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DEVELOPMENT OF METHODS AND TOOLS FOR SIMULATION, IDENTIFICATION AND MULTIOBJECTIVE OPTIMIZATION OF MECHANICAL SYSTEMS AT THE MACHINE AND MECHANISM DYNAMICS LABORATORY

MEHĀNISKO SISTĒMU MODELĒŠANAS, IDENTIFIKĀCIJAS UN DAUDZKRITERIĀLĀS OPTIMIZĀCIJAS METOŽU UN LĪDZEKĻU IZSTRĀDE MAŠĪNU UN MEHĀNISMU DINAMIKAS LABORATORIJĀ

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Keywords: Experimental Design, Metamodeling, Simulation, Optimization

Abstract: This paper gives brief historical review about scientists of Machine and mechanism dynamics laboratory and their research activities. The development of ideas and implementations of design and analysis of experiments from first concepts up to latest results is considered. The application fields of software tool EDAOpt, created in the laboratory, are described. The problems of simulation, identification and optimization of mechanical systems, closely related to industry and actual for researchers of MMD lab are shortly described. The wide range of possibilities of modern approximation methods and metamodeling approach are demonstrated.

Introduction

During the 1960's, a strong group of scientists-theoreticians in the field of mechanics (oscillation theory, mechanics of continuous media) formed in the Riga Polytechnic Institute under the guidance of academician J. Panovko and professor E. Lavendelis. The practical implementation of the scientific ideas became necessary, therefore a laboratory of an according profile was created – the Machine and mechanism dynamics laboratory (MMD). In the following years many fundamental results in the field of machine dynamics, optimization of vibration and vibroimpact systems were obtained by academicians E. Lavendelis, J. Vība and their students. Practically all of the current professors of the Mechanical Institute of the Riga Technical University have worked in this laboratory, many of the highly-qualified former staff of this laboratory now successfully work in many different countries of the world. Along with the restoration of Latvian independence the structure of the laboratory has gone through some change, namely, the experimental base has been reduced - however, computerization and the amount of developments in the field of information technologies and simulation [1, 2, 3] have increased. Computers have always played an important role in the work of the laboratory's scientists. The scientists of MMD laboratory were pioneers of computational mechanics in Latvia. The first use of the finite element method in Latvia (E. Lavendelis), first use of computers for automatic creation of mathematical models of machine dynamics (J. Auziņš), first investigations in robotics (P. Sliede) were done in the MMD lab. In the MMD laboratory worked the brilliant scientist and fighter for the Latvian national independence, co-author of the Declaration of Independence of the 4th of May 1990, Dr. Vilnis Eglājs (1938 - 1993), whose ideas in design of the so-called space filling experiments are used and quoted by scientists in the entire world up to this day. The doctors of engineering sciences P. Auziņš, S. Cifanskis, V. Čamāns, V. Putjatins, P. Sliede, G. Svīķis, M. Zakrževskis, J. Zviedris, as well as many other talented scientists have all significantly contributed to the development of the laboratory. For many years the work of MMD laboratory was managed by J. Zviedris and P. Sliede, the past 16 years the head of the MMD lab is A. Januševskis.

In this paper the active scientists of MMD laboratory briefly present their latest developments.

Design of experiments

Since 1974 the scientists of the MMD lab have developed methods and software tools for planning and analysis of experiments. The first publication in this field was the work [4], in which the principle of space filling designs was formulated and a new type of experimental designs, later named Latin hypercubes (LH), was introduced. It should be noted that the idea of LH designs was formulated some years earlier in the weekly scientific seminar of the MMD lab by J. Auziņš and was described in an unpublished

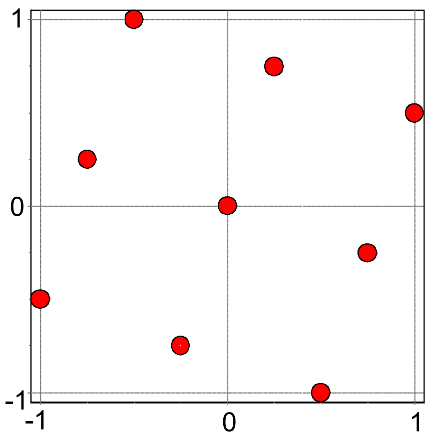


Fig. 1. The first Latin hypercube design, created in the MMD lab

report of the research project of the MMD lab. Fig. 1 shows the first regular Latin hypercube, proposed by J. Auziņš.

It seemed at this time that for a larger number of factors similar designs may be constructed, e.g. 27 experimental points for 3 factors. But soon it was found not to be true. At this time V. Eglājs proposed the "Potential energy" criterion for the estimation of the quality of the space filling property of Latin hypercube type experimental designs [4]. Fig. 2 shows the first optimized Latin hypercube design from this article. The well-known name "Latin hypercube" was introduced 2 years later by McKay and co-authors [5].

In the following years many other space filling criteria were proposed by several authors, see the review in [6, 7]. J. Auziņš [7] proposed the Mean square error (MSE) criterion, which gives better prediction accuracy by using modern nonparametric approximation methods for model building. In the past years the so-called Sequential Average MSE- optimal experimental designs were developed in the MMD lab [8]. Such designs are not LH, but give good space filling properties in the whole space of experimental factors and all subspaces. In addition, these designs can be augmented with

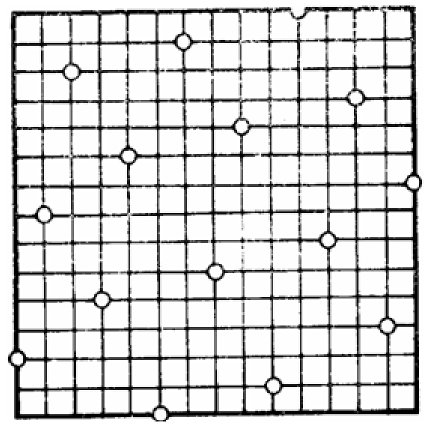


Fig. 2. The first optimized LH, picture from [4]

new experimental tries (points) without worsening of the space filling properties [6, 8]. On the basis of new experimental designs, nonparametric approximation methods and methods of global constrained optimization, the methodology of metamodeling and inverse metamodeling was developed, involving natural experiments as well as numerical computer experiments [6, 8]. This methodology is implemented in the software tool EDAOpt (*Experimental Design, Analysis and OPTimization*).

Software tool EDAOpt

EDAOpt allows to carry out all processes of optimization involving natural and numerical experiments: a) planning of experiments according to several types of experimental designs (classical d-optimal, LH, sequential space filling designs), b) building of direct and inverse mathematical models (metamodels) on the basis of parametrical (polynomial) and nonparametrical (locally weighted polynomial, kriging) approximations and finally c) multiobjective constrained optimization. EDAOpt gives the possibility of solving many optimization problems [9] – from structural optimization [10] to the identification of material properties [11, 12] and parameters of technological processes [13]. Below some examples of metamodeling and optimization will be demonstrated.

Optimization of ribbed sandwich steel constructions

In this research the geometrical parameters of welded ribbed steel construction Fig. 3. were optimized.

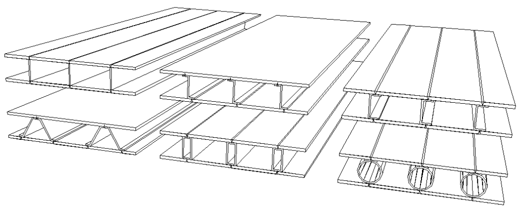


Fig. 3. Laser-welded all-steel sandwich panels

The variable factors were the profile type, number of stiffeners, thickness of plates and dimensions of stiffeners, the height of construction. The objective functions for multiobjective optimization were the weight and cost of construction as well as the deformation under standartized load. Finite element calculations according to MSE optimal experimental designs and natural experiments were involved in this research. Fig. 4, 5 shows the Pareto frontier plots of optimal solutions.

The identification and optimization of the raw concrete vibropressing process

The efectivness of the vibropressing process of raw concrete material for building high-strength concrete blocks depends on many factors: mixture composition, pressing forces, vibration

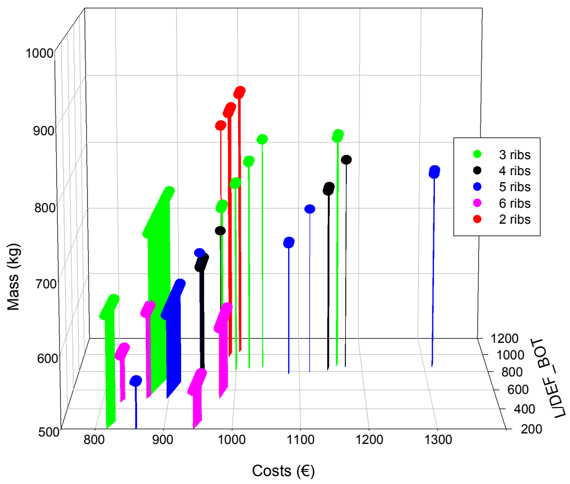


Fig. 4. Pareto frontier plot of welded steel panels

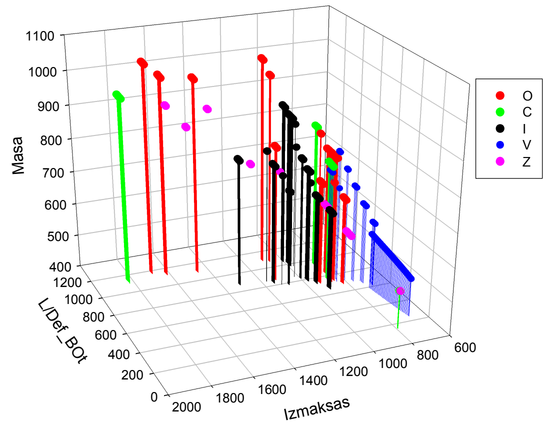


Fig. 5. Pareto frontier plot for panels with several stiffener profiles

frequency and amplitude, process duration etc. In this research the testing machine Instron 8802 was used with specially constructed plunger and mold, see Fig. 6.

The variable factors in this investigation were the pressing force constant component, vibration force amplitude and frequency, process duration. The objectives for multicriterial optimization were the compression rate, consumed energy, process duration. Fig. 7. shows the

Fig. 6. The raw concrete vibropressing experimental equipment on the testing machine Instron 8802

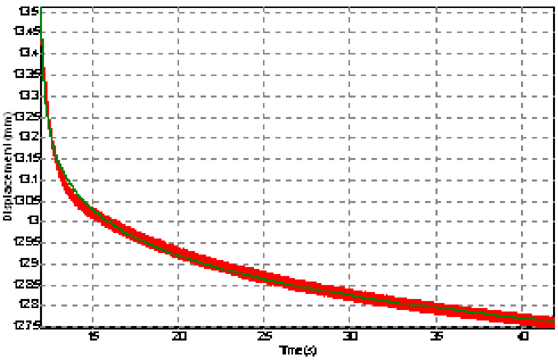


Fig. 7. The approximation of the raw concrete compacting process

approximation of compacting curve, obtained from natural experiments.

The metamodel for multiobjective optimization was built on the basis of the kriging approximation of experimental results. Fig. 8 shows the pareto frontier plot for 3 objectives: compacting rate, consumed energy, process duration.

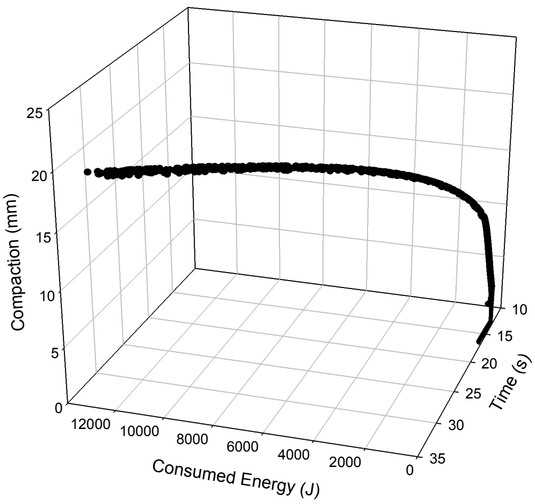


Fig. 8. Pareto frontier plot for 3 criteria

Shape Optimization

The methodology of shape optimization is enhanced on the basis of sample objects such as a concrete construction block. To improve heat transfer properties for walls made of concrete blocks, the insulating air space should be included. For such applications it is more efficient to use hollow blocks. The optimal shape of a hollow block was optimized for different loading conditions. The initial shape is seen in Fig. 9 and is specified using 7 support points

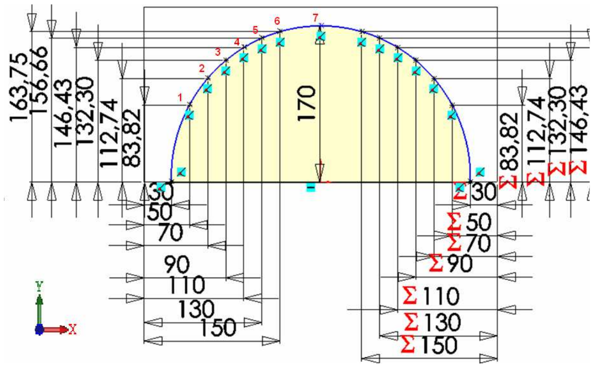


Fig. 9. Shape of the block basic cutout

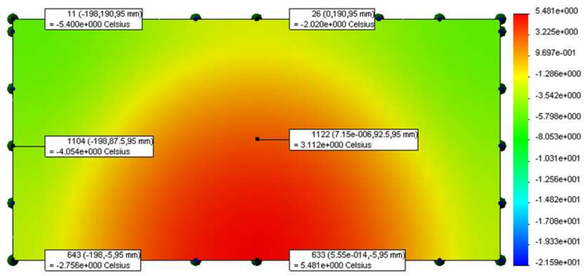


Fig.10. Temperature at nodes on the block inside face

Nr	Kritērijs	Krit.v. Aprox	Krit.v. GEM	Kļūda %	Iegūtā forma
1	Maksimālais FOS:	1.465	1.1	33	
2	Max FOS pie Tvid ne mazākas par 20°C	1.3438	1.16209 20.382°C	15.8	
3	Max Tvid	22.465	22.942	2.1	
4	MinMasa	14.06	14.13114	5	

Fig.11. Obtained shapes of cutout for different objective functions

connected using NURBS. To compare different configurations the stationary thermo analysis (Fig 10.) and strength analysis is performed. The strength analysis is performed for different block models: first a separate block is evaluated and then the stress state of the block in the wall is calculated (Fig.12).

First, the experiments for support points are designed according to the methodology of metamodeling. The computer intensive strength analysis and thermal analysis is solved and the responses calculated (temperature on the block

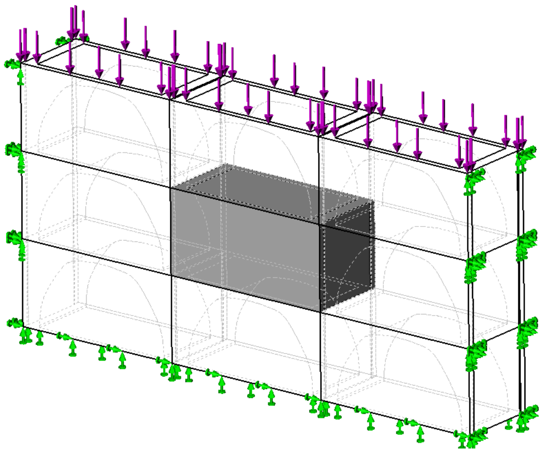


Fig.12. Model for simulation

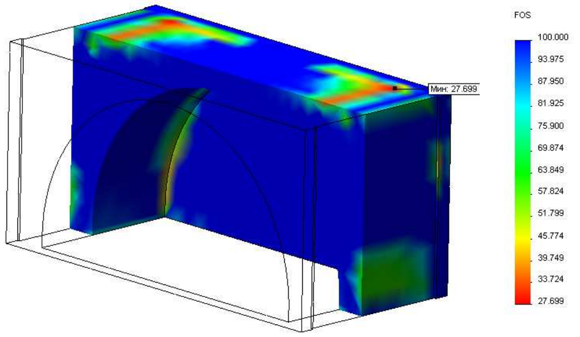
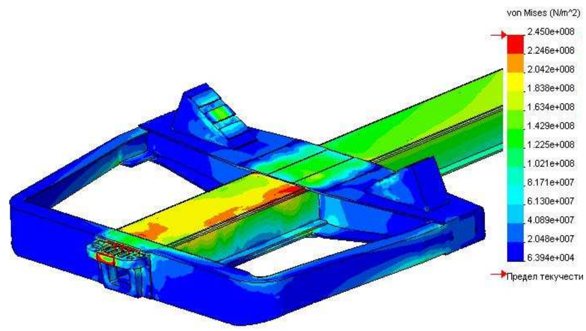


Fig.13. Distribution of FOS (Factor of Safety in the case of Mohr Coulomb criterion) values for the central block of the wall

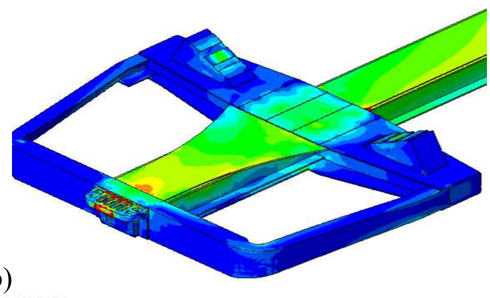
surfaces, main and equivalent stresses, mass etc.). The simplified models are constructed and optimization is performed using the EDAOpt software. The shapes for different criterions (minimum mass, maximum strength according to constraints of thermal conductivity, etc.) using a simplified separately loaded block are shown in Fig.11. The obtained extremes are validated using FE models, and the differences in results are analyzed. In this particular case it is necessary to improve the model of strength analysis. To improve boundary condition impact on the FE model, the calculation was performed on a brick wall and stresses where evaluated in the central block (Fig 13.). It should be noted that the shape of the block can be found relatively simply for different wall types. The discussed methodology leads to significant economy of material and computing resources.

Optimization of the main beam in console part of the tank-car frame

During operating time the tank-cars are subjected to high velocity impacts. Resilient spring friction devices, which absorb longitudinal impacts, are frequently jammed or damaged. At such operational circumstances the strength of the main beam of the tank-car frame is insufficient and as a result high strains, cracks and fractures appear in the console area of the main beam. The implemented shape optimization for reinforcement of the main beam (fig.14) twice reduced stresses allowing significant prolongation of the life-cycle of the tank-car frames.



a)



b)

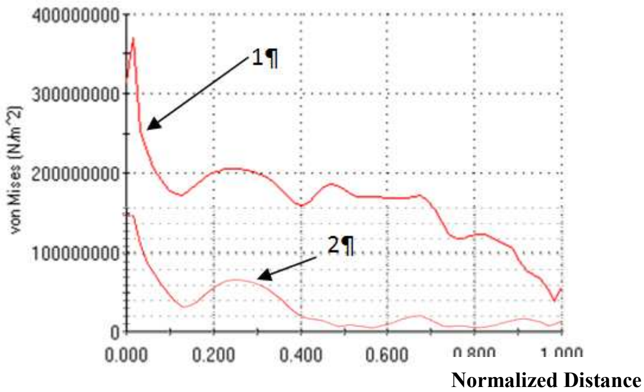


Fig. 14. Comparison of stresses i
console area of the tank-car 15Ц-8
stresses before (a) and 2 - after (b) r

Optimization of technological processes

The developed methodology of metamodeling can be successfully applied to optimization of technological processes. One example is estimation of parameters for the pulling tower (Fig. 15) of optical fibers (Fig.16). Due to changing production configurations (Fig.17), rapid adjustment of optimal technological parameters is necessary. The software tool „Z-Light technologist's assistant" will allow obtaining optimal speed of fiber pulling according to type, shape and dimensions of the work piece (Φ = 10 – 40 mm), fiber shape and dimensions (Φ = 0.05 – 2 mm), work piece feeding velocity (0.1 – 50 mm/min), furnace temperature (~2000°C), fiber coating type (polymer, silicone, etc.), geometry and necessary fiber strength.

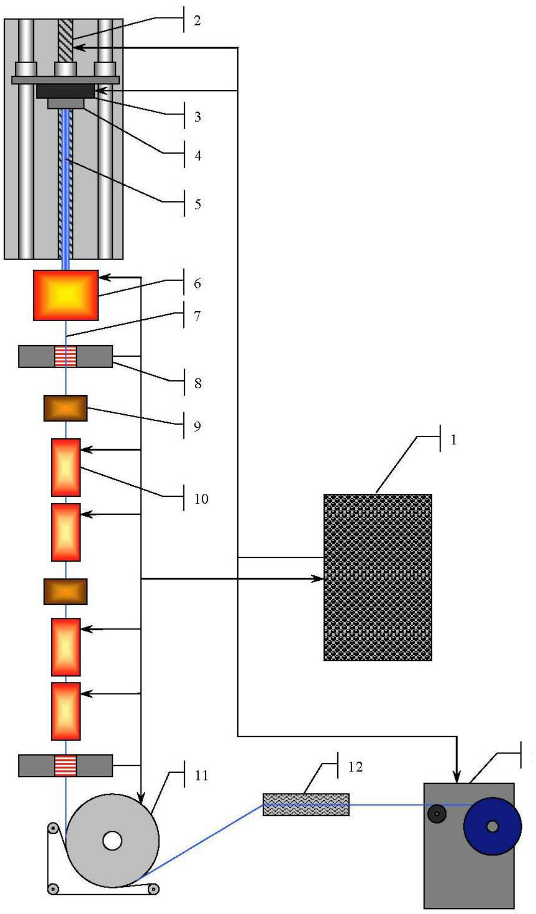


Fig.15. Scheme of optical fiber production line

Fig.16. Optical fiber bundle (Z-Light Ltd)

Fig.17. Some of optical fiber cables (Z-Light Ltd)

Conclusions

Simulation, design of experiments, metamodeling and optimization methods developed in MMD lab have been successfully employed for optimal design of wide range of problems including industrial machines, constructions and technological processes.

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J. Auziņš, A. Boiko, A. Januševskis, J. Januševskis, A. Kovaļska, A. Meļņikovs, J. Pfafrods. Mehānisko sistēmu modelēšanas, identifikācijas un daudzkriteriālās optimizācijas metožu un līdzekļu izstrāde mašīnu un mehānismu dinamikas laboratorijā

Dots īss vēsturisks apskats par RTU Mašīnu un mehānismu dinamikas laboratorijas zinātniskajiem līdzstādniekiem un viņu pētījumiem. Apskatīta eksperimentu plānošanas ideju un izstrādņu attīstība no pirmsākumiem līdz pat mūsdienām. Raksturotas laboratorijā izstrādātās programmatūras EDAOpt pielietošanas jomas. Dots ieskats par pašlaik laboratorijā intensīvi risināmajām mehānisko sistēmu modelēšanas, identifikācijas un optimizācijas problēmām, kas saistītas ar rūpnieciskajiem pielietojumiem. Parādītas moderno aproksimācijas metožu un metamodelēšanas plašās iespējas.

Аузиньш Я., Бойко А., Янушевскис А., Янушевскис Я., Ковальска А., Мельниковс А., Пфафродс Я. Разработка методов и средств моделирования, идентификации и многокритериальной оптимизации механических систем в лаборатории динамики машин и механизмов.

Дан краткий исторический обзор о научных сотрудниках лаборатории Динамики машин и механизмов РТУ и их исследованиях. Показано развитие идей и разработок планирования экспериментов начиная с первых применений до сегодняшнего времени. Дана характеристика областей применения разработанной в лаборатории программы EDAOpt. Вкратце описаны актуальные, связанные с промышленностью проблемы моделирования, идентификации и оптимизации механических систем, которыми занимаются сотрудники лаборатории. Показаны широкие возможности применения новейших методов аппроксимации и метамоделирования.