RIGA TECHNICAL UNIVERSITY

Anatolijs MELNIKOVS

APPLICATION OF METAMODELING FOR SHAPE OPTIMIZATION OF CONSTRUCTIONAL ELEMENTS

Summary of Thesis

Riga 2013

RIGA TECHNICAL UNIVERSITY
Faculty of Transport and Mechanical Engineering
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Scientific Supervisor
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The defense of the thesis in engineering science is proposed to obtain of Doctor from Riga Technical University and in accordance with the decision of the Doctorate Board „RTU P-04", the public defense is going to be held on 11/29/2013 in the TMF Institute of Mechanics, Ezermalas 6, Room 302.

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CONFIRMATION

I confirm that I have independently worked out this thesis for defense at Riga Technical University for being conferred the degree of Doctor of Science in Engineering. The thesis hasn't been presented to any other university for obtaining the scientific degree.

Anatolijs Melnikovs …………………………….

Date: ………………………

The thesis is written in Latvian. It contains 6 chapters, conclusions, 120 references, 112 figures, 13 tables and 143 pages.

CONTENTS

GENERAL DESCRIPTION OF THE THESIS

Problem actuality

The problem of shape optimization of constructional elements has been actual for centuries. The practical experience shows that solutions for design of constructions are searched to reach more efficient use of restrained resources. Nowadays algorithms for shape optimization [Nocedal, 2006; Christensen, 2009; Deb, 2013] are intensively elaborated. As result, it is possible to make accurate calculations of complex constructions. It gives us opportunity to utilize new lightweight materials as well as progressive solutions for shapes of constructional elements [Bendsoe, 2007; Rao, 2012]. However classical methods of shape optimization still require large computational resources.

Therefore we look for alternative methods for shape optimization that allow realization with much less resources. Methods that are based on parametric and non-parametric approximations become actual today hence labor-intensity of optimization problems is significantly reduced.

A lot of [Simpson 2004; Lee, 2004; 2007; Janushevskis, 2006; Jung, 2006; Koziel, 2011] authors work in the same direction in the last decade. They try to give opportunities to perform shape optimization with a small number of variables. As a result, the chosen subject for this thesis is especially significant.

The objective of this thesis

To elaborate a novel technique for optimization of the shape of constructional elements that allows significantly reducing required resources for calculation. To prove that this technique works and can be efficiently used for solution of practical problems.

Objectives of the research

To apply metamodeling technique and NURB splines for shape optimization of CAD 3D models:

- To find efficient approach for shape parameterization and modification with NURB spline, so only smooth shapes are obtained
- To elaborate recommendations for selection a type of design of experiments (DOE) and approximation methods, so it is possible to obtain qualitative approximation for responses of FE calculations.

- To compare the efficiency of elaborated technique with classical methods of optimization (homogenization, et al.)
- To elaborate appropriate macros for CAD/CAE software: automation for input of DOE and registration of output responses, to reduce a time for preparation of optimization and to avoid mechanical mistakes
- To verify elaborated technique by test problems and results of optimization by appropriate natural experiments
- To perform shape optimizations of several real objects: to show the area for practical application of the technique

The scientific novelty

Main scientific novelty of the thesis is the elaborated technique of shape optimization. The technique is based on a new and never applied approach: to apply Latin hypercube (LH) DOE that are optimized by mean square distance (MSD) criterion to obtain local approximations with Gaussian kernel (metamodels) for construction design responses as functions of coordinates of NURB spline polygon points that are applied for shape definition.

The elaborated technique is effectively applied for shape optimization of real objects. As a result appropriate solutions are found and recommendations are made.

Practical significance

The elaborated technique has wide perspectives of application, because it is easily applied (adaptable) together with a variety of modern CAD/CAE software (Solidworks, Catia, Ansys, Autocad Inventor, et al.). The main application of the technique is shape optimization of constructional elements and significantly enhancement of functional parameters of new and original constructions. The elaborated technique, consuming less computational resources, allows finding the appropriate solution faster, than with alternative classical methods, such as homogenization method, for example. It is possible to effectively apply it for design of machine and other areas of products design. As the result of technique application only smooth and technologically easy-realized shape of constructional elements are obtained. This is confirmed by shape optimization of the current work. Recommendation for construction blocks, mounting disk of train wheel dynamic load measurement equipment, gage panel of vehicle and constructions of tetrapod-shaped elements are made.

Proposed theses for defense

- Metamodeling methods and CAD/CAE software based new resource saving technique of 3D objects shape optimization are elaborated
- 3D shape parameterization approach by coordinates of NURB spline polygon points gives the best results of shape optimization in comparison with classical methods
- The results of shape optimization adequacy by the elaborated technique is confirmed by natural experiment
- Optimized shapes of computer models and obtained parameters of construction blocks, mounting disk of train wheel dynamic load measurement equipment, gage panel of vehicle and constructions of tetrapod-shaped elements

The cooperation with enterprises

During the process of thesis preparation, collaborations were carried out with Latvian companies. Specific problems of objects optimization were solved.

The problem of shape optimization of mounting disk of railway vehicle measurement system is solved in the 3rd chapter. The problem was given by Ltd “Baltic Testing Center”.

The problems of dynamic analysis and optimization of gage panels are solved in the 5th chapter. The initial models of automobile and bus gage panels, and also requirements were given by Ltd “Merpro” manufacture.

The approbation of the thesis

Results of the thesis are presented and discussed on 21 international conferences and scientific seminars:

1. Janushevskis A., Melnikovs A., Boiko A. Shape optimization of mounting disk of railway vehicle measurement system. „ 9th International conference - Vibroengineering 2010” Kaunas, Lithuania, October 14-15, 2010
2. Янушевскис А.В., Мельников А.Г., Пакалнс Р.Д. Методика оптимизации формы элементов механических систем проектируемых средствами CAD/CAE: тесты. V Международная научно-техническая конференция „Современные проблемы машиностроения”. Россия, Томск, 23-26 ноября, 2010

3. Янушевскис А.В., Мельников А.Г., Бойко А.Ф. Методика оптимизации формы элементов механических систем: промышленные примеры. V Международная научно-техническая конференция „Современные проблемы машиностроения”. Россия, Томск, 23-26 ноября, 2010

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10. Janushevskis A., Auzins J., Melnikovs A., Staltmanis A., Vaicis I., Viba J. Wood Pole Overhead Lines Strength Problems under Extreme Weather Loads // 11th International Scientific Conference „Engineering for Rural Development”, Jelgava, Latvia, 24.-25. May, 2012

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14. Auzins J., Kalnins K., Labans E., Prieditis R., Melnikovs A. Metamodel building on the basis of globally weighted high order polynomials. WCSMO-10: 10th World Congress on Structural and Multidisciplinary Optimization. REF. 5592. Orlando, USA, May 19-24, 2013
15. Janushevskis A., Melnikovs A., Janusevskis J. Shape Optimization of a Lightweight Tetrapod Element Using CAD/CAE Tools and Metamodels. IRF`2013 – 4th International Conference on Integrity, Reliability & Failure. Funchal, Portugal, 23-27 June, 2013
16. Seminars: "RTU Mehānikas institūta un LNMK apvienotie semināri" (Rīga, Latvija, 13.04.2010, 05.10.2010, 10.05.2011, 19.06.2012, 27.11.2012, 14.04.2013).
Main results of the thesis are presented in 28 publications.

THE THESIS STRUCTURE

In the first chapter the actuality of the thesis is substantiated; main approaches of shape definition with NURB splines, classical methods of shape optimization, recent researches the same direction and problems that discovered other authors are discussed. Objectives and aims of researches are stated. Also there are shown problems that must be solved, so elaborated technique of shape optimization could be efficient.

The capacity of calculations is multiplied rapidly in the last decade. Opportunities of finite elements methods (FEM) are especially increased [Zienkiewicz, 2005], as result, calculation of complex constructions with a lot of components are possible with nowadays office computer. Computer-aided design (CAD) and computer-aided engineering (CAE) [Miltiadis, 2010] have become as inseparable step of any new product development. As results, the time for product development decreased and new higher standards are achieved. However CAD/CAE based classical methods of shape optimization still require a lot of design variables for complex construction, so accurate results could be obtained [Vanderplaats, 2004].

The computer-based topology optimization methods have been applied for mass reduction of constructional elements since 1988. The different realizations of homogenization method are vastly used [Arora, 2004; Bendsoe, 2007] for topology and shape optimization of structures. The method was rapidly improved and has been widely used since that time. This method is highly effective for shell constructions and allows implementing topometry [Mozumder, 2011] and topography [Vanderplaats, 2004], size and shape as well as freeform optimization. However, it is a very time consuming procedure. For example, the software Genesis [Genesis, 2007] has realization of homogenization optimization methods and it allows 2.5 million design variables. As result, it gives the possibility to find the topology of complex object, such as, automobile, rocket hull and et al. In case of solid bodies it frequently produces difficultly manufacturable shapes and enormous labor intensity.

The alternative approach includes application of metamodeling, that is based on DOE and methods of approximations [Montgomery, 2001]. In such cases it is possible to apply a few design variables and to obtain optimal solution [Liao, 2007; Lee, 2004]. As a result, there is no need for enormous capacity of calculations because simplified, however, high-quality metamodel of object is created.

In our days NURB splines are most effective for creation of complex shape in CAD environment, because of several properties such as possibilities of local modification at different order continuity between segments of curves, smooth shape and et al.

The cubic spline curve is often applied in CAD software [Saxena, 2005]. Let function $\phi(t)$ represent the spline in the i^{th} span, $t_i \le t \le t_{i+1}$ so in matrix form:

$$\Phi_i(t) = \begin{bmatrix} 1 & t & t^2 & t^3 \end{bmatrix} \begin{bmatrix} \dfrac{(t_{i+1}-3t_i)t^2{}_{i+1}}{h^3{}_i} & \dfrac{(3t_{i+1}-t_i)t^2{}_i}{h^3{}_i} & \dfrac{-t_i t_{i+1}{}^2}{h^2{}_i} & \dfrac{-t^2{}_i t_{i+1}}{h^2{}_i} \\ \dfrac{6t_i t_{i+1}}{h^3{}_i} & \dfrac{-6t_i t_{i+1}}{h^3{}_i} & \dfrac{(2t_i+t_{i+1})t_{i+1}}{h^2{}_i} & \dfrac{(t_i+2t_{i+1})t_i}{h^2{}_i} \\ \dfrac{-3(t_i+t_{i+1})}{h^3{}_i} & \dfrac{3(t_i+t_{i+1})}{h^3{}_i} & \dfrac{-(t_i+2t_{i+1})}{h^2{}_i} & \dfrac{-(2t_i+t_{i+1})}{h^2{}_i} \\ \dfrac{2}{h^3{}_i} & \dfrac{-2}{h^3{}_i} & \dfrac{1}{h^2{}_i} & \dfrac{1}{h^2{}_i} \end{bmatrix} \begin{bmatrix} y_i \\ y_{i+1} \\ s_i \\ s_{i+1} \end{bmatrix} \tag{1}$$

where s_i and s_{i+1} the unknown slope and y_i and y_{i+1} are coordinates at t_i and t_{i+1} (spline knot points at abscissa); n –number of knot points and h_i is spline in the i^{th} span length between two near knot points at abscissa if each knot span is not normalized ($h_0 \ne h_i \ne .... \ne h_{n-1} \ne 1$).

Differentiating (1) twice gives:

$$\Phi_i''(t) = \begin{bmatrix} \frac{6(2t - t_i - t_{i+1})}{h_i^3} & \frac{-6(2t - t_i - t_{i+1})}{h_i^3} & \frac{2(3t - t_i - 2t_{i+1})}{h_i^2} & \frac{2(3t - 2t_i - t_{i+1})}{h_i^2} \end{bmatrix} \begin{bmatrix} y_i \\ y_{i+1} \\ s_i \\ s_{i+1} \end{bmatrix} \quad (2)$$

$$\Phi_{i-1}''(t) = \begin{bmatrix} \frac{6(2t - t_{i-1} - t_i)}{h_{i-1}^3} & \frac{-6(2t - t_{i-1} - t_i)}{h_{i-1}^3} & \frac{2(3t - t_{i-1} - 2t_i)}{h_{i-1}^2} & \frac{2(3t - 2t_{i-1} - t_i)}{h_{i-1}^2} \end{bmatrix} \begin{bmatrix} y_{i-1} \\ y_{i+1} \\ s_{i-1} \\ s_{i+1} \end{bmatrix} \quad (3)$$

For continuity of the second derivative $\phi''_{i-1}(t_1) = \phi''_i(t_i)$ at knot point (t_i, y_i):

$$\frac{s_{i-1}}{h_{i-1}} + 2s_i\left(\frac{1}{h_{i-1}} + \frac{1}{h_i}\right) + \frac{s_{i+1}}{h_i} = \frac{3y_{i+1}}{h_i^2} + 3y_i\left(\frac{1}{h^2{}_{i-1}} - \frac{1}{h^2{}_i}\right) - \frac{3y_{i-1}}{h^2{}_{i-1}}, \quad i = 1, \dots, \quad n-1 \quad (4)$$

Elaborating the novel technique of shape optimization, required calculations sources must be minimized. The novel technique of shape optimization should be realized using sources of ordinary PC and optimization result must be with appropriate accuracy.

In the second chapter the alternative technique for shape optimization is elaborated using metamodels. The technique consists of designing location of the control points of polygon and knot points of NURB splines for the shape definition and building of the appropriate metamodels of responses for subsequent optimization. Only the smooth shapes defined by NURB splines are analyzed using proposed technique. The jagged shapes are not analyzed and are excluded from the optimization process. The technique is based on using the commercial CAD software as well as the original code EDAOpt developed in RTU for DOE, approximation and optimization.

The proposed approach includes 6 steps (Fig. 1). Factors of construction, its number and intervals are defined at the first step. The variable shapes of object are intended to define with curves of non-uniform rational B-splines (NURBS). Coordinates of control polygon or knot points of NURBS are used as independent factors. Factors intervals are chosen in accordance with optimized element or assembly size, mass, technological or other important constraints. The interval of factors should be in the possible optimal solution borders, otherwise optimization process must be repeated in loop, adjusting intervals of factors. At the second step DOE are generated by EDAOpt software taking into account number of factors and intervals. The priority is given to LH DOE that are optimized by mean square distance (MSD) criterion. Geometrical models are created using CAD software in conformity with DOE at the third step. During this step it is possible obtain volume, mass and other inertial characteristics of model that could be used for optimization at firth step. Calculation of responses for complete FEM model by CAE software is performed at the fourth step. FE model must ensure sufficient accuracy for responses. Responses are approximated with local polynomial functions with Gaussian kernel in EDAOpt software at the fifth step. Accuracy of approximations and prediction errors are estimated. If results are satisfactory, extremums of objective function are searched with global stochastic search procedures taking into account known constraints(mass, volume, stresses, displacements, strains et al.). Optimal values of factors are used for creation of the optimal shape of object 3D model in CAD software at the sixth step. Calculated responses of complete FEM 3D model are compared with metamodel and errors are estimated.

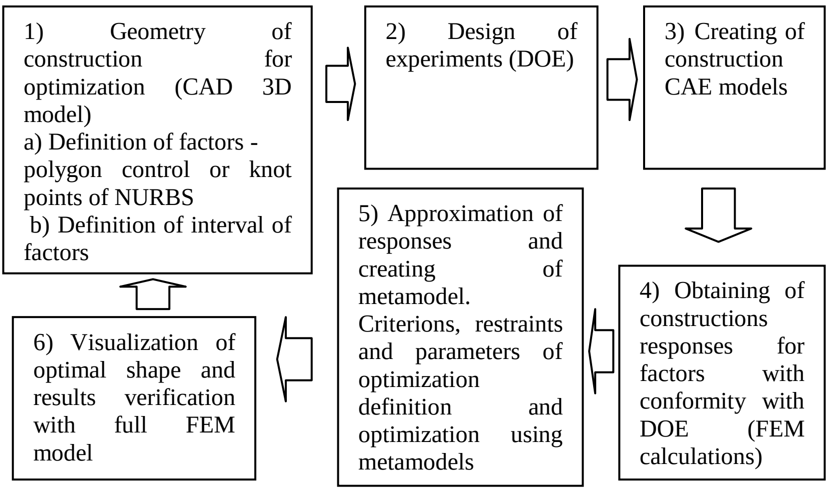


Fig.1 Main steps of the technique of shape optimization

For automation of steps 3-5 the special Visual Basic macros for SolidWorks software was created for EDAOpt DOE points input and registration of output responses.

In the most cases approximation of responses is possible to obtain by quadratic polynomial and the following expression is often the best one to use:

$$\hat{y} = \beta_0 + \sum_{i=1}^{d} \beta_i x_i + \sum_{i=1}^{d-1} \sum_{j=i+1}^{d} \beta_{ij} x_i x_j + \sum_{i=1}^{d} \beta_{ij} x_i^{\,2} + \varepsilon \quad , \qquad (5)$$

where there are d variables $x_1,\ldots, x_d$, $L=(d+1)(d+2)/2$ unknown coefficients β and the errors ε are assumed independent with zero mean and constant variance σ^2. In case of local approximation the coefficients $\beta=(\beta_1, \beta_2, \beta_3,\ldots, \beta_L)$ depend on the point x_0 where prediction is calculated and are obtained by using of weighted least squares method:

$$\beta = \arg\min_{\beta} \sum_{j \in N_X} w(x_0 - x_j) \times (y_j - \hat{y}(x_j))^2 \quad , \qquad (6)$$

The significance of neighboring points in the set N_x is taken into account by Gaussian kernel:

$$w(u) = \exp\left(-\alpha u^2\right) \quad , \qquad (7)$$

where u is Euclidian distance from x_0 to current point and α is a coefficient that characterize significance.

Quality of the approximation is estimated by leave one out crossvalidation error:

$$\sigma_{Xrel} = 100\% \frac{\sqrt{\frac{1}{n} \sum_{i=1}^{n} (\hat{y}_{-i}(x_i) - y_i)^2}}{\sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (y_i - \bar{y})^2}} \quad , \qquad (8)$$

where root mean squared prediction error stands in numerator and mean square deviation of response from its average value stands in denominator, n is a number of confirmation points and $\sum_{i=1}^{n} \hat{y}_{-j}(x_i)$ denotes sum of responses calculated without taking into account j-the point.

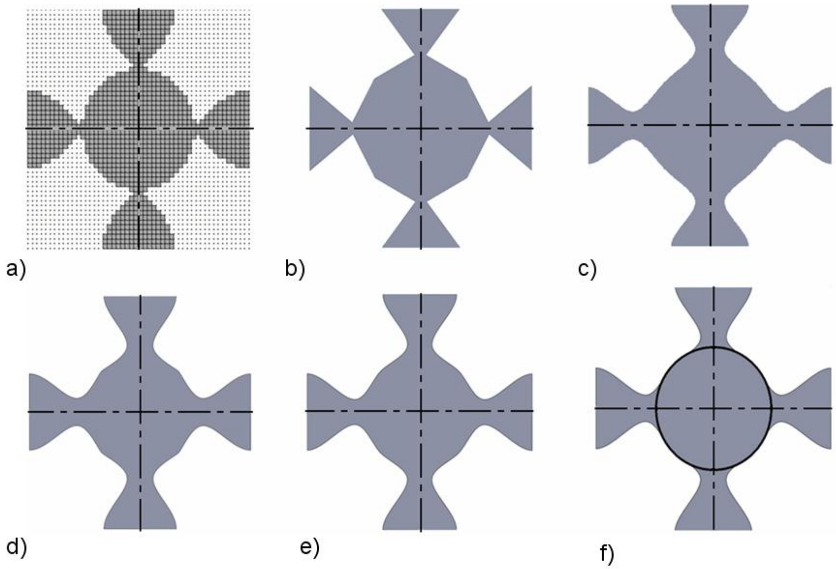


Fig. 2 Cutout shapes of bending plate obtained by a) homogenization method [Liang, 2001]; b) the points that are connected with straight lines; c) with NURBS knot points; d) with control points of NURBS polygon; e-f) same as "d" but with additionally optimized tangent weighting at spline endpoints and with circle added

Next the proposed technique of the shape optimization is verified on the base of two test problems. The first is concerned with the shape optimization of the plate bending problem with displacement constraints and the second – of the plate biaxial tension problem with stress constraints. The optimization results (Fig. 2 and 3) are compared with results of other authors [Papadrakakis, 1998; Liang, 2001]. The efficiency of the three procedures of the shape definition is analyzed. It is shown that the utilization of the proposed technique and the definition of a shape by procedure of the polygon control points of NURB spline give better results than the results obtained by classical homogenization method.

To be fully confident that such approach will work for real objects, optimizations results of the first test - plate bending problem - were validated (Fig. 4 left). 13 samples are manufactured: shape A – 1, E – 4, F – 4 and G – 4 (Fig. 5). The obtained data points of experiments are used to obtain averaged curves for each shape (Fig.4 right).

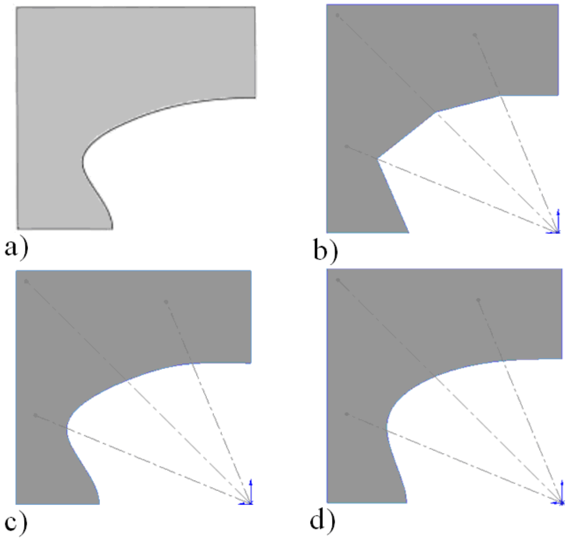


Fig. 3 The obtained plate shapes: a) in [Papadrakakis, 1998]; b) the points that are connected with straight lines; c) with NURBS knot points; d) with control points of NURBS polygon

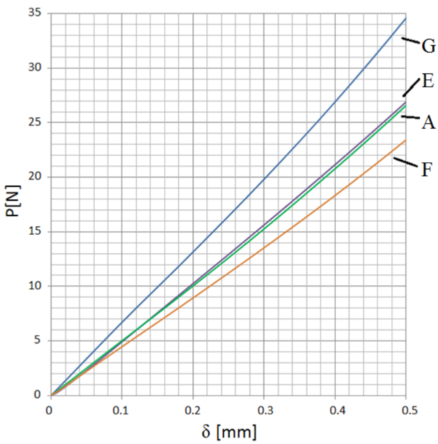


Fig. 4 Natural experiments of plates bending: on Zwick Roell Z 150 machine and the averaged curves of each type of samples: [Liang, 2001] (A); obtained by the current approach (E); the cross-shaped plate (F) and square plate (G)

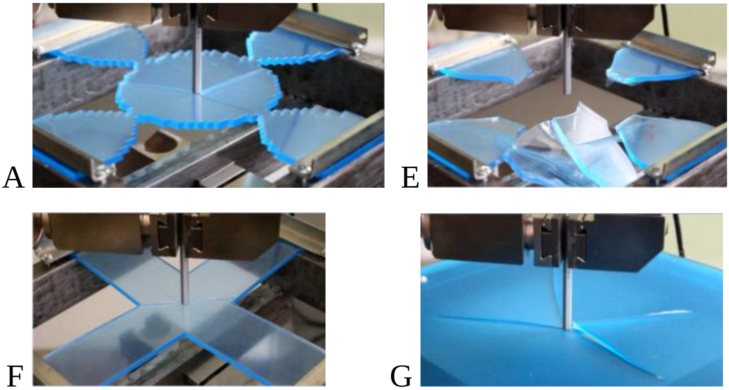


Fig. 5 Fracture behavior of the each sample

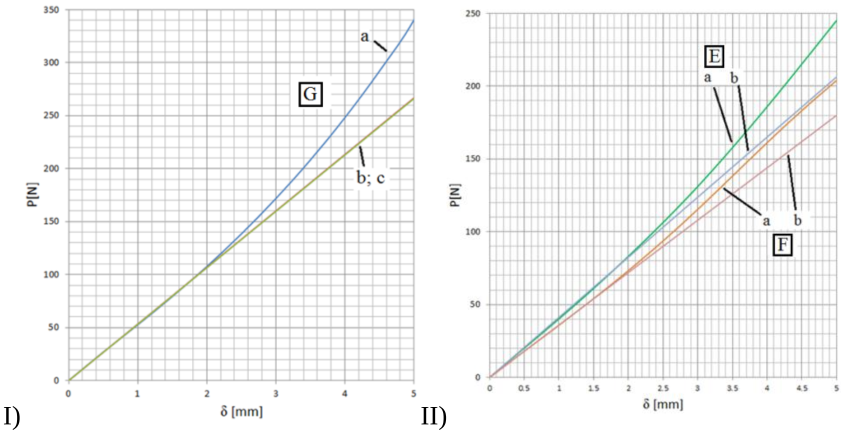


Fig. 6 Average curves of samples test and linear models: I) G: a) test (average), and b); c) –linear FE and analytical models; II) E and F: a) test (average), and b) linear FE model

Physical experiments, FEM and analytical models are compared for samples G (Fig. 6(I)). The good agreement is obtained at the beginning interval of elastic deformation (< 2.2 mm) for all 3 curves. The agreement between the FE model and the analytical model is within 0.2 % limits of error.

FE models and experiments results of samples (E and F) are compared (Fig. 6(II)). Similar agreement as for samples G is obtained at the beginning loading interval (<2.2 mm). Consequently, natural experiments confirmed that the result of the optimization of the plate (Fig. 2e) is the optimal material distribution.

In the third chapter the problem of the shape optimization of measurement system disk is solved.

At the present special tensometric wheel pairs are used for the wheel - rail system monitoring. For each type of rolling stock (electric locomotive, diesel train or electro-diesel locomotive) these wheel pairs must fit vehicle's wheel wearing conditions, diameter and bearing box connection type. Using and delivering of the tensometric wheel pairs are expensive and it takes a lot of time for preparation of strength – dynamics tests. In this thesis removable equipment for monitoring is proposed to mount on the ordinary wheel pairs. Monitoring wireless system for 80 tons wagon (freight car) is taken as prototype. The removable part of equipment (Fig. 7) consists of disk, two transmitters and transmitting antenna [Григоров, 2004] as well as strain gauges bonded to the wheel at defined places. Circular transmitting antenna and two transmitters are mounted on outside of the disk.

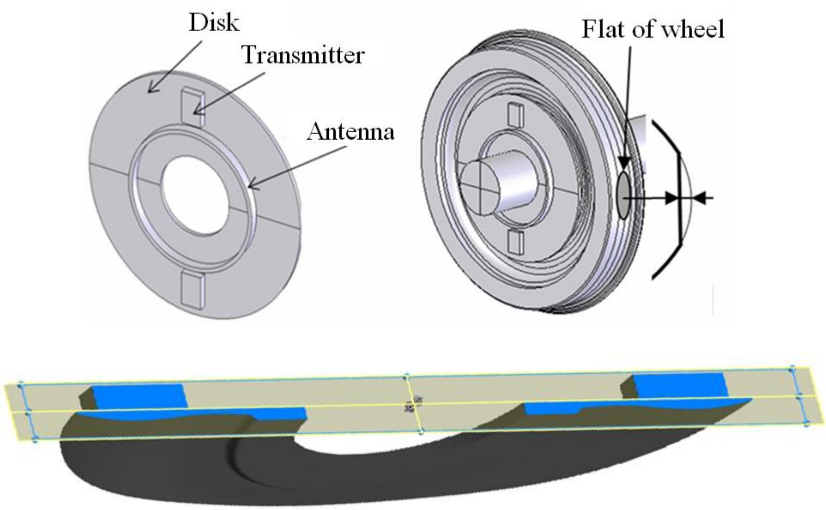


Fig. 7 Removable disc with elements of measurement system, its mounting place and the obtained shape of ellipsoidal disk cross section

Removable equipment must be lightweight to minimize distortions of measurements and at the same time it must have appropriate durability. During testing dynamical loads, caused by rail joints, railroad switches and other irregularities as well as due to defects of wheel geometry, are transmitted from wheel pairs to removable disk which is rigidly mounted on the wheel set axis. Therefore shape optimization of the mounting disk - that is main heavy weight part of equipment - is very important to reduce its total weight.

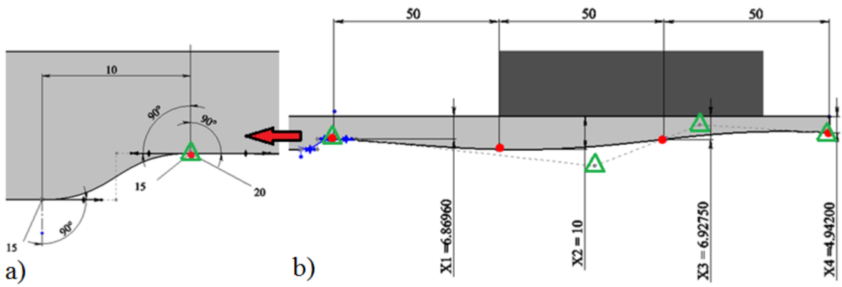


Fig. 8 Definition of the ellipsoidal disk cross section with NURBS: a) definition of continuity and b) shape definition with polygon points (green triangles) or knot points (red dots)

To be able to get the further insight, as with the test plates, three procedures of the disk cross-section shape definition using only 3 design variables are considered (Fig. 8b): 1) with knot points of NURBS; 2) with polygon points of NURBS and 3) with points that are connected with straight lines. The variable cross section shape is defined with 4 vertical coordinates. To obtain smooth shape of the ellipsoidal disk cross section and avoid possible stress concentrations, for variants of "1" and "2" NURBS 3 continuity vectors are defined (Fig. 8a).

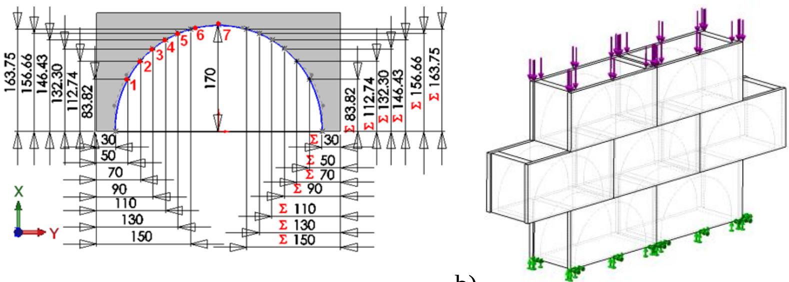
The problems of the disk optimizations is defined as minimization of its volume V subject to constraints: a) maximal equivalent stresses $\sigma_{vonMises} \leq 4$ MPa, b) axial directions displacement $U_Z < 2$ mm and c) fundamental frequency $f > 25$Hz.

Specificities of obtained shapes removable disc are presented in Fig. 8. The thickness of the disk is higher in this area beneath the transmitter where additional load are undertaken.

By means of optimization the total mass of the removable disk is reduced on ~64 % in comparison with initial design. The ellipsoidal shape of disk with variable thickness is obtained which is necessary for strength, allowable displacements and natural frequency.

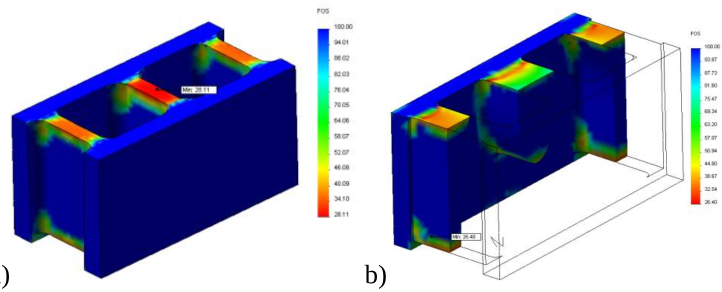
In the fourth chapter the optimization problem of a hollow concrete block is solved. It is shown that elaborated technique has wide application and is not limited by object optimization of ductile materials.

The problem consists of finding optimal shape of hollow block cutout considering material consumption, strength and thermo insulation. Single block is used for a thermal model which takes into account heat conduction of block materials and convection process on block’s external wall. Single block model with different boundary conditions and wall models with different stacking are used for strength calculations (i.e., Fig. 9b). Block strength is defined by Mohr-Coulomb criterion.



a) b)

Fig. 9 a) The initial cutout shape of block and b) The calculation model with shifted blocks



a) b)

Fig. 10 FOS coefficient distribution in a) Columbia Kivi and b) concrete block of the alternative shape of cutout

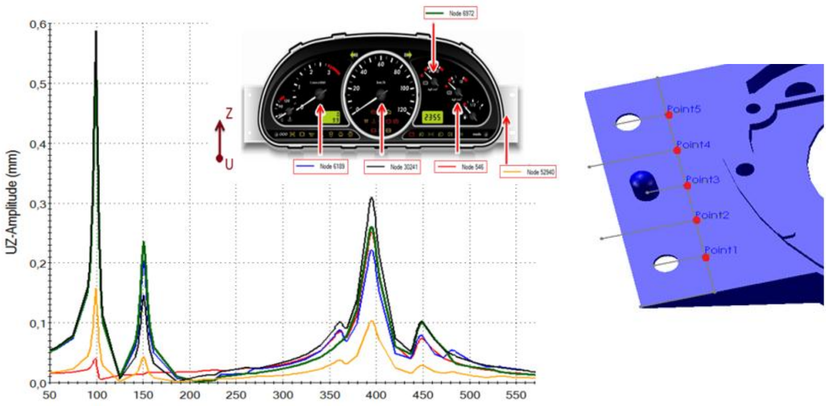
Internal cutout shape of block is defined by smooth NURB spline that is given by 7 polygon points (Fig. 9a).

Optimization is performed subject to the essential criteria. The following nonlinear programming tasks are solved: 1) maximization of the minimal DOF coefficient of block subject to constraints of minimal average temperature of internal wall, 2) maximization of average temperature of blocks internal wall, 3) minimization of block mass and 4) maximization of the minimal DOF coefficient of block. The average temperature of the internal wall is assumed as arithmetic mean of all points values located on a block wall.

Results of the optimization show that mass of block is possible to reduce by ~8% using the obtained cutout shape of the alternative block (Fig. 10).

In the fifth chapter dynamic analysis of automobile and bus gage panels (GP) and the shape optimization of GP was performed.

The GP must meet many requirements - precisely measurable functional characteristics, stiffness, stress levels, weight and minimal pollution of environment. Geometrical 3D models of GP are elaborated. Dynamic and static responses are obtained. The environmental impact responses of GP, such as, carbon footprint, water eutrophication, air acidification and total energy consumed in the GP life cycle are analyzed. Dynamic behaviors of GP are verified by analysis of the full FEM model in case of deterministic and non-deterministic excitations, respectively, harmonic analysis of GP (Fig. 11a) and random vibration analysis of GP.



a) b)

Fig. 11 a) Harmonic analysis of bus GP. The comparison of amplitudes of vertical displacements at the defined points of the GP and b) Registration of equivalent stress at 5 places on the GP bracket

The GP brackets parameterization with NURBS polygon points is performed (Fig. 12a-c).

Responses of FEM model are calculated for approximation. The linear approximation of the volume is shown at Fig. 13. On the other hand responses of maximal equivalent stresses $\sigma_{vonMises}$ are required a higher order approximation. There is found that local polynomial approximation could be successfully used for approximation of responses of complex constructions.

The problem of shape optimization of the bus GP brackets are defined as follows: minimization of volume V of GP components with brackets subject to constraints: 1) on the GP maximal displacement $URES$ < 1.5 mm, 2) on maximal equivalent stresses $\sigma_{vonMises}$ at 5 points (Fig. 11b)) $\sigma_{vonMises} \leq 1.5$ MPa and 3) on fundamental frequency f >120 Hz.

The obtained smooth shape (Fig. 12b) of GP bracket gives design with 40% less maximal equivalent stresses level in comparison with the initial design with constant thickness of brackets.

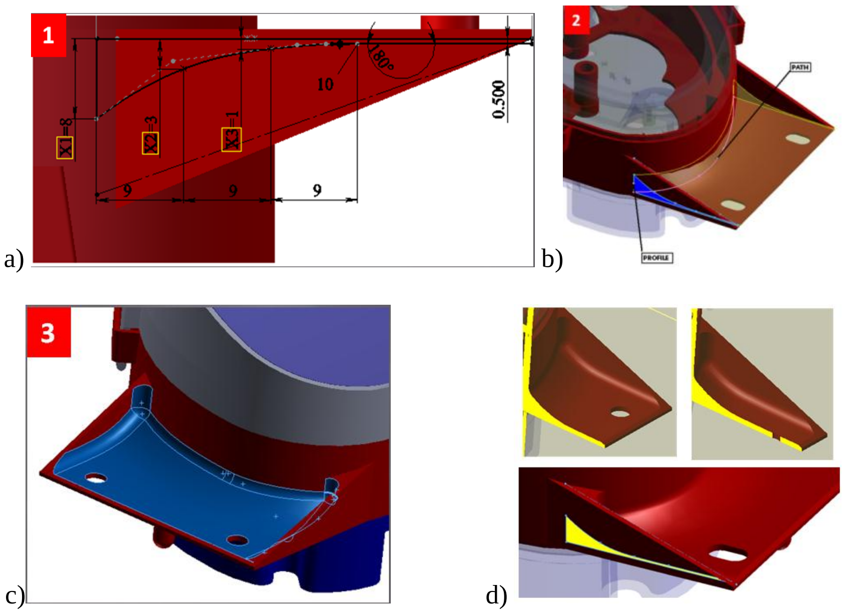
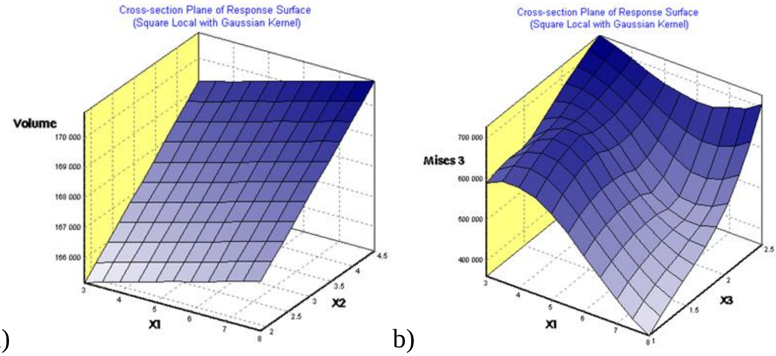


Fig. 12 The parameterization of brackets shapes (a-c): a) cross-section shape definition with NURBS; b) 3D- shape creation through path curve; c) additional fillets and d) obtained shapes of GP brackets

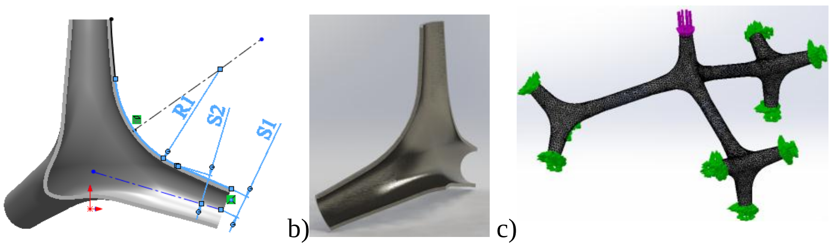


a) b)

Fig. 13 Obtained functions dependence on design variables X1, X2 and X3 (Fig. 12a): a) volume and b) maximal equivalent stress $\sigma_{vonMises}$ at the point 3

In the sixth chapter the shape optimization of the tetrapod-shaped element is performed.

The lattice of tetrapod-shaped elements [Hyde, 1989] could be used for the synthesis of constructions with high stiffness properties [Yaghi, 2003; Bervalds, 2009] using steel or new types of composite lightweight materials. One of the possible applications of the tetrapod lattice could be constructions with unconventional design when special conception of design must be taken into the account [Weaire, 1994; Carfrae, 2007].



a) b) c)

14. att. Parameterization of the tetrapod-shaped element (a-b): a) Definition of shape with S1; S2 knot points of NURBS polygon and radius R1, b) Smooth molded shape of the 1/3 tetrapod and c) 7 elements (4 tetrapod-shaped elements and 3 pipes) meshed shell FE model with initial shape

The parameterization with 3 parameters of the tetrapod 3D shape is proposed (Fig. 14a), that allows to obtain only smooth boundary shape. The central part shape of tetrapod is controlled by radius R1. R1 is connected continuously along a tangent to NURBS curves that shape is controlled by 2 parameters S1 and S2 - NURBS knot points. In this case, NURBS greater number of parameters is not necessary because it will only make more difficult definition of smooth shape.

The biggest problem of this construction is strength of the connection, therefore a shape of tetrapod must be found, which would be with minimal stresses. According to this, compressive loading model is chosen for optimization that consists of 7 elements (Fig. 14c).

a) b1) b2)

Fig. 15 The constructions with equal *V* volume comparison: a) Spherical and b(1-2)) Shapes of initial and obtained tetrapod elements

Next the optimization of tetrapod shape is performed: objective minimization of maximal equivalent stresses with constraints on construction volume $V < 646.933$ mm^3.

The obtained shape of tetrapod compared to initial design and spherical pipe connection (Fig. 15). The obtained shape of tetrapod element ensures 27.3 % higher strength and 0.2 % lower volume in comparison with spherical connection element. The obtained results could be used for design of unconventional supporting constructions.

CONCLUSIONS

- The resource-saving shape optimization technique is elaborated and that includes: DOE are optimized with corresponding criterions; creating metamodels of responses of structure as functions of control polygon points coordinates of non-uniform rational B-spline (NURBS) that are used for shape definition and optimization with global stochastic search procedures.
- It is experimentally proven by optimizations of the test problems and validation that the utilization of the elaborated technique is less time-consuming and gives better results than the results obtained by classical homogenization method.

- Various results of shape optimization problems show that best results of shape optimization are obtained with proposed parameterization using control polygon points of NURBS.
- The problem of the shape optimization of element of measurement system is solved. The ellipsoidal disk with variable thickness of the cross section is obtained that has ~64% less mass, required strength, permissible displacements and natural frequencies.
- The optimization of a hollow block is performed taking into account brittle material strength and thermo insulation properties. As result, the alternative shape of block is obtained that requires ~8% less concrete comparing with existing block.
- The realized shape optimization of the gage panel (GP) brackets reduces maximal stress of brackets by ~40% comparing with GP initial design and ensures appropriate dynamical et al. responses.
- The optimization of 3D shape of the pipe joint - tetrapod-shaped element for specific construction - was performed. The optimal shape of the tetrapod-shaped element for specified criteria and constrains is obtained, as result, its strength is achieved for 27.3% higher comparing with spherical connection element.
- The best results are obtained by Latin Hypercube DOE that are optimized with mean-square distance (MSD) criteria and utilized for local polynomial approximation with Gaussian kernel.
- Macros for appropriated CAD/CAE software for input of DOF and registration of responses are developed. As result, time-consumption of optimization for data transfer is reduced.
- Solutions of real problems confirms that elaborated technique is effective and has wide range of application possibilities with CAD/CAE software.

LIST OF PUBLICATIONS AND PATENT

Results of the thesis are published in 28 publications, including scientific monograph (chapter of the book), 21 research papers, 1 patent and 5 abstracts:

1. Januševskis A., Auziņš J., Kovaļska A., Meļņikovs A., Ozoliņš O. Vibrotriecienpreses ģeometriskā un aprēķinu modeļu izstrāde // RTU zinātniskie raksti. ISSN 1407- 8015, 6. sēr., Mašīnzinātne un transports, 28. sēj., 2008. - 63.-77. lpp.
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