MECHANICS AND MECHANICAL ENGINEERING
International Journal
Vol. 2 No. 1 1998

FUTURE PERSPECTIVES OF THE SCIENTIFIC DISCIPLINE OF MACHINE DESIGN FUNDAMENTALS

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1. Historical outline instead of an introduction

Machine Design Fundamentals (MDF) are a new developing scientific discipline belonging to the applied sciences. From the historical point of view, MDF takes its origin from the course of "Machine Parts", called also "Machine Elements", which was and still is the basic course in the process of training of mechanical engineers. Educational activities were predominant at Chairs of Machine Parts. In those times numerous interesting design projects were developed at the Chairs for the industry as well. Research projects were, however, very infrequent, especially those devoted to modern approaches to design processes.

Prof. Wacław Moszyński, the author of the first 4-volume monograph published in Polish and entitled **"Elementy Maszyn"** (1948), has been acknowledged the precursor of the transformation of this academic course into a scientific discipline.

In the mid 50s, following the initiative of **Prof. Janusz Dietrych** and **Prof. Witold Korewa**, a discussion devoted to the needs and possibilities of the transformation of the course of "Machine Parts" into the course and scientific discipline called

Machine Design Fundamentals

was started in the Polish academic community.

The essence of this discussion is well rendered by the quotation, which at the same time is assumed to be the foundations of the philosophy of the transformations initiated then:

> *"Machinery should be understood as an entity, and one should look at its components from the point of view of this entity, and not vice versa"*[1]

The attitude of creative activities, assumed then and still maintained, has caused a rapid development of research activities at individual Chairs. The numerous research projects are undertaken and they concern:

- general and detailed design methodology, in particular analysis as a design method and design evaluation methods;

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[1] *"Maszynę należy rozumieć jako całość i przez tę całość należy patrzeć na jej części składowe a nie odwrotnie"*
The quotation is taken from the dust-jacket of the first monograph entitled "Podstawy Konstrukcji Maszyn" by J. Dietrych, S. Kocańda, W. Korewa (WNT, 1964).

- development and investigations of new models and modelling typical assemblies and elements widely used in machines and devices.

These are theoretical and experimental investigations. The results of these investigations often find application in designing practice. The investigations are characterised by wide employment of results and methods of basic disciplines of applied mechanics, for instance, of machine dynamics, theory of elasticity, fluid mechanics, thermodynamics, etc.

In the 70s, along with the advancement in computer technology and accessibility to computers in Poland, the development of computer-aided design (CAD) methods can be observed. **Prof. Zbigniew Osiński**, the creator of general and detailed design methods which were written in a numerical form for the first time, is treated as an initiator and precursor in the field of machine design fundamentals. This numerical form exerted an essential influence on the problems of optimisation and polyoptimisation of design and contributed to the foundation of a new trend in the investigations (apart from the above mentioned trends), which in general can be defined as computer-aided design.

In many Polish academic centres the investigations concerning this modern trend are conducted. The broad experience and scientific assistance of **Prof. Z. Osiński** and his co-workers, whose outstanding achievements both in Poland and abroad entitle us to determine this group as a scientific school of CAD, have been widely used.

In the beginnings of this new discipline, doctoral studies were very needed to educate scientific workers, especially for centres with a little tradition and experience in the field of research. For this purpose the

Doctoral Studies on Machine Design Fundamentals, the first in Poland, were organised at the Technical University of Łódź. These studies were founded and headed by **Prof. Witold Korewa**. It was in 1963. Extending the scope of scientific interests, in 1976 the Doctoral Studies on Machine Design Fundamentals were transformed into the Doctoral Studies on Machine Design. Along with these doctoral studies, a rapid development of scientific activities directed towards the scientific development of research staff could be observed at numerous Chairs of MDF. It has yielded several hundreds of Ph.D. and D.Sc. dissertations in the field of machine design fundamentals, the works which have contributed significantly to the development of this discipline.

Following the initiative of **Prof. Zbigniew Osiński and Prof. Jerzy Wróbel**, since mid 70s the course of **"Theory of Design"**, being the natural extension of MDF, has been taught at the Department of Vehicles and Heavy Machinery Engineering, Warsaw University of Technology. The general features of this course are well reflected by the quotation: *"The basic aim is to try and formulate the Theory of Design in a way which will enable an introduction of computer-aided design. The final aim is to make optimal design possible"* (Z. Osiński, J. Wróbel: Theory of Design (textbook), Wrocław Technical University Publishers, 1977 - Introduction). The curriculum of this course is continually being modified, taking into account the state of the art and the level of computer techniques available.

Taking advantage of the experience gathered at the Institute of Machine Design Fundamentals, Warsaw University of Technology, and also often with the assistance of its staff, the course of **"Theory of**

Design", or its mutation **"Computer-Aided Design"**, has been introduced into the curriculum of the studies devoted to mechanics and machine design at faculties of mechanical engineering of many technical universities for 10 years.

For more than 10 years at the Institute of Machine Design Fundamentals, Warsaw University of Technology, following the initiative of **Prof. Z. Osiński**, the Post-graduate Studies on Computer-Aided Design have been conducted. The studies are popular among engineers working for the industry and among researchers and academic staff. The aim of this form of education is to minimise the unsatisfactory state of computer utilisation in the Polish machine industry, caused frequently by the fact that engineers lack training how to use such a specific tool as a computer is.

The origin, transformation and development of a new discipline are rendered by, among others, literature devoted to it. The first monograph of the discipline and course of MDF is the 3-volume study by **Prof. Janusz Dietrych, Prof. Stanisław Kocańda, Prof. Witold Korewa and Prof. Kazimierz Zygmunt** entitled **"Podstawy Konstrukcji Maszyn"**. Part I of Volume 1 was published by WNT in 1964. The contents of the 4-volume monograph **"Podstawy Konstrukcji Maszyn"**, edited by **Prof. Marek Dietrich**, are updated and extended. Volume I of it was issued in 1986 by PWN.

Following the initiative of **Prof. Wiesław Kaniewski and Prof. Zbigniew Osiński**, who is the editor-in-chief, a series entitled **Machine Design Fundamentals** has been published by PWN since 1982. This series comprises books devoted to design of typical elements and assemblies used

in machines and devices. Individual books belonging to this series are written by authors from scientific centres which specialise in designing individual machine elements and assemblies. So far, 24 publications have been issued.

The first trial to formulate an outline of the general theory of design was presented by **Prof. J. Dietrych** in the book entitled **"Konstrukcja i konstruowanie"** (WNT, 1968). The innovative character of this study is reflected by the following quotation: *"This book does not contain detailed instructions or, all the more, design codes, but it includes general fundamentals one should follow while searching for an optimal design understood as a distribution of the product structure and the limits of the material system state as a product"* (From the Author, p. 11).

In the years that followed, numerous books on the theory of design were written, in which authors put emphasis on various aspects of the design process.

One of the lately issued books is **"Theory of design"** (PWN, 1995) by **Prof. Osiński and Prof. J. Wróbel**. This publication is the result of considerations and experience gathered while conducting courses of "Theory of Design" and "Computer-Aided Design" at faculties of mechanical engineering of technical universities. The authors have presented a concise theory of machine design, which enables a complex approach towards computer-aided design and makes the basic possibilities of modern computer systems familiar.

The titles of monographs and books cited here and numerous textbooks for students are examples of the wide literature devoted to this

subject and reflect the transformations and the scientific level of the discipline and course of Machine Design Fundamentals.

The bibliography of this discipline is supplemented by several hundreds of papers in renowned Polish or international journals and by not fewer papers presented at Polish and international conferences and published in their proceedings. Many works which have been prepared in Polish scientific centres are quoted in foreign literature as well. It reflects not only their scientific level, but also manifests a significant impact of Poland on the international formation of the discipline of Machine Design Fundamentals.

Among the scientific community of MDF, a tradition of scientific meetings, initiated in the 50s by a meeting of the heads of the Chairs of MDF, is well established. These meetings are an occasion to exchange directly the ideas and experience, they integrate the community as well. The meetings are characterised by different rank, scope and fields of interest. One of the oldest form is the Symposion of Machine Design Fundamentals. This is a nation-wide forum, often visited by guests from abroad, at which different issues of this discipline and detailed problems and results of projects and investigations carried out in various centres are discussed. Symposions are held periodically, every second year and are organised by successive academic centres. I Symposion was held in 1963 and was organised by the Chair of MDF, Technical University of Gdańsk, the latest one (XVIII) took place a year ago and was organised by the Division of MDF, Świętokrzyska Technical University.

The conference "Methods and Equipment of Computer-Aided Design" has also entered firmly the calendar of Polish scientific meetings. It has been held cyclically since 1977 by the Institute of Machine Design Fundamentals, Warsaw University of Technology. The characteristic feature of these conferences is that apart from papers concerning general problems of the theory of design, detailed particular issues are presented during poster sessions, at which computer demonstrations are possible. This form is especially important when the computer software for design of actual machine assemblies is presented.

The symposions and conferences mentioned here yield their own literature. Conference proceedings comprise volumes, several hundreds of pages each, whose contents reflect well the scope of interest and the level of research projects carried out at different divisions of MDF.

This very short outline entitles us to state that those who have initiated and implemented the transformation of the traditional course of "Machine Parts" into a modern discipline of Machine Design Fundamentals can have profound satisfaction with their achievements so far.

2. Development trends

The history of machine design fundamentals as a discipline of the applied sciences till now, the number of publications and Ph.D. and D.Sc. dissertations concerning it, the scope of problems of currently conducted research projects at Polish and foreign centres, especially academic centres

which exert a significant influence on the development of MDF, allows for determination of trends of development of this scientific discipline.

It should be expected that the further development of the discipline of MDF will follow two intermingling and complementary, equivalent directions, which in general deal with:

a) development and applications of the theory of design,

b) development of models and properties of typical machine assemblies and elements.

a) Theory of design

In the nearest future, a significant progress will take place in the field of projects devoted to applications of the general theory in machine design processes. These investigations will deal, among others, with the following problems:

- development of general and detailed design principles, especially search for the relations between the design criteria assumed and the relation: design criterion vs. design phase - conceptual, initial, detailed design,
- development of mathematical design models corresponding to design principles, the design phase, and allowing for reducing the optimisation task to a mathematical task,
- development of optimisation and polyoptimisation methods, directed towards the design of basic machine assemblies and elements by means of computer techniques,

- computer-aided design. Computers were initially used in the design process for engineering calculations. The development of hardware and software has enabled their more "advanced" application in optimisation computations, database creation, preparation of design documentation. Possible, more "sophisticated" applications of a computer were presented in the book "**Teoria konstrukcji**" by **Prof. Z. Osiński and Prof. J. Wróbel** (PWN, 1995, Warsaw).

In the present study, the scope of interest has been restricted to the development trends of engineering computations only. As far as the development of software for engineering computations is concerned, the following periods can be distinguished conventionally. The first period was characterised by the fact that the classical "pre-computer" calculation models and methods were used - a computer played the role of a "fast calculator". The second period consisted in the development of "computer-oriented" software devoted to new programming languages and philosophy, graphic user's friendly interfaces, computer systems, etc. In this period a new job emerged - a computer specialist/programming specialist. Recently, for a few years, a development of more advanced application software adapted to modern computer technology has been observed. A new generation of application software, reflecting the computer-aided design methods, has been created as a result of the experience of the first and second period and, more often, of the complementary activities of the team: engineer - designer - computer specialist/programming specialist.

The essence of this new generation of software lies in the adaptation of computational models and methods to individual phases of computer-

aided design. In general, it can be stated that as a result of initial designing, a set of 'good designs" is created, and as a result of detailed designing - "an optimal design". Inasmuch as the state and development trends of the above mentioned design phases can be considered to be satisfactory, the further works aiming at conceptual computer-aided design as the first design phase should be expected.

b) Development of models, modelling typical machine assemblies and elements

Like in other disciplines of the applied sciences, model investigations allow one to understand physical phenomena. This knowledge is the basis for conscious modelling the required properties of typical assemblies and elements used in machines.

In theoretical and experimental investigations of models of machine assemblies and elements, the results of investigations, scientific methods of basic disciplines of applied mechanics, material engineering, metrology, etc., are widely used. The development of these disciplines exerts also an influence on the development of machine design fundamentals. The development of the theory of lubrication is an example.

B. Towers found experimentally that different local pressures occur in the oil film of the slide bearing in the wagon axle. The results of these investigations inspired O. Reynolds (1886) to develop a physical and mathematical model of the oil film in the slide bearing. For this aim he used the equation of motion and the equation of continuity for viscous liquids (fluid mechanics) and the equation of oil state (material

engineering). In those days, the developed models corresponded quite sufficiently to the results of experimental investigations.

Simultaneously, N.P. Pietrow (1882), through theoretical investigations of possibilities of solving a set of equations of motion, continuity and state, developed a physical and mathematical model describing the case of a rotary motion of a roller in the cylinder, with the gap being completely filled with oil. The results of these investigations have been used to improve the design of slide bearings.

Comparing the works of O. Reynolds and N.P. Pietrow, it can be stated that in the first case the experiment outdistanced the theory, while in the second case the theory outdistanced the experiment. These are equivalent couplings. In such a way

the hydrodynamic theory of lubrication

has been founded.

A further improvement of assumed physical models, results of experimental investigations, engineering experience in the field of bearing operation yield a development of physical models and mathematical models corresponding to them, and thus, an approximation of the models to the reality is achieved. With these models, a development of the theory of lubrication consists in accounting for thermal phenomena and processes (thermodynamics) and for a variable shape of the oil gap as a result of the elastic and thermal deformations (theory of thermal elasticity) generated by the pressure and temperature field in the oil film. In this way

the thermoelastohydrodynamic theory of lubrication

has been developed.

Depending on the degree of exactness of the physical model assumed, different mathematical models of machine assemblies and elements are characterised by various degrees of complexity and solution methods. As an example, the mathematical model of the slide bearing operation under fluid friction is a system of more than ten algebraic partial differential equations of different orders and with variable coefficients.

If we consider the short slide journal bearing whose scheme is shown in Fig. 1 and assume an adiabatic oil flow in the oil film, for the parallel position of the axis of the journal and the bush, then the mathematical model is described by the following set of equations:

- geometry of the oil gap:

$$H = 0{,}5 \cdot \psi \cdot R \cdot \left[1 + \lambda \cdot \cos(\varphi - \alpha)\right] \tag{1}$$

- pressure distribution in the oil film:

$$\frac{\partial}{\partial z}\left(\frac{H^3}{\eta}\frac{\partial p}{\partial z}\right) = 6U\frac{dH}{Rd\varphi} \tag{2}$$

- temperature distribution in the oil film:

$$\rho \cdot c \cdot U\frac{\partial T}{R\partial\varphi} = \eta\left(\frac{\partial u}{\partial y}\right)^2 \tag{3}$$

- equation of conservation of mass:

$$Q_E = Q_Z + Q_A \tag{4}$$

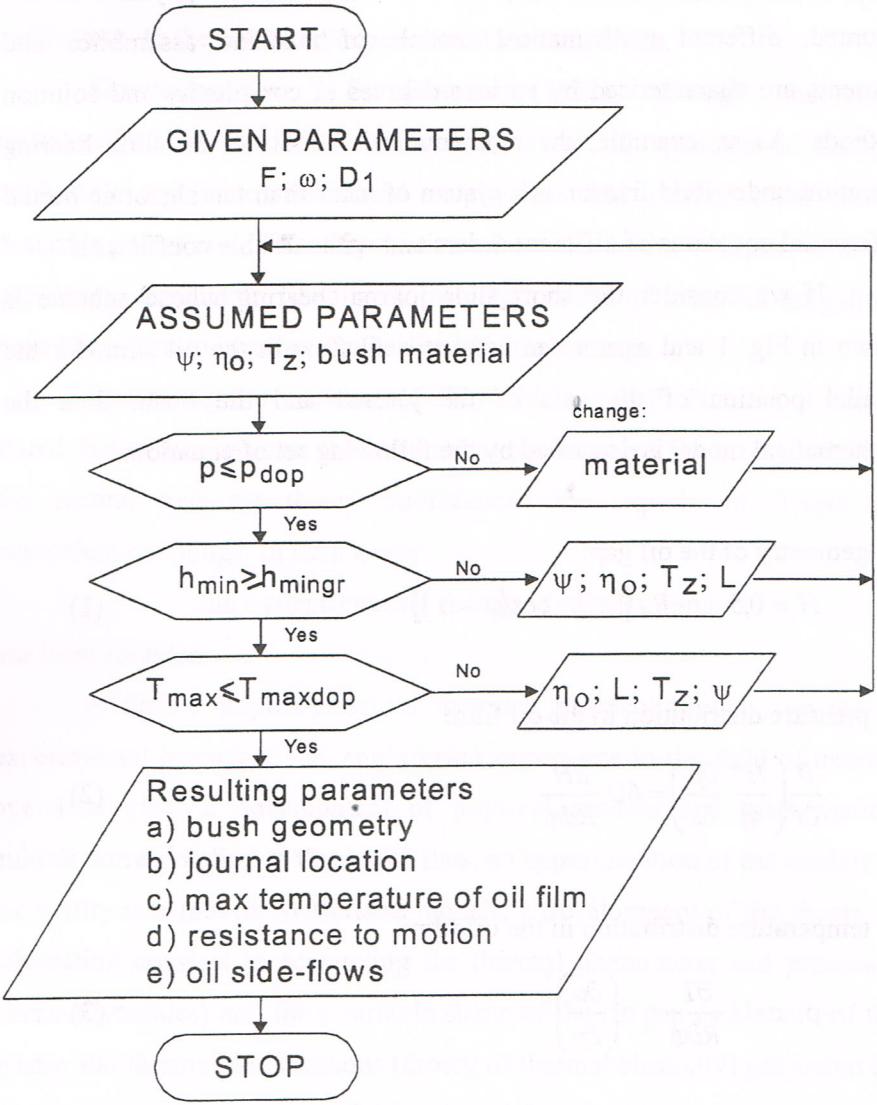
START
GIVEN PARAMETERS
F; ω; D1
ASSUMED PARAMETERS
ψ; ηo; Tz; bush material
change:
p≤pdop
No
material
Yes
hmin≥hmingr
No
ψ; ηo; Tz; L
Yes
Tmax≤Tmaxdop
No
ηo; L; Tz; ψ
Yes
Resulting parameters
a) bush geometry
b) journal location
c) max temperature of oil film
d) resistance to motion
e) oil side-flows
STOP

Fig. 1.

- equation of conservation of energy:

$$Q_E \cdot T_E = Q_Z \cdot T_Z + Q_A \cdot T_A \tag{5}$$

- equation of oil state:

$$\eta = \eta_{01} \cdot e^{a_1(T-20)} \quad \text{for} \quad T < T_{gr1}$$

$$\eta = \eta_{02} \cdot e^{a_2(T-20)} \quad \text{for} \quad T_{gr1} < T < T_{gr2}$$

$$\eta = \eta_{03} \cdot e^{a_3(T-20)} \quad \text{for} \quad T_{gr2} < T \tag{6}$$

The above set of equations, along with the boundary conditions:

for pressure:

$$p\left(\varphi_2 \le \varphi \le \varphi_3; z = \pm\frac{B}{2}\right) = 0$$

$$p\left[\varphi_1 \le \varphi \le \varphi_2; z = \pm\frac{B}{2} \cdot \frac{1+\lambda\cos(\varphi_1 - \alpha)}{1+\lambda\cos(\varphi - \alpha)}\right] = 0$$

for temperature:

$$T(\varphi=\varphi_5; z) = T_E = -A^{-1} Q_A \cdot Q_E^{-1} \cdot \ln\left\{e^{-AT_E} - 2A\left[B(\varphi_1) - B(\varphi_5)\right]\right\} + \left(1 - Q_A \cdot Q_E^{-1}\right) T_Z$$

has not been solved analytically yet and different approximation methods are used. In solving such complex tasks, the computer is a perfect tool. The results of investigations are presented in tables or in the form of characteristics of the bearing operation. An exemplary static characteristic curve of a short journal bearing is presented in Fig. 2.

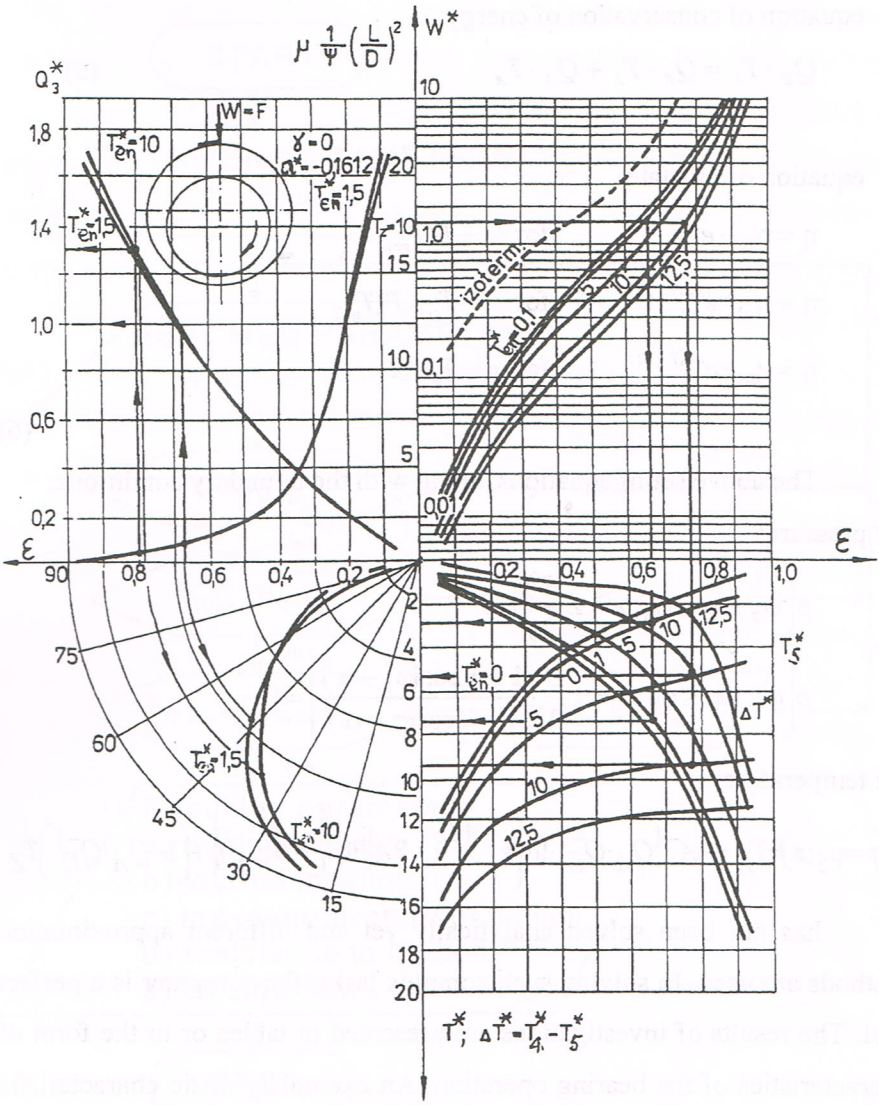

Fig. 2.

It should be noticed here that the results obtained from the investigations of mathematical models for a majority of objects need further processing in order to use the obtained results in engineering calculations. Again, let us consider an example of a slide bearing. In model investigations such properties of the oil film as: load capacity, temperature field, pressure field, etc., are determined for the given position of the journal in the bush, whereas in engineering calculations, the position of the journal in the bush is sought for the given load. The design computation algorithm is presented in Fig. 3.

Simultaneously with theoretical investigations, it is indispensable to carry out experimental investigations, whose aim is to verify the results of theoretical investigations and to develop empirical formulae for the phenomena and processes which have not been fully understood yet. Again, let us take an example of a slide bearing, and not only. Many machine elements operate under mixed friction conditions. The lack of a coherent theory of mixed friction causes that empirical formulae are used in engineering calculations of these elements. These formulae very often correspond to the state of knowledge dating to the beginning of our century.

It should be expected that the trends of development of model investigations of typical assemblies and elements, with regard to theoretical and experimental investigations, will be devoted to the following problems:

a) within the scope of theoretical investigations:

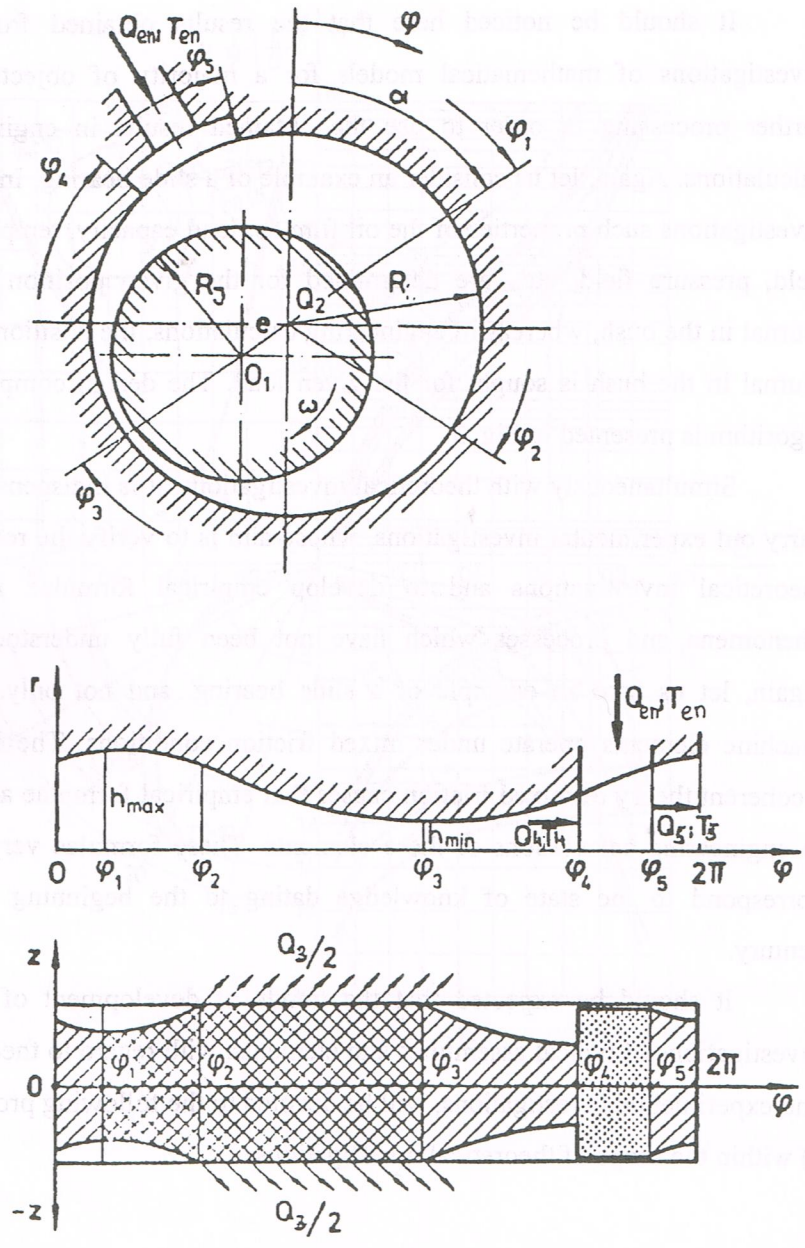
Q_en, T_en
φ
φ_5
α
φ_1
φ_4
R_J
Q_2
R_r
e
O_1
ω
φ_2
φ_3
r
h_max
h_min
Q_4; T_4
Q_en, T_en
Q_5; T_5
0
φ_1
φ_2
φ_3
φ_4
φ_5
2π
φ
z
Q_3/2
φ_1
φ_2
φ_3
φ_4
φ_5
2π
0
φ
-z
Q_3/2

Fig. 3.

- development of more exact physical models, better corresponding to the reality. It is expected that the development of machine dynamics, cracking mechanics, fatigue strength, reliability, material engineering and many other disciplines affecting the degree of understanding and designing the properties of actual assemblies and elements will be further reflected in their modelling.

  It is also purposeful to make a survey and to update "old" models according to the state of the art. Let us consider a trivial example, which, however, reflects well this need. Up to the 70s, the hexagonal head of the normalised M8 screw was characterised by the wrench opening equal to S=14 mm. Today the same screw has a head opening equal to S=13 mm and fulfils the same requirements as before. Why 13 millimetres and not fewer?

- development of mathematical models describing the assumed physical models. The development of approximation methods, especially the finite element method as a computer method, should be more widely used in the investigations of machine assemblies and elements.

b) within the scope of experimental investigations:

  development of experimental models with a wider application of the theory of similarity;

- computerisation of experimental investigations, which is particularly vital for the investigations of dynamic processes;
- generation of experimental formulae including the hierarchy of influences and the properties of machine assemblies and elements.

Recently, a decrease of interest in experimental investigations has been observed in Poland and abroad. Is it only an influence of computerisation? I think that this tendency should be stopped. Numerical experiment will not replace physical experiment, whose procedure and results often inspire theoretical investigations.

3. ...

The frame of the present study, very general in its nature, does not cover the whole problem scope of the development of machine design fundamentals.

It is purposeful to continue the discussion about the development of this discipline and the role and tasks of MDF in the education of 21st-century mechanical engineers.