STRENGTH ANALYSIS OF GEARS IN DUAL-PATH GEARING BY MEANS OF FEM

Jacek PACANA, Bogdan KOZIK, Grzegorz BUDZIK

Katedra Konstrukcji Maszyn, Politechnika Rzeszowska
Al. Powstańców Warszawy 8, 35 - 959 Rzeszów, fax (0-17) 854 31 16, pacanaj@prz.edu.pl

Summary

The paper contains a strength analysis of gears in a dual-path gearing made of plastic. Computation was carried out using Abaqus program by means of finite elements method (FEM). The results of calculations allow the interpretation of the results of diagnostic tests. Due to the fact that the dual-path gearing had wheels with straight teeth, it was possible to simplify the computation using two-dimensional models. The paper shows activities related to preparation of models, defining boundary conditions, the process of computation and the presentation and interpretation of obtained results. In the carried out FEM analysis, stress distribution was determined on models of pinions and gears, paying particular attention to key points like teeth feet or their flanks. In order to improve readability of these solutions and to ease interpretation, some results were also presented in a form of charts. Conclusions drawn from the analysis will make it possible to introduce conceivable changes in the structure of designed gearing already at the stage of modelling.

Keywords: dual-path gearing, FEM, strength analysis for diagnostic purposes

ANALIZA WYTRZYMAŁOŚCIOWA KÓŁ ZĘBATEJ PRZEKŁADNI DWUDROŻNEJ Z ZASTOSOWANIEM MES

Streszczenie

Niniejsze opracowanie zawiera prezentację przebiegu obliczeń wytrzymałościowych kół zębatych przekładni dwudrożnej przeprowadzonych w programie Abakus z wykorzystaniem metody elementów skończonych (MES). Wyniki obliczeń pozwolą na interpretację wyników badań diagnostycznych. Zaprezentowane zostały działania związane z przygotowaniem modeli, definiowaniem warunków brzegowych, przebiegiem obliczeń, oraz prezentacją i interpretacją otrzymanych wyników. W przeprowadzonej analizie MES wyznaczono rozkłady naprężeń na modelach zębników i koła zębatego, zwracając szczególną uwagę na miejsca kluczowe jak podstawy zębów, czy ich powierzchnie boczne. W celu poprawienia czytelności rozwiązań i ułatwienia ich interpretacji wybrane wyniki zostały także zaprezentowane w formie wykresów. Wnioski otrzymane w wyniku przeprowadzonej analizy pozwolą na wprowadzenie ewentualnych zmian w konstrukcji projektowanej przekładni już na etapie modelowania.

Słowa kluczowe: przekładnia dwudrożna, MES, analiza wytrzymałościowa do celów diagnostycznych

1. INTRODUCTORY INFORMATION

Designing mechanical gearing is more and more often carried out with the help of or exclusively by means of numerical computation methods. Computational programs are based on the theory of known analytical methods, and the most commonly used for strength analysis and different types of simulation is finite elements method (FEM). Although computing programs are widely available and easy to use, it is necessary to point out that using them correctly requires significant experience and knowledge of both the strength of materials and computer techniques. Numerical computation applying FEM in construction engineering are carried out going through the following basic stages [8]:

- building a discrete computational model,
- analysis of individual elements forming the computational model,
- solving a system of equations that make a mathematical model,
- determining necessary static and geometrical values.

Computing programs can work automatically, but the designer should consciously control the course of calculations to be able to influence the range and quality of received results.

An undeniable advantage of computing programs is the ability to carry out serial calculations i.e. a large number of FEM computation for the same virtual model, differing in one or more parameters. With this function one can carry out an analysis of a loaded element with different load values or changing direction, without having to perform many stand tests. What is more, the process of carrying out serial numerical computation in some programs, such as for example Abaqus, can also be automated.

This study contains an analysis of mating of wheels in a dual-path gearing applying FEM. In the carried out FEM analysis, stress distribution was determined on models of pinions and a toothed wheel, paying special attention to the key points like the tooth root or their surface of mating. We also drew charts presenting the nature of bending stresses for individual teeth which results from the gear load.

2. PREPARING A COMPUTATION MODEL

This analysis of gear wheels mating in various load conditions was carried out using planar models. Such simplification of computational models was possible because the analysed gears were spur gears that along their entire width have the same shape. In addition, it was assumed that the width of computational model of dual-path gearing is small in relation to the rest of its dimensions and the external load is distributed evenly along the entire width of wheels and that it works only in an allocated section. The assumptions for the plane model made it possible to carry out an analysis for many models with sufficiently high accuracy while the calculations did not take too much time. Additionally, full gear models were limited only to their extracts including seven teeth in case of pinions, and twenty one in case of the toothed wheel. This simplification also allowed to shorten calculation time, without causing deterioration of its quality, because in the examined area, it does not cause changes to e.g. the nature of work, or the stiffness of the structure in relation to the original solution [6, 10]. Only mating area for several central teeth of each virtual model was analysed, which allowed to eliminate the influence of boundary conditions on mating of gears' teeth.

Virtual models of gears used in these computation were made in Autodesk Mechanical Desktop. Surface models of the gears were created by means of computer simulated machining of toothed-wheel rim with rack-type cutter. Thanks to that, a very accurate tooth profile was obtained. The created models were exported from CAD in a universal *.IGS format with activated options for recording and the original positioning of the models was preserved. These models were then imported to ABAQUS 6.10-1 [1], and the following steps were made connected with preparing the models for computation in the pre-processor of this program.

The computation was carried out for wheels made of ABS plastic, specifying its basic material properties as: Young module 2400 [MPa] and Poisson number 0,4.

Wheels of the dual power-path gearing were set at their axis of rotation in a pre- processor of Abaqus and could only rotate around their own symmetry axis. Linking models to their axis of rotation was made by inflexible joints and additionally for a gear model we assumed extorted rotation about its own axis by an angle of 0,4 rad. This allowed to trace mating of six pairs of teeth for each of the two pairs consisting of a gear and a pinion. Load of gearing was implemented by defining torque of the output value of 2,860Nm in axes of pinions model. Relatively low value of torque is the consequence of the material adopted for computation because both numerical analysis and stand tests conducted later will concern toothed wheels made of plastics. Models of toothed wheels defined in this way, assuming computational width of gears to equal 35 mm, make it possible to get the required stiffness of models [2, 5, 9].

The created planar model was subjected to digitization in the processor of Abaqus 6.10-1 by means of linear quadrilateral elements of CPS4R type. The most accurate division was defined on the toothed-wheel rim, especially at tooth flanks and at the tooth root (fig.1), due to the expected high stress values in these areas [4].

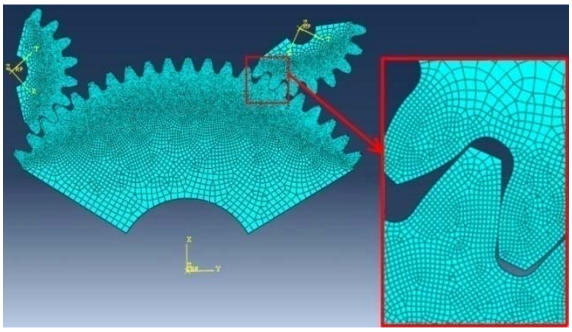

Fig. 1. Models of wheels in the dual-path gearing ready for FEM computation

In the remaining part of the model it was much less dense grid which is presented in the Abaqus window together with the model of dual-path gearing ready for numerical computation FEM.

For correctly and completely prepared models of dual-path gearing we carried out numerical computation in the solver of Abaqus applying finite elements method.

3. PROCESSING AND ANALYSIS OF FEM COMPUTATION RESULTS

As a result of carried out computation we obtained correct solutions for all four prepared computational models. Processing and analysis of solutions was conducted in post-processor of

Abaqus 6.10-1, which has many features to help users in their presentation.

A graphic interpretation of solutions can be seen in a window of the program when you select a Visualization module. The results, after loading the calculation file, are automatically displayed in a form of reduced stress distribution on models of gears, as shown in Figure 2.

In addition, in a window of Abaqus a legend of values may be presented, as well as information about the location and the level of maximum and minimum stress. Figure 2 additionally describes components of the assembly, that is pinion no1and pinion no 2, in order to facilitate their identification in the carried out analysis.

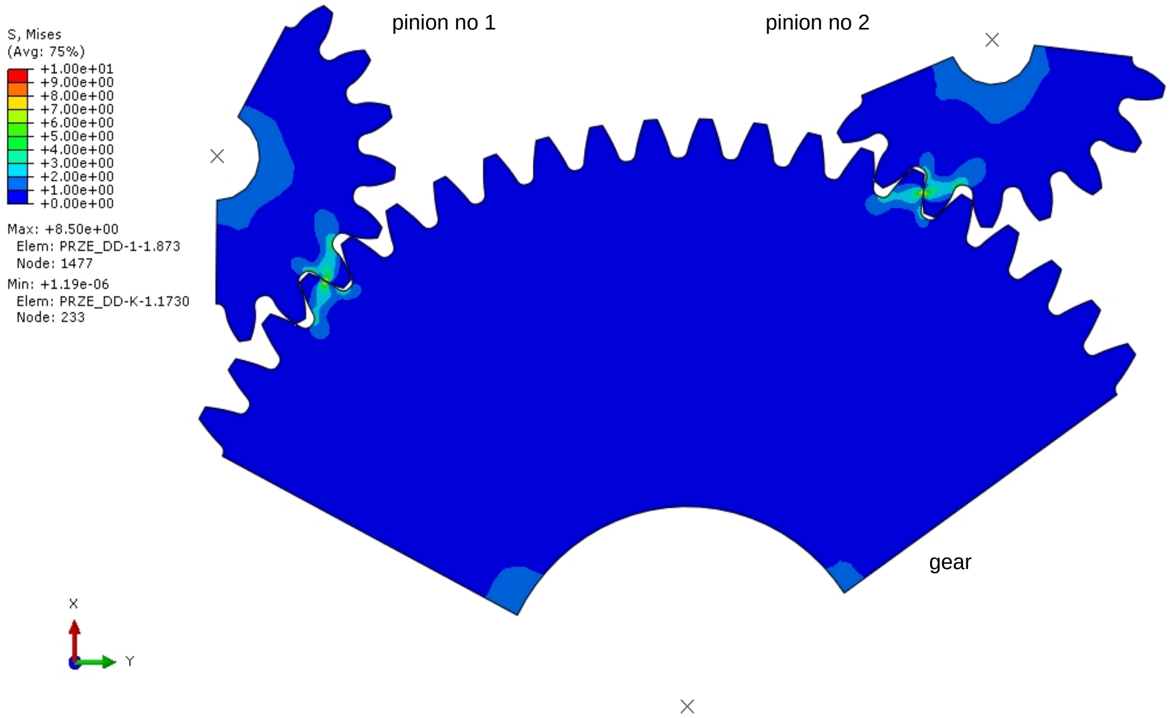

Figure 2 Distribution of reduced stress [MPa], in wheels of dual power-path gearing obtained by FEM computation in Abaqus.

Due to small readability of solutions on the general view, the following figures show a zoom of selected fragments including the toothed-wheel rim.

Figures 3 and 4 show areas of contact of the gear and pinion no1and pinion no 2 while they remain in one-pair toothing.

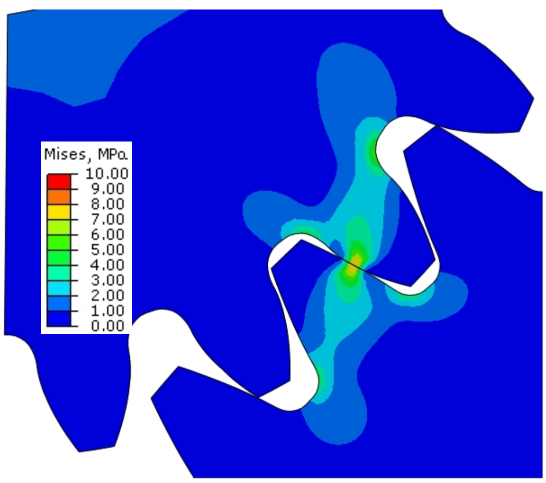

Fig. 3. Distribution of reduced stress for one-pair teeth mating of the gear with pinion no1

For both areas of mating the distribution looks similar, also maximum values of contact stresses at tooth flanks of teeth are the same and equal 8,5MPa.

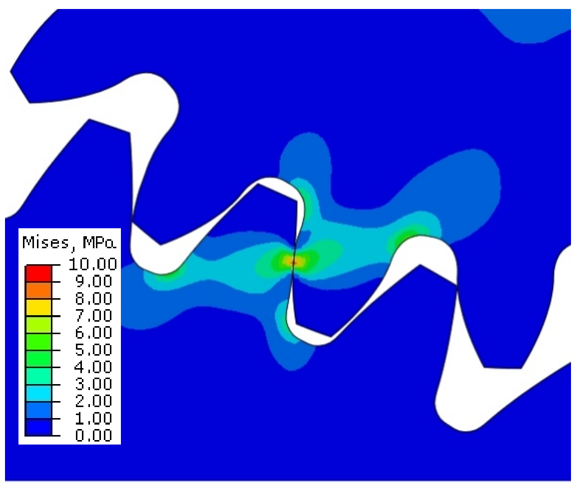

Fig. 4. Distribution of reduced stress for one-pair teeth mating of the gear with pinion no2

Figures 5 and 6 show the phase of meshing of wheels where two pairs of teeth cooperate with each other at the same time. As the example presented below concerns the case of two-pair cooperation, maximum stress values are lower and amount to 5,24MPa.

Just like in case of one-pair toothing they are located at tooth flanks of mating teeth.

Clearly higher values of stress appear at the tooth root, although its value is much lower than in case of contact stress. Areas of increased bending stress at the tooth root are at the side opposite to applied load. Such stress distribution is known from literature, and maximum values of stress can be calculated analytically on the basis of standards ISO 6336 [7].

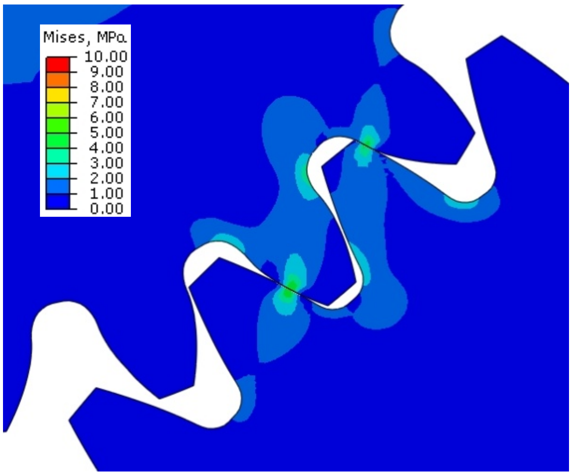

Fig. 5. Distribution of reduced stress for two-pair teeth mating of the gear with pinion no1

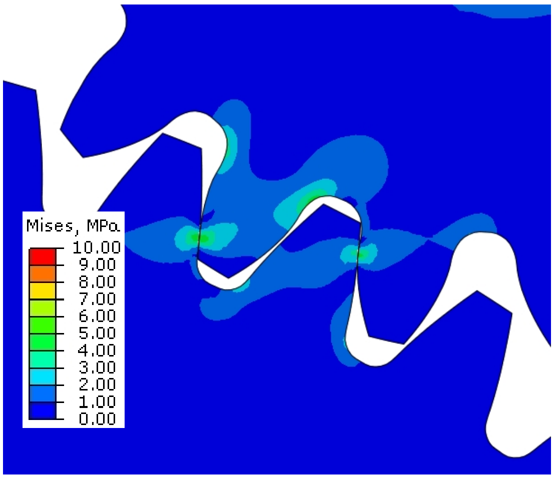

Fig. 6. Distribution of reduced stress for two-pair teeth mating of the gear with pinion no2

Characteristics of stress variation while the gearing is working can be more easily traced on the basis of prepared charts. These charts present a load pattern of several consecutive teeth of the gear (fig. 7) and pinion no 1 (fig. 8) for the whole path of contact [10]. Thanks to the charts prepared directly in Abaqus, interpretation of obtained results is much more readable. It also significantly accelerated the processing and analysis of results, as it was not necessary to load graphic presentation of stress distribution on models for subsequent steps of computation which is very time consuming.

Charts concerning each tooth were drawn in different colours. For each of them one can distinguished a period of mating corresponding to the two-pair toothing, where stresses are at the level of 2,5 ÷ 3MPa. The highest stress values at tooth root are in the phase of one-pair toothing.

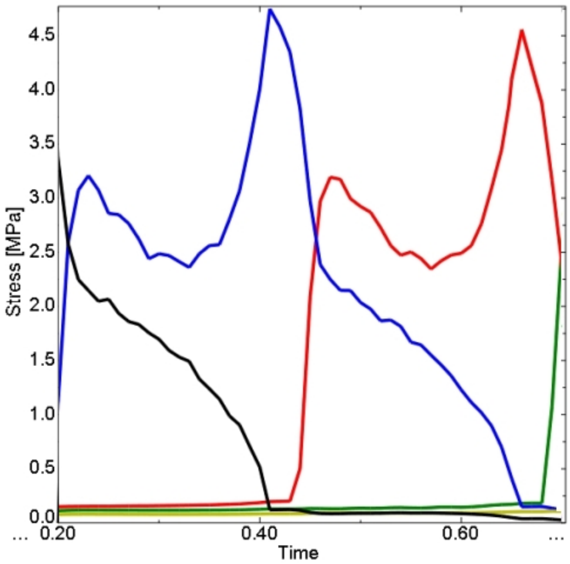

Fig. 7. The pattern of bending stress σ_z at roots of selected teeth of the gear

Charts of bending stress at roots of subsequent teeth in case of both pinions are almost identical and are shown in figures 8 and 9. It is a result of assuming in this computation model equal load distribution for each of pinions and it is also visible in results presented earlier (fig. 3÷6).

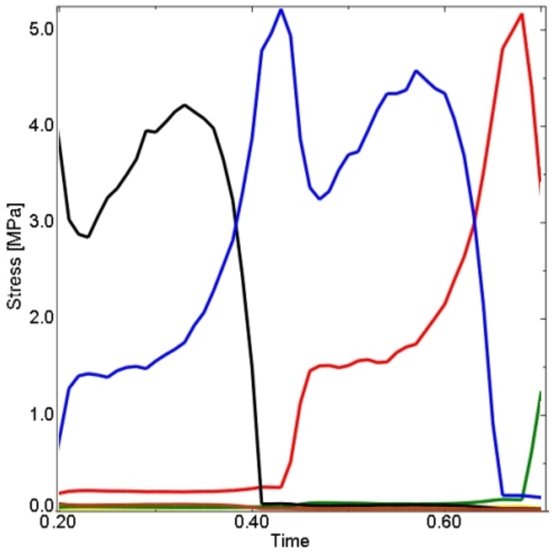

Fig. 8. The pattern of bending stress variation σ_z at roots of subsequent mating teeth of pinion no 1

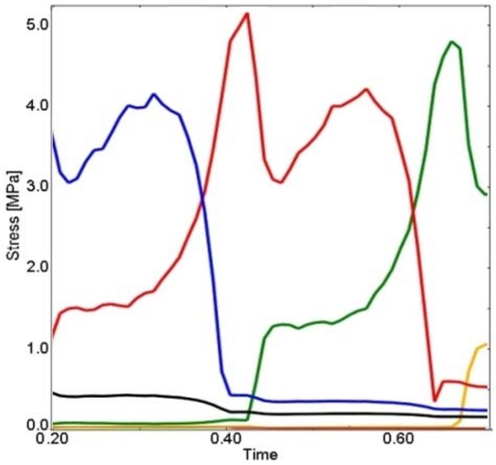

Fig. 9. The pattern of bending stress variation σ_z at roots of subsequent mating teeth of pinion no 2

As for the gear, stresses for subsequent teeth have been drawn in different colours. Maximum values of bending stress at tooth root in case of the gear equal about 4,7MPa whereas in case of pinions they are higher by approximately 15%. The level of bending stress at tooth root at the side opposite to applied load is half lower than in the case of contact stress at tooth flanks of mating teeth.

Tooth load charts based on FEM computation have irregular pattern, because they take into account, in addition to complicated conditions of mating, also some inaccuracy of scale and outline and the fact of replacing smooth model outlines by discrete mesh of finite elements. Analyzing posted charts one can notice that the ones concerning the gear have exactly opposite pattern than in case of the pinions.

4 SUMMARY

The conducted qualitative analysis of various tooth profiles concerned checking the nature of mating wheels of gearing in different load conditions applying FEM. The computation was carried out using Abaqus program and concerned spur gears of dual-path gearing made of ABS plastic. Such approach has been adopted because of the need to verify the results of this computation by stand tests. Wheels to be used for tests will be made of this plastic by means of POLIJET method. The results of this research and analysis will be used for examining the actual gear after taking into account certain approximations and properties arising from the assumptions of model similarity [3]. In order to make the display of results more readable we created bending stress charts at tooth foot for all gear wheels in a post-processor of Abaqus. They have known from the literature course corresponding to different stages of teeth mating. Charts for pinion no1 and no 2 are almost the same because identical values of load were defined for them.

Contact stresses at tooth flanks were also specified for the examined dual-path gearing. The highest values in this case amounted to 5,24MPa. It should be pointed out that the results are on a safe level, far from limit values due to relatively low load value adopted.

Conclusions drawn from numerical computation are helpful in determining the nature of work of dual-path gearing, however, as all numerical methods they should be reviewed and verified by stand tests. The results of the calculations presented in this article, will help interpret the results of diagnostic tests of gears in a dual-path gearing.

Acknowledgement

Financial support of Structural Funds in the Operational Programme - Innovative Economy (IE OP) financed from the European Regional Development Fund - Project "Modern material technologies in aerospace industry", No POIG.0101.02-00-015/08 is gratefully acknowledged.

BIBLIOGRAPHY

[1] Barbero E. J.: *Finite Element Analysis of Composite Materials*: using Abaqus, CRC Press, 2013

[2] Budzik G., Kozik B. Pacana J.: *Defining influence of load conditions on distribution and value of stresses in dual-power-path gear wheels applying FEM*, Aircraft Engineering and Aerospace Technology: An International Journal 85/6 (2013) 453–459, pages 453-459

[3] Budzik G., Kozik B., Pacana J.: *Determining of model similarity for flexsplaine of harmonic drive with the use of FEM and extensometer method*, Journal of KONES Powertrain and Transport, Vol. 16, No 2 (2009),

[4] Matuszek J., Hernia S.: *Ewolwentowe przekładnie zębate ogólnego przeznaczenia*. Część 1. Podstawy projektowania., Wydawnictwo Akademii Techniczno-Humanistycznej, Bielsko-Biała 2002,

[5] Pacana J.: *Development of Bevel Gear Motion Transmission Graphs with FEM*, Key Engineering Materials Vol. 490 (2012), Trans Tech Publications, Switzerland 2012,

[6] Pisula J., Płocica M.: *Numerical Model of Bevel Gears Cutting by Duplex Helical Method*, Key Engineering Materials Vol. 490 (2012), Trans Tech Publications, Switzerland 2012,

[7] ISO 6336-1:1996 *Calculation of load capacity of spur and helical gears*. Basic principles, introduction and general influence factors,

[8] Rakowski G., Kacprzyk Z.: *Metoda Elementów Skończonych w Mechanice Konstrukcji*, Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa 2005,

[9] P. Rokicki P., Budzik G., Kubiak K., Dziubek T., M. Zaborniak M., Kozik B., Bernaczek J.,

Przeszłowski Ł., Nowotnik A.: *The assessment of geometric accuracy of aircraft engine blades with the use of an optical coordinate scanner*. Aircraft Engineering and Aerospace Technology, Emerald Group Publishing Limited,

[10] Wiktor J.: *Analityczno numeryczne metody analizy parametrów geometrycznych, zakłóceń ruchu i wytrzymałości przekładni walcowych*, Oficyna Wydawnicza Politechniki Rzeszowskiej, Rzeszów 2004.

Jacek PACANA, PhD, Eng. works in the Department of Machine Design at the Faculty of Mechanical Engineering and Aeronautics of the Rzeszów University of Technology.
His scientific research interests include issues related to the use of CAD/CAM/CAE methods in designing and mechanical design calculations, and gears in particular.

Bogdan KOZIK, PhD, Eng. is an employee of the Department of Mechanical Engineering at the Rzeszów University of Technology.
He is engaged in issues related to computer-aided design methods and calculating machine components, in particular gears. He conducts research from the scope of CAD systems for analysis and testing gears and carries out stand tests for gear transmissions made by means of traditional methods and by Rapid Prototyping.

Prof. **Grzegorz BUDZIK,** DSc works for Department of Mechanical Engineering at Rzeszów University of Technology. His interests include the field of construction and maintenance related to elements of internal combustion engines and drives. His research work is both theoretical and practical and deals with using the latest computer-aided design tools, manufacture and analysis of CAD/CAM/CAE/RE/RP in construction of machinery.