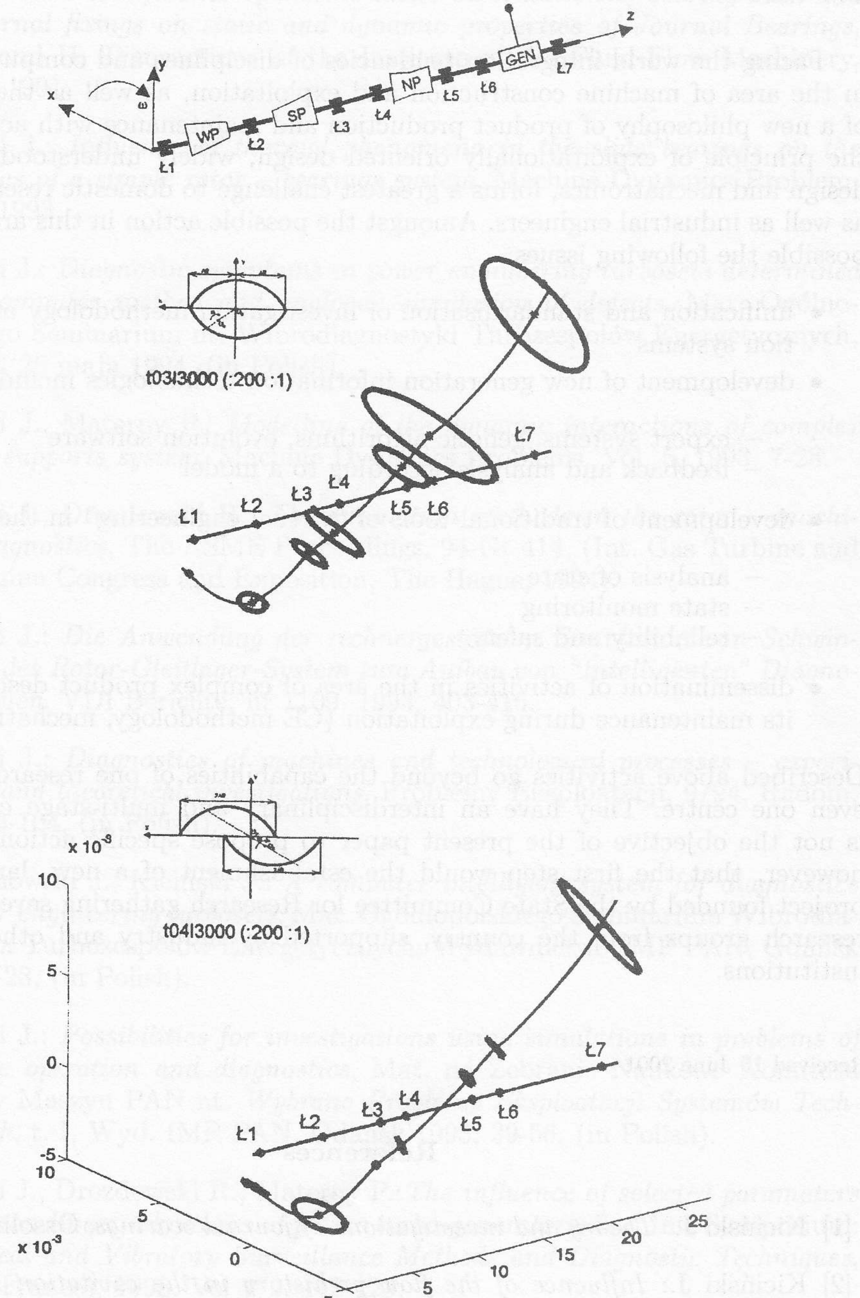


Fig. 17. Relative vibrations of oil film for real bearings (lens type) and anti-vibrational with offset bushes) at infinite support stiffness. Effect of change of bearings is now clearly perceptible.

6. Contemporary challenges

Facing the world integration tendencies of disciplines and computer software in the area of machine construction and exploitation, as well as the conjecture of a new philosophy of product production and maintenance with accordance to the principle of exploitationally oriented design, widely understood concurrent design and mechatronics, forms a greatest challenge to domestic research centres as well as industrial engineers. Amongst the possible action in this area there are possible the following issues:

- unification and standardisation of investigation methodology and information systems
- development of new generation information technologies including:
  - expert systems, genetic algorithms, evolution software
  - feedback and analysis according to a model
- development of traditional tools of "virtual engineering" in the area of:
  - analysis of state
  - state monitoring
  - reliability and safety
- dissemination of activities in the area of complex product description and its maintenance during exploitation (CE methodology, mechatronics).

Described above activities go beyond the capabilities of one research group, or even one centre. They have an interdisciplinary and multi-stage character. It is not the objective of the present paper to propose specific actions. It seems, however, that the first step would the establishment of a new, large research project founded by the State Committee for Research gathering several different research groups from the country, supported by industry and other domestic institutions.

Received 15 June 2001

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