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Structural optimization in product design process

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1. Introduction

New competitive products must meet the growing market needs. In order to satisfy the market requirements they must be light-weighted, efficient stock-in look. At the same time, the product must be quickly introduced to the market, without the loss of competitiveness.

The computer software and hardware programs are widely applied in each area of modern mechanics, whether it is the car industry, machine tools design or else. On the other hand, these programs are used for speeding up the product development process and, at the same time, to improve the quality and ensure minimal cost of the product. Digital optimization methods can systematically provide the right solutions group. The decisions automatically generating these tasks can give to designer new, previously unused potential solution.

Combined together to develop, design, produce, and distribute their common product, enables engineers to use a virtual prototyping environment more effectively. Engineering in virtual environment helps saving the costs and time of the product and process development [1].

In the design process finite element methods (FEM) can significantly reduce the number of prototypes and expensive experiments and, at the same time, to reduce the time-to-market. Optimization of the new measures will accelerate the product development, improve productivity and make minimum changes in early stages of product development.

Experimental modal analysis is becoming a commonly used technique for studying dynamical behavior of mechanical structures. The problem of extending the concept of modal analysis to nonlinear mechanical systems has been widely studied since the second half of the last century. The first definition of a ‘‘Nonlinear Normal Mode’’ (NNM) of a conservative system [2], according to whom a NNM is a periodic oscillation where all material points of the system reach their maximum displacement at the same instant of time, and they all pass through their equilibrium position at another instant of time more recently; besides this definition was also extended to non-conservative systems. NNM is defined as a motion which takes place on an invariant manifold of co-dimension two in the phase-space. Analysis of natural modes and frequencies is easy to run, but difficult to adjust to reality. In finite element models damping is always an input, so it must be included as an approximate value. However, in real machines damping comes mainly from the contact in the guide ways, where rolling bearings in one case or friction sliding ways in the others include uncertainty in the model. On the other hand, a careful experimental modal analysis can measure the natural frequencies and modes of a just designed real machine with sufficient accuracy, and at the same time could be used for updating the FEM model used in design [3].

Research objective of this paper is a methodology creation to improve the first mode shape of any mechanical product avoiding resonance and using topology optimization. The developed methodology was tested by receiving results of developing and testing a first mode shape of a grinding machine tool.

2. Engineering of product properties and characteristics

A consideration of product properties and characteristics with market needs is related. This may come from external or internal sources [4]. External forcing for a new product may be due to an order from a customer, obsolescence of an existing product, availability of new technologies and change in market demands. Internal to the organization, new product ideas may come from new discoveries and developments within the organization need for a product identified by the marketing department.

Product properties and characteristics are closely related with its value. The value V of a product is defined by the equation [5]

$$V = F / C \quad (1)$$

where F is product functions and performance; C is product cost. Value V aims to obtain the maximum performance for a minimum cost. This procedure employs cross-functional teams to evaluate each step in the product realization process to achieve its aims – design, procurement and manufacturing. Value engineering focuses particularly on the design process, materials used, and the manufacturing process to reduce costs and improve the performance.

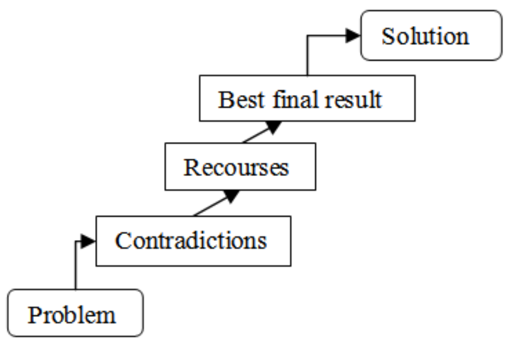

Fig. 1 Features of good solutions

Designer has to feel and to understand the difference between product characteristics and properties. Designer can directly determine the characteristics as creation form, material, dimensions and product structure. Such properties as functions, safety, aesthetics, manufacturing, assembling, testing, environmental properties, cost, etc., cannot be determined directly by the designer. A designer using 3D CAD system may provide geometric modelling of a new product and solve its characteristics determination. There are some additional programming tools as FEM, BOM (Bill of Materials) and DFMA (Design for Manufacturing and Assembling) used in assistance in order to achieve the desired product properties. In most design situations the compromises among product characteristics and properties cannot be avoided. While input data is being different, variation enters into the product design. Production processes do not always make perfect products and, eventually, they introduce more variation and even products defects. In most cases, the quality of product design directly affects its production costs. Making the best choice of the available product and process alternatives is usually finding the trade-offs in each product life cycle stage between characteristics and properties. Trade-offs must be solved while searching for good design solutions and reaching a settlement among properties value and characteristics. The logic scheme for such solution was applied [6]. It suits when product design problems and likely contradictions are known (Fig. 1). The systematic work and employ of idle, easily available resources during product design procedure can clarify contradictions and find the best final result. A good solution resolves the contradiction that is the cause of the problem. There are two kinds of contradictions: trade off contradiction means that if something good happens, something bad happens, too; and inherent contradiction means that one thing has two opposite properties, let say two features – useful and harmful. A conflict between useful contradiction, for instant, machine stiffness that is going to be bigger and then harmful one – machine mass that in logic decision way also is going to be bigger, illustrates the interaction among two contradictions. A bigger mass leads to increased material consumption and, finally, a bigger manufacturing cost that is a harmful product feature.

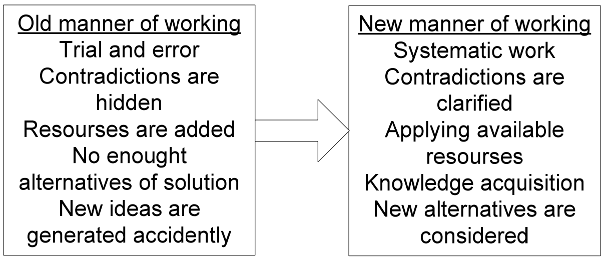

Fig. 2 Reorganization of a creative activity

In order to resolve this conflict, i.e. increase the stiffness, designer has to find a solution how to decrease product mass applying better materials, rational geometrical configuration, exchanging number and layout of design features or at least number of product parts and structure and so on. In general, the best decision making result can be found applying the reorganization of creative activity going from the old way of product and process development to the new one (Fig. 2).

3. Topology optimization

Traditional optimization methods most of deal with geometry optimization problems, while topology optimization has microstructure based on homogeneous approach with density function. The topology optimization approach based on the force flow principle is used to design the forces transport paths in volume-to-point problem. The transport paths are designed by finding optimal patch from uniform or nonuniform force sources. The optimal material designs are obtained by numerically simulating the evolution and degeneration process according to the uniformity principle of the material conditions. The features of optimal designs must be preserved for the convenience of engineering manufacturing. The material is concentrated in the force source regions and it designs several highly effective force transport paths to connect the regions to the outlet. This means that topology optimization forms the microstructure which ensures the better use of material.

Correctly defined topology optimization provides guidelines to the final product model design and is especially helpful while used to batch and mass production. It helps to save costs (material, operational, design of a product and process) while leading to more safe, functional and economical product, both to manufacturers and buyers. Focused on reducing the movable masses, the topological optimization of structural components is a critical issue, because this optimized mass-to-stiffness ratio will be the key to tackle effective strategies to reduce the total masses. Starting from known loads, boundary conditions and the maximum design space available, a design concept of a product which is as light as possible while meeting all requirements on can be obtained. With the aim of supporting this objective, there are commercial programs with optimization algorithms that, starting with a given structural component, remove material from that component until no further removal is possible without deteriorating the static and dynamic properties, thus achieving a topologically optimized component. Besides, an important additional objective of topological optimization programs is to assure that the topologically and dynamically optimized structures could be manufactured in an economic way [7].

Unnecessary product areas are removed from the given design space [8]. The new structure shows an indication of the optimal energy flow. The result of topology optimization serves as a design draft for the creation of a new FE model for the subsequent simulation calculation and shape optimization. This method provides the developer a tool capable of creating a mass-optimized design proposal at development design stage.

Mathematical formulation for topology optimization of a continuum structure, the classical problem of topology design, is a consideration of maximum stiffness of statically loaded linearly elastic structures under a single loading condition. This problem is equivalent to the design of minimum compliance defined as the work is done by the set of given loads against the displacements at equilibrium, which, in turn, is equivalent to minimizing the total elastic energy at the equilibrium state of the structure. This can be verified by considering the work done by given external forces [8].

4. Results and discussion

In the shape optimization problem it must be assumed that the machine components consist of simple geometrical primitives determined by a few design parameters. Therefore, it must be adjusted to all special inputs-outputs and special needs. The adaptive solver guarantees the automatic detection of critical regions and ensures a good approximation to the exact solution of the direct problem. For the big overall dimensions machine small issues may be ignored.

A mode shape represents the relative displacement of all parts of the structure for that particular mode. The actual physical displacement at any point will always be a combination of all the mode shapes of the structure [9].

The main aim of creating single model topology optimization is to decrease design time and to increase model stiffness. The object in this case is to find a design, which meets the requirement of increasing the first shape mode. Topology optimization technology is used to obtain an optimal mechanism layout achieving the best overall system performance. Designing using topology model provides guidelines to the main parameters in early design stage.

In the primary design stages when optimal structure dimensions must be chosen, reaction forces determined, components mass and stiffness balance evaluated, static analysis is used and concept model is created (Fig. 3). The modular design methodology to this aim was employed [10].

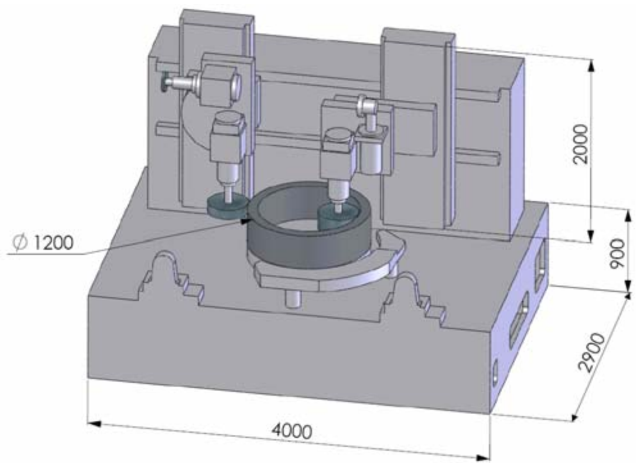

Fig. 3 Concept model

The following requirements were raised for the static analysis as follows:

- to make a FEM for concept design;
- to compare the results obtained from different geometries and different approaches using finite element method calculations;
- to determine the most loaded structure elements and the influence that geometry has for the strength and deformation state, and total displacements of components.

A mode shape is an inherent dynamic property of a structure in "free" vibration (when no external forces are acting and damping is not applied). It is an abstract mathematical parameter, which defines a deflection pattern as if that mode existed in isolation from all others in the structure [11].

A model has a low first shape mode (Fig. 4). Then, in this case, optimized model provides improved first shape mode.

In the planning phase a fundamental object structure can be determined using topology optimization. Starting from known loads and boundary conditions and the maximum design space available, a design concept of a product which is as light as possible while meeting all structural, stiffness and strength requirements can be obtained. This method provides a tool capable of creating a weight-optimized design proposal for the designer and the development engineer, even in the early planning stage [12].

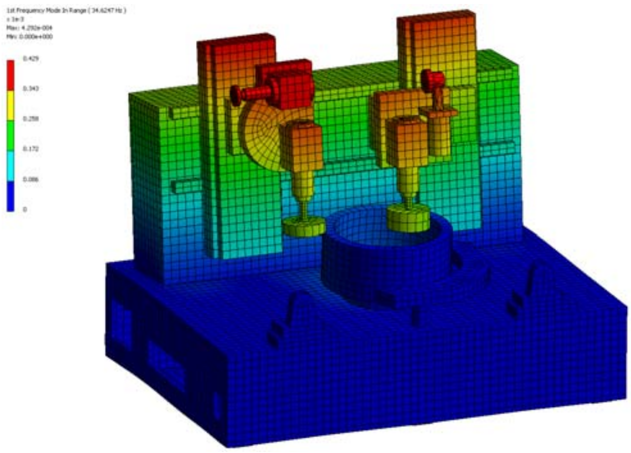

Fig. 4 First shape mode (“bending”) at 34.6 Hz (Ansys)

In this case 2D topology optimization was made with following rules:

a) a preliminary design of material layout in the cross section will be generated;
b) the objective: to increase the natural frequency of the first normal mode by introducing ribs in the designable region;
c) upper bound constraint of 30% for the designable region.

Design variable in expressed by micro structural void sizes and orientation in the design space.

For this 2-D FE model a topological optimization was created (Fig. 5). The first model data, its inputs and outputs chosen designable region, nondesignable and lumped masses was applied to 2D model [13].

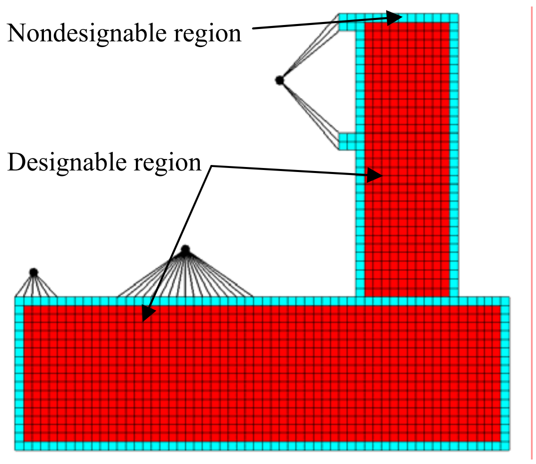

Fig. 5 Model for topology optimization

Topology optimization shows element distribution between work piece *1*, tool unit *2* and machine frame *3* (Fig. 6). Optimized model with adjusted geometry was created applying this data. New model concept increased data for all five modes (Fig. 7).

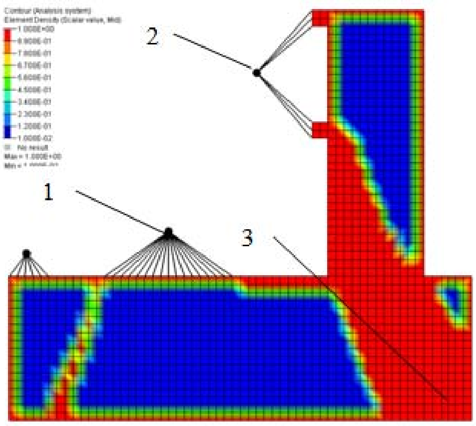

Fig. 6 Distribution of elements density in designable region

This chart shows that going from product mode 1 to mode 5 natural frequencies are increased, due to product model is improved applying received research topology optimization. The modular design methodology to this aim was employed [10].

From Eq. (1) it could be noticed, what value of product functions and performance is increasing, while product cost stays almost the same. From this we can do count what product properties and characteristics increases in compare with the old model.

The grinding machine value index *V* applying Eq. (1) is defined. Product development cost *C* in these calculations, was used as relative cost exchange in percentage developing. Product is going from no optimized to optimized. Value index data is presented in Table.

Table

Value *V* increase (times) depending on mode

	1 mode	2 mode	3 mode	4 mode	5 mode
value *V*, %	1.30	1.36	1.41	1.65	1.94

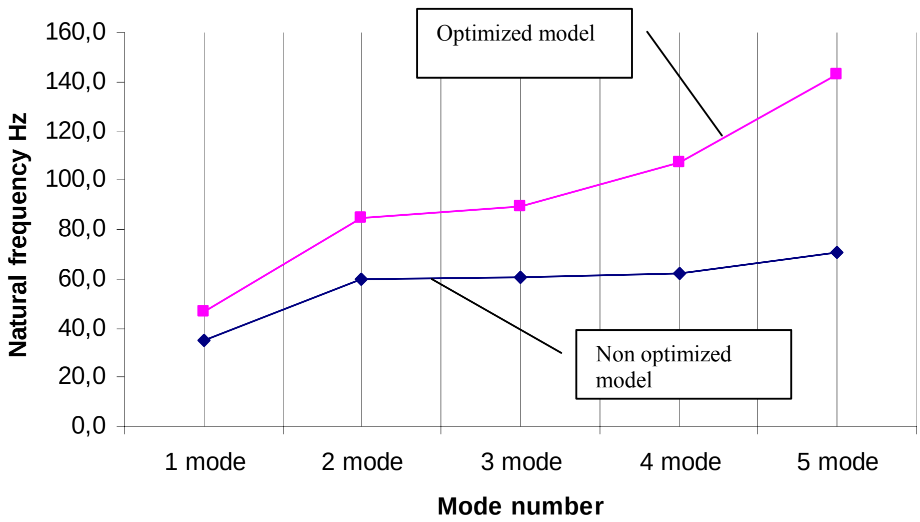

Fig. 7 Natural frequencies of optimized and nonoptimized models graph

5. Conclusions

The created topology optimization method in this paper accomplishes the objective of this research. Briefly, it can be concluded as follows.

1. Topology optimization in early product design stage gives the advantage of narrowing possible design solutions, while ensuring more economical and functional product approach.

2. New model concept has shown the increase of value for 1.30 times in 1 mode; other compared modes have better results up to 1.94.

3. This shows that simple 2D topological optimization and right adoption of its results can improve the model significantly.

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STRUKTŪROS OPTIMIZAVIMAS GAMINIO PROJEKTAVIMO PROCESE

R e z i u m ė

Straipsnyje analizuojama sukurta topologijos optimizavimo metodika ir gaminio specifinių svyravimų formų optimizavimo būdas. Ši metodika padeda optimizuoti produkto matmenis ar savybes. Pradedant nuo žinomų apkrovų ir kraštinių sąlygų bei didžiausios įmanomos dizaino erdvės, 2D topologijos optimizavimas leidžia sukurti produkto koncepcinę struktūrą, kad produltas būtų lengvas ir atitinktų keliamus reikalavimus. Šis metodas padeda produkto kūrėjui kurti lengvos optimizuotos struktūros koncepciją ankstyvajame naujo gaminio projektavimo etape. Sukurta metodika buvo pritaikyta kuriant ir bandant pirmuosius šlifavimo staklių variantus pagal specifines svyravimų formas.

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STRUCTURAL OPTIMIZATION IN PRODUCT DESIGN PROCESS

S u m m a r y

This paper analyzes developed methodology to apply a topology optimization of a product's first shape mode. This methodology helps to optimize the overall dimensions of a mechanical product. Starting from known loads and boundary conditions and maximum available design space, 2D topology optimization leads to the design concept of a product structure which is as light as possible. This method helps the product developer creating a mass-optimized structure proposal at the early new product design stage. The created methodology was tested by obtaining results of developing and testing a first mode shape of a grinding machine tool.

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СТРУКТУРНАЯ ОПТИМИЗАЦИЯ В ПРОЦЕССЕ ПРОЕКТИРОВАНИЯ ИЗДЕЛИЙ

Р е з ю м е

В статье рассматривается разработанная методология применения метода топологической оптимизации первых форм колебаний продукта. Метод позволяет оптимизировать размеры продукта или его характеристики. Начиная известными нагрузками и краевыми условиями, а также максимально возможным пространствам дизайна, 2D оптимизация топологии продукта позволяет создать концептуальную структуру, которая должна быть легкой и удовлетворяющей требованиям. Такой подход помогает разработчикам продуктов построить легкую оптимизированную структуру новой концепции в ранней стадии разработки продукта. Созданная методология была испытана при создании и тестировании первых форм колебаний шлифовальных станков.

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