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Shape optimization of mechanisms' covers

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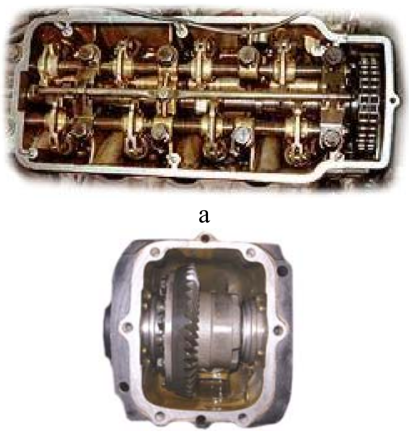
1. Introduction

The current development trend for automotive engines is directed towards increased specific output. The reduced engine weight, manufacturing cost and, last but not least, reduced engine noise is important goals. The mechanisms usually have some sort of covers, protecting them from external factors such as dust, humidity, mechanical interference and other. The same covers play an important role as acoustic shields and vibration dampers, absorbing the mechanism's generated noises [1, 2].

Let's consider a pre-conceived mechanism that needs to be covered by some thin shell structure. The investigated mechanism may contain moving parts that generate noise. It must be handled in one way or other by absorbing, shielding and covering it. Some examples of such mechanisms may be seen on Fig. 1. The numerous possible examples include engine covers, air intake manifolds, the rocker covers, various fan and thermostat housings, also the housings of electronic throttle controls and devices.



a

b

Fig. 1 Examples of the mechanisms that need to be covered and noise-shielded: a - engine head close-up; b - the differential slip mechanism

The achievable noise cancellation level is strongly dependent on the cover design concept [3, 4]. Knowledge about the expected noise characteristics is essential for the specification of appropriate noise and vibration targets for subsystems. After the concept phase is over, the main bounding conditions and the geometry for the mechanism are set constant. This is especially true when several different system suppliers are involved [5].

Here we must go to the model's refinement phase, when we optimize the design in order to minimize the mass or material volume, while maintaining the basic design specifications, such as cover's base line, fixation points, height and other parameters. At the same time, during the optimization, we cannot lose the damping ability of such a cover. The cover's response to nominal excitation must comply with the acoustic requirements, which tend to be stricter each time. That's why we must be able to observe and to control the natural frequencies and vibration modes of the thin shell covers. They strongly depend on shell's design.

2. The modeling approach

The optimization task is to find $b \in Z^n$ and $\omega \in Z^m$, minimizing the objective function $\Phi_0(b)$. Here b are the optimization parameters, and ω are the state variables, Z^n and Z^m are the n- and m-dimensional real number spaces correspondingly. The state equation for vibratory process can be written in form

$$K(b)\varphi = \omega^2 M(b)\varphi \tag{1}$$

subject to constrains

$$\psi(b,\omega) \geq 0 \tag{2}$$

The corresponding quantities may be developed into the following

$$\Phi_0(b) = \Phi_0(b_1, b_2, \ldots, b_n) \tag{3}$$

$$\psi(b,\omega) = [\psi_1(b,\omega), \psi_2(b,\omega), \ldots, \psi_m(b,\omega)]^T \tag{4}$$

The quantities in (1) may be developed into

$$K(b) = [K_{ij}(b)_{ij}]; i,j = \overline{1,l} \tag{5}$$

is the stiffness matrix of the considered structure,

$$M(b) = [M_{ij}(b)_{ij}]; i,j = \overline{1,l} \tag{6}$$

is the mass matrix, and l is the structure's number of degrees of freedom.

Geometrical size limitations for the shell might be present as well – for example, the height of the cover. To begin with, a rough evaluation of the cover's geometric limits must be made. Then the concept refinement phase begins with the initial model taken into consideration, aiming the goal to minimize the cover's mass via its geometric shape modification.

The proposed strategy to find the cover's optimal geometry consists of several key steps:

1. discretization of the mechanism to volumes;
2. initial cover's geometry generation;

3. application of the special technique to initialize and control the shape of the cover during the further optimization;

4. performing the optimization analysis.

Each step will be the object of further discussion.

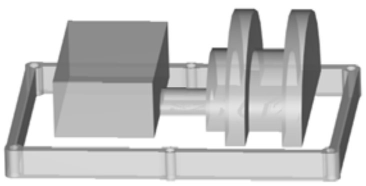
3. Discretization of the mechanism

A part or multiple parts of a mechanism that are not fully enclosed in the base body need to be discretized. That means, the complicated forms of the mechanism must be simplified and described in terms of primitive volumes. The choice of mechanism's discretizing volume is a focal point in this research. It is a very important phase of the whole cover's optimization process, as the chosen discretized geometry of the mechanism will strongly influence the final optimal shape of the cover.

The discretization of the mechanism is to be done using three main primitive volume types: boxes, spheres and cylinders, or parts of them. The guidelines to follow are described below.

First, the chosen volumes must approach geometrically the mechanism from outside as closely as possible, without challenging technological limitations and requirements. Moving parts of the mechanism must fully fit inside the chosen volumes. The chosen primitives must have a minimal volume.

The total number of discretizing volumes must be minimized. The coarser discretization is preferred over the detailed discretization, as shown in Fig. 2. Detailed models would complicate the mathematical part of optimization procedure and would significantly increase the computation time, so the discretization should be made using simpler configurations, where possible (Fig. 2, b or c).



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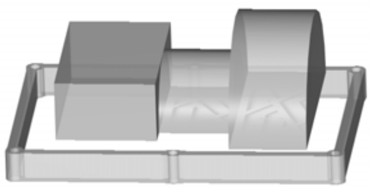

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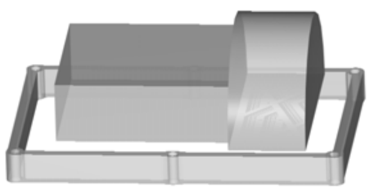


c

Fig. 2 Level of discretization. The more complicated configuration shown in a - should be replaced by the simpler ones, as shown in b or c

The discretizing volumes must not intersect the base body at fixation (cover's ground) level and imaginary walls above it – such a cover cannot be mounted. These requirements are purely geometrical.

All the primitives are then logically united into one body, called "discretizing body". Then, one of the main requirements for such a body is that any ray traced from the origin point may and must intersect the body surface in one and only point. This means that the discretizing body should not have hollow nor heavily concave regions. After the unification of the primitives, the discretizing body should contain minimum possible resulting surfaces. At the same time, some care should be taken to generate neighboring intersection lines of the comparable dimensions. Last but not least, the advantages of the symmetry must be exploited, where possible.

The discretization procedure is based on experience and cannot be strictly expressed in terms of numbers or equations. The result also depends on human factor and the intuition.

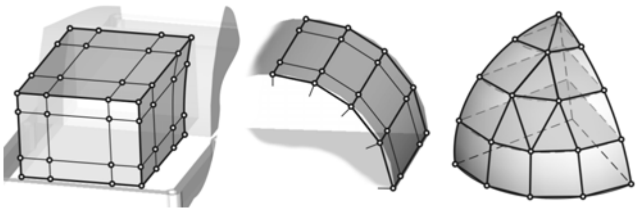
4. Initial cover generation

The second important phase of the proposed cover's optimization strategy is the choice of the initial cover geometry and its discretization. At this point, we have the discretizing body, described as the union of some primitive volumes. Only a part of the body above the baseline of the cover fixation will be taken into consideration.

The initial geometry of the cover is chosen in a way that it replicates exactly the discretizing body that was generated in the first phase. The resulting surface is composed of three types of primitive surfaces or their parts: plane, cylindrical and spherical. This result follows from our previous choice of discretizing primitive volumes.

Since the final optimal geometry of the cover is unknown beforehand, we must provide a general description of the cover's geometry to the finite element software in such a way that it could easily generate any less or more possible shapes during the optimization process. At the same time, it must be able to generate smooth, transitional shapes. To accomplish that, the strategy of optimization points is proposed, relying on the generation of additional intermediate control points on each primitive surface of the initial cover. Each of three types of surfaces has different strategy of choosing the optimization points.

Plane surfaces. The main control (optimization) points are located in the corners of plane areas. Additional optimization points are put at the intersections of auxiliary lines, and also at the intersections of auxiliary lines and the area boundary (Fig. 3, a).



a b c

Fig. 3 Locations of optimization points for various types of surfaces: a - plane, b - cylindrical, c - spherical

As for cylindrical surfaces, the optimization points on plane parts of cylinders are taken following the same procedure as for plane areas. The proposed locations of optimization points for cylindrical surfaces are shown in Fig. 3, b. The number of divisions on the arc of a cylinder depends on desired accuracy.

The choice of optimization points on spherical surfaces is more liberal. An example for a part of a sphere is shown in Fig. 3, c. The sphere is divided into several slices, and several optimization points on each obtained arc are taken. It is in our interest to minimize their quantity, as each additional point weights on CPU time while optimizing.

Additional design points must be taken on the perimeter of the base (body) line, which serves for cover's fixation. These new points are chosen at the minimal distance from the nearest point of the nearest surface. At the same time, the optimization points of the cover at the baseline level are dismissed. Having all these points, we may generate a thin shell model which is composed of numerous triangular or rectangular areas.

5. Optimization

Naturally, each optimization point may move in three directions in space. Multiplying the number of optimization design variables by three is not an attractive perspective. Moreover, it would be very difficult to control mutual positions of the points during the optimization. And finally, geometric limitations for location of the point are quite hard to describe and impose, especially for more complicated discretizing shapes.

Therefore a new strategy is proposed.

The optimization point is considered as an end point of the vector $\overrightarrow{R_i}$, whose origin coincides with the global origin O, which lies at the gravity point of the baseline figure. The optimization point can only be displaced in one single direction, called optimization direction. This direction is collinear with the described vector (Fig. 4).

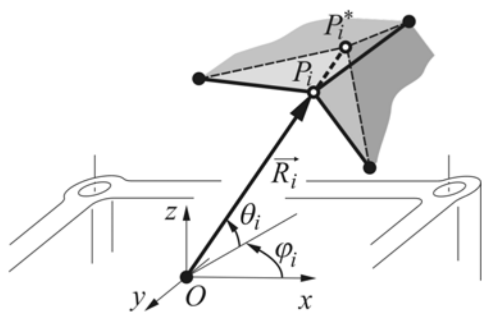


Fig. 4 The optimization point P_i is described by a vector $\overrightarrow{R_i}$ with constant spherical coordinates φ_i and θ_i. P_i^* shows one of the possible intermediate optimization point's P_i locations during optimization

Each optimization point is provided by a constant and individual optimization direction in space, described by spherical coordinates φ_i and θ_i. As the method requires choosing the points on the mechanism's discretizing volume's surface, this is the limit position for the optimization point, and the minimum length for the vector $\overrightarrow{R_i}$. One single common origin should be taken for all optimization points (though several origins may be present in special cases).

The designed cover will serve as an acoustic shield for the mechanism beneath. Each mechanism has its nominal frequency or several frequencies, or a frequency range that is the most probable while functioning. It is our interest to design a cover that would not resonate at these working frequencies. That means, we must choose the state variables outside of normal functioning frequencies of the mechanism. Therefore, state variables the optimization procedure are the first m natural frequencies in working range.

As it was discussed before, the optimization objective function is to minimize the mass of the cover. We consider only the covers with uniform and constant thickness of the walls. In this case, the cover's mass will be directly proportional to its surface area, and the objective function will be

$$\Phi = min\ A(k_1 ... k_n) \tag{7}$$

subject to constrains

$$1 \le k_i \le k_{i\,max},\ i = \overline{1, n} \tag{8}$$

and state variables

$$\omega_{j\,min} \le \omega_j \le \omega_{j\,max},\ j = \overline{1, m} \tag{9}$$

yielded by the structure vibrations equation

$$[K(k)]\varphi = \omega^2 [M(k)]\varphi \tag{10}$$

Here n is the number of optimization points, $k_i = OP_i^* / OP_i$ is the scaling factor for the i th optimization vector (Fig. 4). So the optimization variables are relative elongations of the optimization vectors.

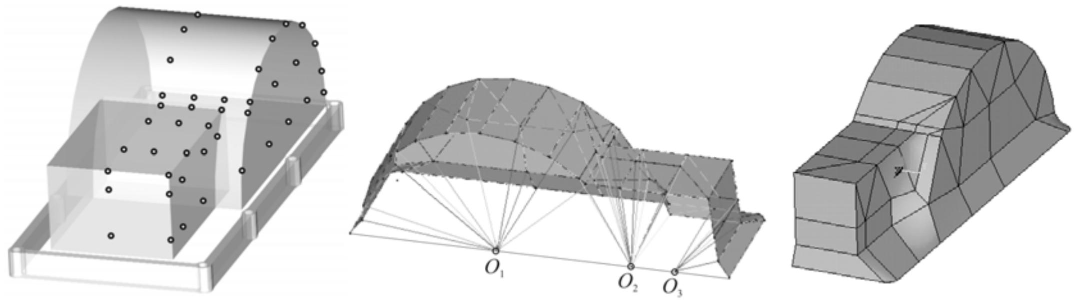
We may freely choose the software and the optimization method for performing the optimization analysis. In most cases, finite element modeling software producers offer one or several algorithms for analysis. A multi-parameter optimization tool is necessary.

6. Example and results

Let us optimize a cover for a mechanism that may be similar to the one shown in Fig. 1, b. To begin with, the underlying mechanism is discretized by volumes (seen in Fig. 5, a. The initial cover is generated, and the optimization points are chosen on its walls. The optimization points on the baseline level are replaced by constant points on fixation perimeter of the cover (Fig. 5, a). We choose three different origins for optimization vectors for groups of nearly located points to describe better their optimization directions (Fig. 5, b). The shell's symmetry condition can and will be applied while modeling.

The final step is to produce the initial cover that is composed of plane triangular and rectangular areas (Fig. 5, c).

To illustrate the method we use the "Ansys" finite element modeling software. The method used is a first order approximation, where linear search step for each design variable gradient calculation is performed [6]. The task in this case is to minimize the mass of the cover, while maintaining ω_1 higher than the first natural frequency of the non optimized cover.

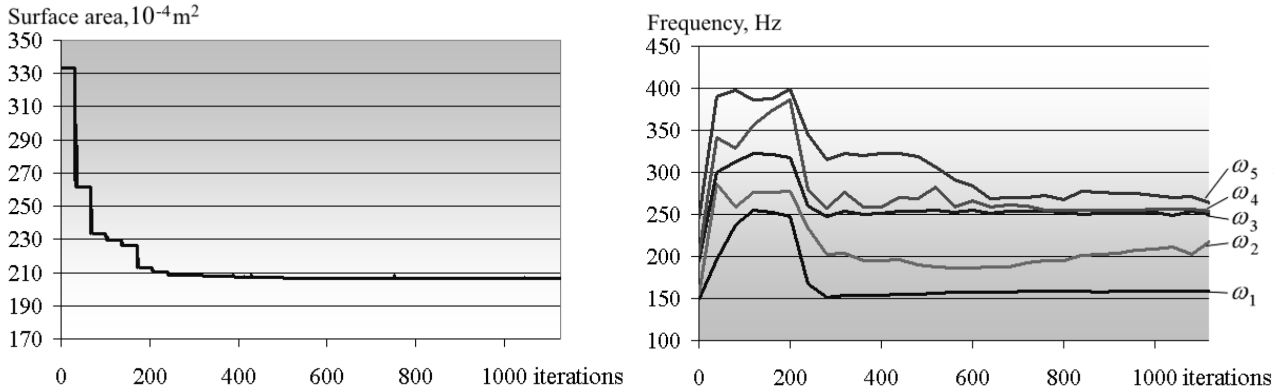


a b c

Fig. 5 Example of initial cover's generation process: a - the choice of discretizing volumes and the locations of optimization points; b - three origins and the optimization directions; c - discretization of the initial into triangular and rectangular areas

We have two discretizing volumes, for mechanism with base length approximately 23 cm, width 12 cm, and height 9 cm. A triangular "SHELL63" element type is used, which provides six degrees of freedom at each node, *ux*, *uy*, *uz*, rot*x*, rot*y* and rot*z*. Nylon is supposed as the material for the cover, with Young's modulus 2100 MPa, Poisson's ratio equal to 0.4, the density equal to 1140 kg/m^3. Nylon is one of the most frequently used materials for such type of covers. The total of 38 active optimization points (and therefore 38 optimization variables) is generated on 5 primitive surfaces.

After the optimization procedure, the final shape of the cover let us reduce the surface area, and the mass of the cover by 36%, while maintaining its first vibration frequency ω_1 6-7% higher than the initial one (Fig. 6). The optimization routine completed as the objective function change was lower than its tolerance between iterations (10^5 cm^2) and between design sets 31 and 32.



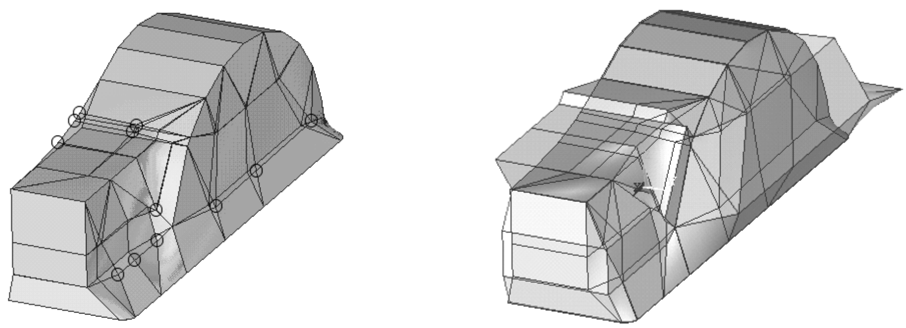
a b

Fig. 6 Changes of: a - surface area (the objective function); b - first five natural frequencies of the cover during the optimization process

With no additional expense, we may operate with the second, third and other frequencies as state variables of the optimization routine, in order to fulfill special required damping features of the cover.

The optimal shape of the cover is just slightly different from its initial state, but it enables us to reduce its mass by more than one third.

Superposition of the final optimal shape versus its initial state is presented in Fig. 7, a. The most significant changes occur at the places where volumes intersect, and near the clamping perimeter of the cover (these optimization points are marked by circles). We see also that optimization points located at the top edges of the cover remain at their initial positions.



a b

Fig. 7 Superposition of initial and optimal shapes of the cover: a - all optimization variables initialized at their minimum values, the most significant changes are encircled; b - all optimization variables are initially at their maximum values (for control purposes)

The other areas tend to form a sleek and fluent design that covers the discretizing volumes in a vacuum packaging style.

Just for control reasons, the initial values for optimization variables were changed to their maximum values. This generates a large initial cover shown in Fig. 7, b.

Using the same software and optimization procedure, the same final result was received as in previous case. Though the optimization takes considerably more time in this case, nevertheless all the optimization variables take almost the same final values, and the cover obtains the same final shape (Fig. 7, b). This is a remarkable result for multi parameter optimization.

7. Conclusions

Assuming the above discussion and presented results, several main conclusions may be drawn. First, and most important, the presented method may be successfully employed for the optimization of the covers of preconceived mechanisms. The method for cover's shape optimization presented here can decrease noticeably the final mass of the cover, while maintaining its natural frequencies in the initial or given range.

The proposed method allows reducing the number of optimization variables by a factor of three, and therefore decrease the CPU time by even more, depending on optimization routine used.

Overall, the stability of such a modeling approach is very high, compared with the traditional three-dimensional point displacement description. The shape generation stability and quality leaves the traditional methods far behind.

One of the main advantages of this method is the software-independent approach. The convergence relies on the optimization software and its internal numeric routines, so the finite element modeling software must have a reliable multi parameter optimization tool. The method relies on changing locations in the space of multiple control (optimization) points, that's why some recommendations presented above must be followed.

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OPTIMALUS MECHANIZMŲ GAUBTŲ PROJEKTAVIMAS

R e z i u m ė

Straipsnyje pateikiama originali mechanizmų gaubtų optimizavimo metodika. Optimizavimo tikslas yra sumažinti akustinių ekranų masę, išlaikant jų dinamines savybes, kad mechanizmo darbo metu jie nesusižadintų patys, o jų savųjų virpesių dažniai išeitų už mechanizmo darbinių dažnių zonos.

Pateikiama optimizavimo strategija yra nepriklausoma nuo programinės įrangos pasirinkimo. Ji leidžia žymiai sutrumpinti optimizavimo laiką, tuo pačiu metu padidinant gaubto geometrijos generavimo stabilumą optimizavimo proceso metu.

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SHAPE OPTIMIZATION OF MECHANISMS' COVERS

S u m m a r y

This paper presents the method for cover's shape optimization whose objective is to decrease the final mass of the cover, while maintaining its natural frequencies in the initial or given range, out of nominal frequencies' range of the functioning mechanism.

The presented optimization strategy is software-independent. It permits to improve the stability of cover's shape generation process and to diminish the convergence time during the optimization process.

Д. Дагис, В. Осташевичюс, Р. Гаидис

ОПТИМАЛЬНОЕ ПРОЕКТИРОВАНИЕ АКУСТИЧЕСКИХ ЭКРАНОВ

Р е з ю м е

В настоящей работе приведена оригинальная методика проектирования акустических экранов. Цель оптимизации состоит в том, чтобы минимизировать массу экрана, в то же время, контролируя динамические характеристики экрана, чтобы он не резонировал при работе механизма.

Предлагаемая стратегия не зависит от выбора программного обеспечения. Она позволяет значительно ускорить конвергирование в процессе оптимизации, и улучшить стабильность процесса генерировании геометрии экрана.

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