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Structural Optimization of Long and Flexible Composite Cover with Topography Method and Examination of Frequency Values

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Abstract

In this study, the finite element model of the long, thin, and flexible carbon fiber reinforced composite cover design prepared using the Unigraphics NX program CAD module was analyzed in ANSYS program. Topography optimization was performed by transferring the analysis results to the GENESIS program. The cover rib created after optimization was combined with the initial design, and necessary corrections were made in the design based on the topography guide. The rib design, created by conventional methods, weigh the same as the optimum design, is combined with of the initial design. Modal analysis of initial, conventional rib and optimum rib design was performed in ANSYS environment. When the findings were evaluated it was observed that the composite cover, which was remodeled after topography optimization, increased by 33.3% compared to the initial design, while its natural frequency (mode 2) increased approximately 1.6 times. In addition, the lowest moment of inertia value has been obtained in the cover design with optimum design geometry. Then, the conventional design, which has the same mass as the new design, was compared and it was revealed by the data that the new design was more resistant. According to the results obtained, the most suitable rib geometry to be preferred for this and similar types of long and flexible structures to have a more resistant structure has been determined.

Keywords: Topography, optimization, composite, design, modal analysis, frequency

1. INTRODUCTION

In the production process of a product, parameters such as cost, quality calculations, appropriate material usage, and environmental compatibility should not be ignored [1]. In addition to the aesthetic appearance of the designed and produced products, the strength of the parts is also of great importance, especially in the defense, aviation and space industries. Today, one of the most emphasized issues in terms of

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product features needed in these sectors is the weight / strength ratio [2, 3]. Most of the technological work being done is about reducing this rate to as low a level as possible. In line with these demands, the design should be well formed in order to make the parts lighter and more durable [4].

For a technological product, after the conceptual design is revealed, moves on to the stages of design analysis and optimization processes [5]. In addition to durability analysis, kinematic analysis, analysis of factors affecting product quality, assemblability, and manufacturability analysis are also carried out at this stage [6].

Computer-aided engineering (CAE) software is used for analysis and optimization [7-9]. At this stage, the simplified model is subjected to structural analysis (finite element analysis) by dividing it into a finite number of elements. In addition, the optimization process can also be performed to reveal the optimum design at the conceptual stage. At this stage, a conceptual design that can form the basis for the final design is created by using different software with a wide variety of algorithms. Optimization is an important step in the design process. The optimization process can be described as selecting only one of them by creating different design alternatives throughout the process.

Structural optimization involves optimizing the target function by covering the other boundary conditions along with the structural conditions such as weight, cost, fundamentals of target functions such as stiffness or manufacturability, size, highest allowable stress, and largest acceptable weight [10]. Optimization techniques can be classified into three main groups as topology, shape and size optimization. Developed new optimization techniques can be listed as topometry, topography and freeform. Topology optimization is the technique of finding the optimum material distribution. In the defined design area, the most suitable structure is prepared and the form of the part is determined [11-13]. Size optimization is an optimization technique that enables obtaining the most appropriate dimensions of any part such as shells, bars and composites [14]. Shape optimization allows the user to obtain the best possible fit. The program determines the form of the structure by discovering the most accurate position of the nodes [15]. Topometry optimization ensures the best material distribution in the structure. Freeform optimization obtains the most appropriate arrangement of elements such as bars in order to increase the stiffness of the structures [16].

Topography optimization finds the most suitable shape and region for the distribution of reinforcement elements to stiffen their plate-like structures. Topography optimization is a special case of shape optimization. Topography optimization is mostly applied to thin & wide parts. Topography optimization is an advanced form of shape optimization. It provides rib-based shape changes in certain areas on the structure. These changes help to create the rib pattern that will optimize the stiffness of the piece and the area where it will be located [17]. The topography optimization technique is very similar to the technique used in topology optimization except that shape variables are used more than density variables. When determining the optimization method to be chosen for the part, the methods by which the part will be produced are also important. Therefore, the structural optimization method can be used according to production methods such as deep drawing, casting, and extrusion. Topography optimization can be applied to deep drawn and cast parts.

Optimization methods are generally used to increase the rigidity or strength of a part. Basic design and rigidity can be applied in all optimization methods. The purpose for which the optimization methods can be used is specified in Table 1 [16].

Table 1 Optimization technique and objective function table

Structural Optimization Type	Strength	Final Design	Strengthening	Joining (welding)
Size	+	+	+	Rarely
Figure	+	+	X	X
Topology	X	Rarely	+	+
Topometry	X	Rarely	+	+
Topography	X	Rarely	X	X
Free Shape	X	Rarely	X	X

There are many studies on optimization in the literature. Leiva, demonstrated in his study that the stiffness of a car body can be greatly increased without adding too much mass by using structural optimization techniques. GENESIS software was used for this optimization [16]. Dutta, increased the stiffness of the structure by increasing the frequency of an automobile door by 10% using topography optimization in his study [18]. Darge et al., in their structural optimization study, increased the stiffness of the structure with the reinforcing form they made on a suspension arm with topography optimization. Compared to the old design, they both decreased the stress levels and increased the mod 1 frequency of the structure [19]. Balkan, in his study, achieved lightness and durability by optimizing various parts of the N3 / M3 commercial vehicle seat with the topography method. As a result of the study, approximately 7% (3818 grams) of lightness was obtained in the driver seat [20]. Polavarapu et al., in their studies, achieved a reduction of 29% compared to the first design by applying shape and topology optimization to the back frame structure to be produced as a casting for the seat that provides ECE17 regulation [21].

The examination of dynamic properties of systems in the frequency domain is carried out by modal analysis [22]. Vibration, which is a sub-branch of dynamics, deals with repetitive movements. Vibration is undesirable and in some cases destructive to many mechanical systems. Vibration is expressed as the repetitive motion of objects relative to a fixed reference axis or a nominal position. The theory of vibration deals with the oscillatory motion of bodies and related forces. The oscillating motion seen in Figure 1 is called harmonic motion [23].

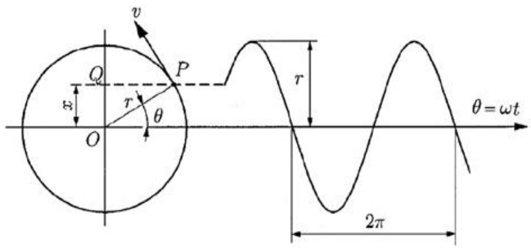

Figure 1 Simple harmonic motion

Harmonic motion is expressed by the formula below. In the equation, X is the amplitude of the motion, ω is the frequency of the motion and t is time [23].

$$(t) = X \cos \omega t \quad (1)$$

Nowadays, composite materials have gained an important place with the development of materials technology and the need to improve product properties [24-26]. Composite materials are defined as materials created by combining two or more materials at a macro-level and have new properties [27, 28]. The advantages of composite materials can be listed as high strength, high rigidity, low weight, high fatigue strength, high wear resistance, high corrosion resistance, thermal and thermal properties in the desired direction, and aesthetic appearance [29-31]. The disadvantages are the higher cost, processing difficulties, generally the absence of recycling, low fracture elongation, production difficulties for some composites compared to metals. Usage areas are; aviation and defense industry, maritime transport, land transport, space programs, energy sector, infrastructure products, building / construction, sports products, household products, tanks and pressure vessels [32-34]. As a result of the research in most of the studies on both structural optimization and composite materials, it has been determined that the modal analysis method is used to examine the part behavior.

Composite materials consist of three basic phases: matrix, continuous and main. The matrix phase holds the aquarium phase together and they share the load. The reinforcement phase is the secondary phase in the matrix, it increases the strength and rigidity of the matrix. The interface is the phase between the matrix and the reinforcement phase [35, 36]. This phase determines adhesion. The composite material structure is shown in Figure 2.

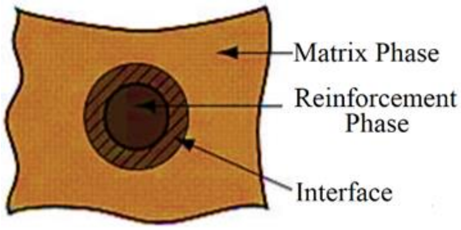

Figure 2 Composite material structure

Atlıhan, studied computational and experimental modal analysis on delaminated composite structures with different orientation angles consisting of 16 layouts. He observed the dynamic behavior of the structures according to the orientation angle change and the delamination condition. He used ANSYS software for analysis studies [37]. Khorshid et al., performed the hydrostatic vibration analysis of rectangular composite plates with fluid contact by using Rayleigh-Ritz method. Using the numerical data they obtained, they investigated in detail the effects of different variables such as thickness ratio, aspect ratio, boundary conditions, orientation angles on the result [38]. Choudhury et al., while analyzing composite plates under the effect of thermomechanical load, examined the effects of layer stiffness and layer orientation angle changes on vertical displacements. They used ANSYS software in their studies [39].

In the literature research, it has been observed that many studies have been done and are still being done to increase the strength of the structures. When we look at the studies in the literature, it is seen that most of the studies are about to reduce the weight / strength ratio of the structures. The resource research carried out, it was determined that topology and topography optimization methods were used effectively especially for parts used in the automotive industry. It has been observed in the literature that many studies have been and are still being done for the proper design of layered composite materials.

In this study, the optimum design of a cover with a large surface where the vibration parameter is critical is aimed. The usage of this designed piece in the defense industry, being an industrial design product and made of laminated composite material can be considered as a part of its difference from the studies in the literature. Topography optimization was applied to the designed part and the behavior of the structure in the system was examined according to the material characteristics. Cover designs with different characteristics were evaluated by obtaining frequency values with modal analysis. No such study has been found in the literature and this issue has been clarified.

2. MATERIALS AND METHODS

With the acceptance that the lack of rigidity at a level that would adversely affect the performance of the covers in the existing systems in use is the most obvious indication that the study has become mandatory, topography optimization was made on the cover structure, and the optimum rib geometry was obtained by evaluating the obtained data. Then, modal analysis was applied to the final rib design geometry to observe the performance of the structure. In addition, the modal analysis results of a conventional rib geometry modeled with the optimum rib geometry were compared, thus supporting the optimization results. Thanks to the studies, the ideal rib shape for this and similar products has been determined. Each stage and scope of the study has been examined under subheadings.

2.1. Purpose Function

Increasing the stiffness of the protective cover is the purpose of the optimization study. This can be achieved by obtaining a design that can behave rigidly against the loads on it with minimum material for the existing structure.

2.2. Design Variables and Boundary Conditions

The first of the design variables in this study is the shape of the design geometry structure. The decisive factor here is to create the most suitable design form for the building. Every structure has a natural frequency. These frequencies, defined as modes, are used to determine the dynamic characteristics of the structure. A state of resonance arises when the natural frequency of the structure coincides with an effect of the same frequency. As the shape of the structure changes, so does the center of gravity and inertia. With the optimum geometry, the highest natural frequency of the building is determined.

In this study, the size of the piece is a design constraint. The area to be covered in the system has been requested to be limited to at least 354x1710x234 mm and is shown in figure 3.

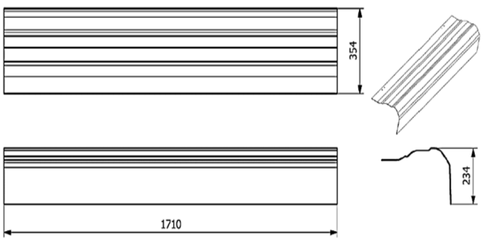

Figure 3 Long and flexible cover dimensions

2.3. Material Properties and Initial Design

According to the usage conditions of the part, different laying angles were determined in each paving layer by using resin-impregnated one-way carbon fiber (prepreg) materials to reduce the effect of vibration loads on the part. Laying angle arrays were made using the rules that took place in the literature under the main title of the design rules of layered composites [40-42]. In this way, it is aimed to increase the strength. The mechanical properties of the material are given in Table 2.

Table 2 Unidirectional carbon / epoxy prepreg material properties from ANSYS Workbench

Parameter	Symbol	Carbon prepreg
Elasticity Module (0°)	GPa	121
Elasticity Module (90°)	GPa	8.6
Slip modulus	GPa	4.7
Poisson's ratio	-	0.27
Density	g/cc	1.49

Multi-layer composite board is created by superimposing orthotropic single layer composite plates with different fiber directions. A total of 7 layers of symmetrical laying has been made with each layer thickness of 0.48mm, and the laying directions are shown in Figure 4.

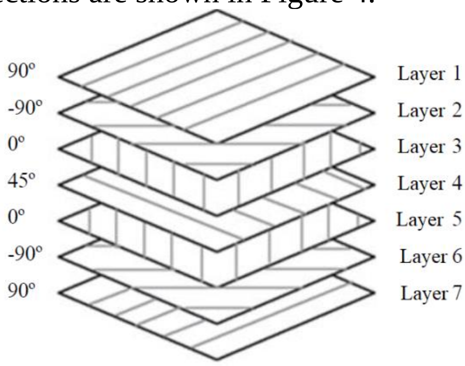

Figure 4 Composite material laying angles

The cover was originally designed without ribs. Figure 5 shows the inner and outer surfaces of the cover.

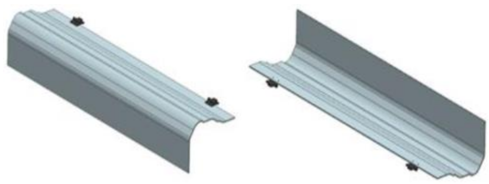

Figure 5 Initial design model

2.4. Modal Analysis with ANSYS Software

The finite element model was used as the analysis method in the optimization study. The finite element model was created in ANSYS program. The protective cover designed with the NX CAD program has been transferred to the ANSYS program with STEP (STP) extension. Then, mesh is applied to the model. Typically the surface, element shape is predominantly quadrilateral. According to the size of the part, the mesh gap value was chosen as 5 mm in order not to increase the processing time excessively. Figure 6 shows the mesh quality of both the inner and outer surfaces of the part. Element and node number values of the model used in the study are given in Table 3.

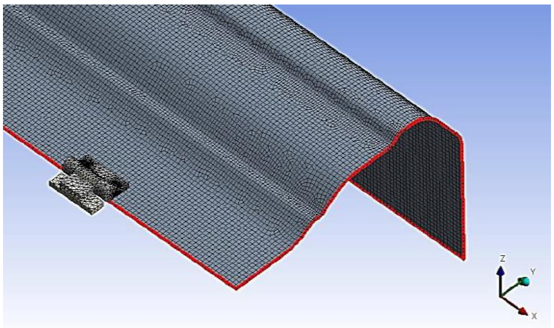

Figure 6 Finite element model of a long and flexible composite cover

The cover and the hinge movable lug are defined as fixed joint and can be seen in Figure 7.

Table 3 Number of elements and nodes of the model

	Modal Analysis
Elements Number	54138
Nodes Number	112859

It is connected as a revolute joint between the movable hinge part and the fixed hinge part. In revolute joint connection, only rotation on the rotation axis (x axis) is allowed and is given in Figure 8.

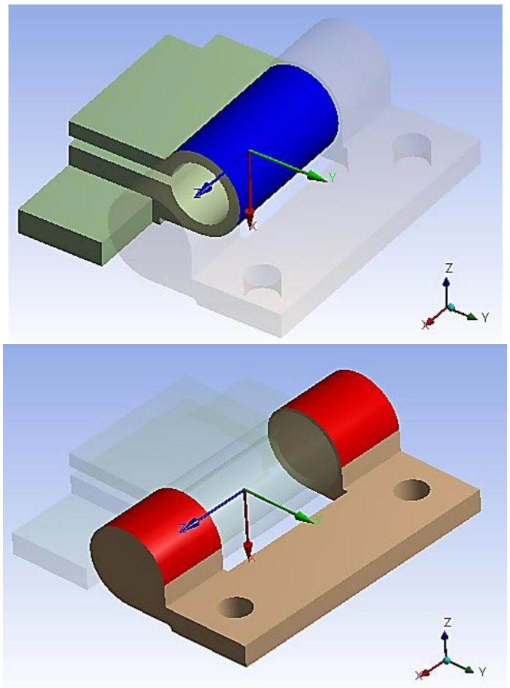

Figure 7 Hinge movable lug and door and non-moving hinge connection

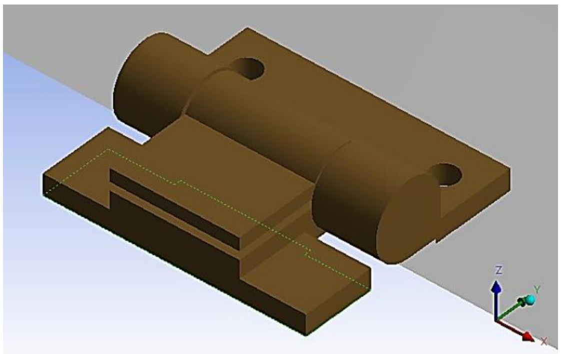

Figure 8 Fixing the fixed lug of the hinge (fixed support)

After these processes, a modal analysis was performed to give the part the first six modes. The part is considered to be vibrating freely with no force applied.

2.5. Topography Optimization with GENESIS Software

Topography optimization was carried out in GENESIS, a fully integrated finite element optimization package. The model, together with the analysis results, was transferred from the ANSYS program to the GENESIS optimization program. In this program, since the boundary conditions and relationships used for analysis are transferred automatically, optimization was made directly without the need for redefining. The optimization goal is to maximize the frequency of the building in mode 2. No boundary condition will be used and conical geometry type topography optimization is applied. The geometry (colored in red on Fig. 9) and the initial design (colored in gray on Fig. 9) formed after optimization are shown in Figure 9, as superimposed.

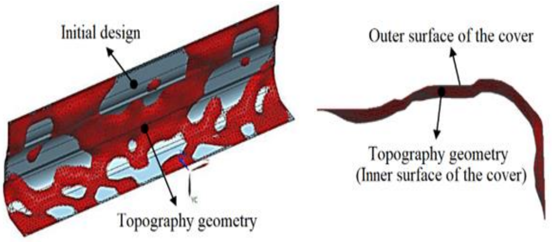

Figure 9 Rib and initial design image after optimization

2.6. Optimum Design Model

Considering the obtained geometry, current technology and manufacturability, it was seen that the production of the proposed hills and valleys, as well as their effects on the functionality of the area where the cover will be used, will not be suitable for the target. Therefore, the initial design and the geometry that emerged after the optimization were overlapped and the topography on the inside of the composite cover was taken as a guide and the rib design as shown in Figure 10 was made.

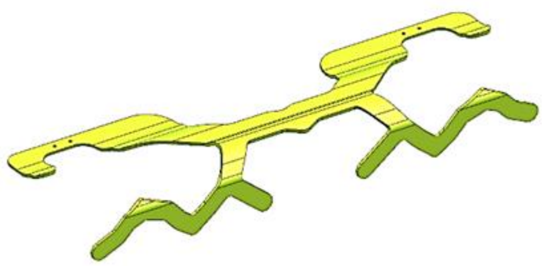

Figure 10 Rib design geometry

Rib thickness is determined as 3.36 mm as in the plate and has the same layer and laying angles. Modal analysis has been applied to the composite cover whose design has been updated according to the optimization results and is shown in Figure 11.

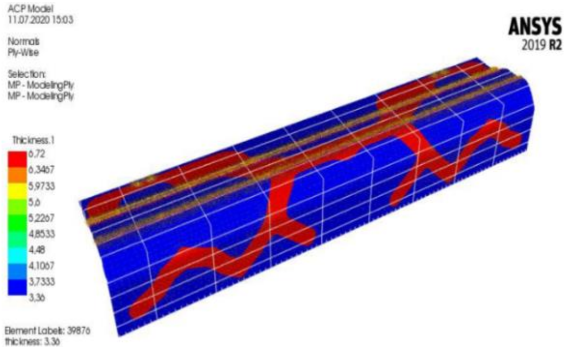

Figure 11 Final cover design with ribs added

2.7. Production Method for Composite Cover

For the production of the final cap with ribs, a master model suitable for the geometry should be designed first. After the master model is produced from wood, a mold must be produced using this model. The master model should be designed according to the outer surface of the cover, because if it is removed from the master model, the inner surface of the mold is a reference in the production of the product and provides an increase in the quality of the outer surface of the cover. It is thought that the rib geometry of the produced part will be painted according to RAL 1024 and other regions with RAL 6025 coded color.

2.8. Initial, Conventional and Optimum Cover Design

The weight of the cover was calculated to be approximately 6.4 kg with the optimization studies performed as a result of the evaluation of the data obtained. Modal analyzes were conducted to compare post-optimization design, conventional design and initial design. The most important point found is that the conventional rib geometry has the same weight as the geometry that arises after optimization. All of the other analysis parameters (mesh spacing, contact and boundary conditions etc.) were selected for the post-optimization geometry to be the same as the parameters used in the analysis.

As can be seen in Figure 12, a conventional rib geometry with a weight of 6.4 kg has been modeled.

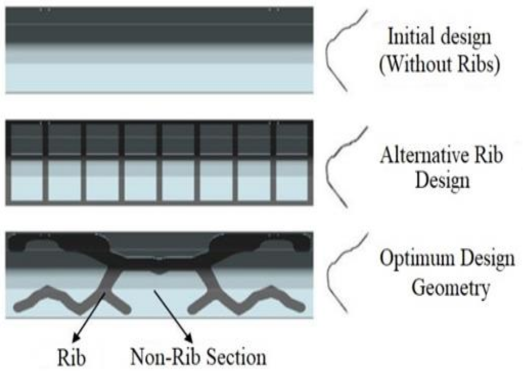

Figure 12 Initial and optimum design geometries

3. RESULT AND DISCUSSION

The effect of the rib shape, center of gravity and mass moment of inertia values on the covers with different rib geometries on the modal analysis using the same analysis parameters was evaluated. The effects of the angle orientations and the angle orientation sequences on the mode 2 natural frequency of the door were observed on the composite structure which has 7 layers in the non-rib part and has 14 layers in the ribbed part and the analysis results were evaluated.

In Figure 13, the natural frequency values of the first six modes of the initial design are given. According to the results obtained in the analysis, the mod 1 natural frequency of the structure is 0 Hz, the mode 2 natural frequency is 4.4 Hz, the mode 3 natural frequency is 23.7 Hz, the mode 4 natural frequency is 29.3 Hz, the mode 5 natural frequency is 39.1 Hz, the mod 6 natural frequency were found to be 47.7 Hz.

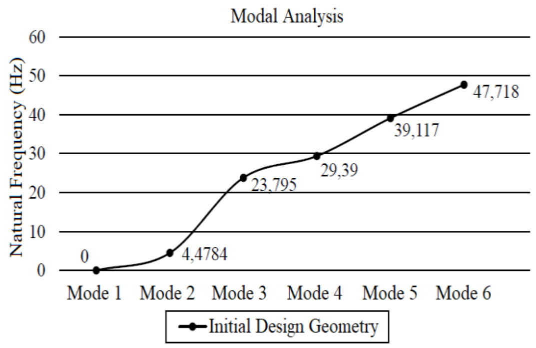

Figure 13 Initial design modal analysis results

In Figure 14, the natural frequency values of the first six modes of alternative (conventional) rib geometry are shared. According to the results obtained in the analysis, the mod 1 natural frequency of the structure is 0 Hz, the mode 2 natural frequency is 6.4 Hz, the mode 3 natural frequency is 28.4 Hz, the mode 4 natural frequency is 37.8 Hz, the mode 5 natural frequency is 47.1 Hz, the mod 6 natural frequency were found to be 59.3 Hz.

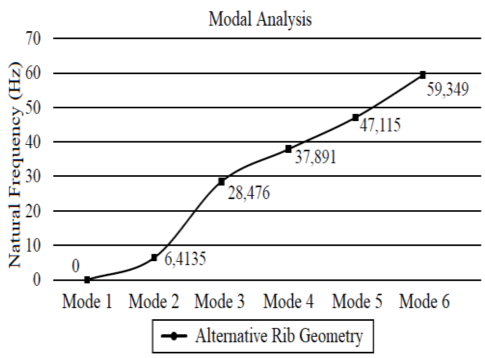

Figure 14 Alternative rib geometry modal analysis results

In Figure 15, the natural frequency values of the first six modes of optimum design are shared. According to the results obtained in the analysis, mode 1 natural frequency of the structure is 0 Hz, mode 2 natural frequency is 7 Hz, mode 3 natural frequency is 29.1 Hz, mode 4 natural frequency is 37.6 Hz, mode 5 natural frequency is 48.1 Hz, mode 6 natural frequency was found to be 64.9 Hz.

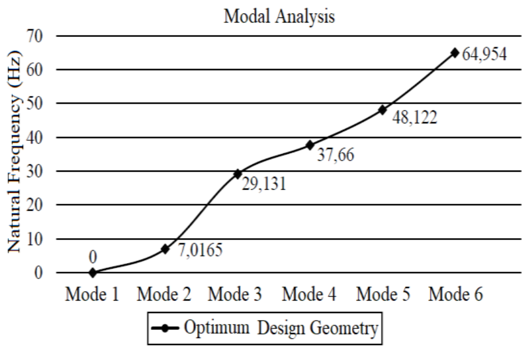

Figure 15 Modal analysis results of the valve with optimum rib geometry.

For the long and flexible composite cover whose design was updated after the optimization in Figure 16, the results of the modal analysis using ANSYS software is revealed. 1. mode (a), 2. mode (b), 3. mode (c), 4. mode (d), 5. mode (e) and 6. mode (f) figures are given.

In the form of the 1st mode, the part gave the reaction that can be described as the 1st bending. In this mode, the greatest deformation has been observed at the farthest point (red area) of the part's rotation axis. The part in the form of the 2nd mode gave the reaction that can be described as the 1st torsion. In this mode, the greatest deformation has been observed at the farthest and the extreme point (red area) of the rotation axis of the part. In addition, as the natural frequency of the structure increases compared to the initial design, the deformation value has decreased. In the form of the 3rd mode, the part gave the reaction that can be described as the 2nd bending. In this mode, deformation is more irregularly distributed compared to the first bending case. In this mode, the largest deformation has been observed in the middle part (red colored area) and in the farthest section from the rotation axis of the part. In addition, as the natural frequency of the structure increases compared to the initial design, the deformation value has decreased. The part in the form of the 4th mode gave the reaction that can be described as the 2nd torsion. In this mode, deformation is more unevenly distributed compared to the first torsion case. In this mode, the greatest deformation has been observed in the farthest and end regions (red colored area) of the part. In addition, as the natural frequency of the building increases compared to the initial design, the deformation value has decreased.

In the 5th mode shape, the part produced a mixture of bending and torsion. In this mode, the greatest deformation has been observed in the farthest and end regions (red colored area) of the part. In addition, as the natural frequency of the building increases compared to the initial design, the deformation value has decreased. In the 6th mode, the part reacted as with a mixture of bending and torsion. In this mode, the most distant to the rotation axis of the part and the largest deformation in the middle (red colored area) has been observed. In addition, as the natural frequency of the structure increases compared to the initial design, the deformation value has decreased.

The purpose of increasing the mode 2 frequency value in the optimization goal is to have the first and smallest natural frequency value mode 2. Mode 1 frequency is neglected because it comes to 0 due to degrees of freedom. Analysis results of design geometries are given in Table 4. Modal analysis results for all geometries are given in the graphic in figure 17.

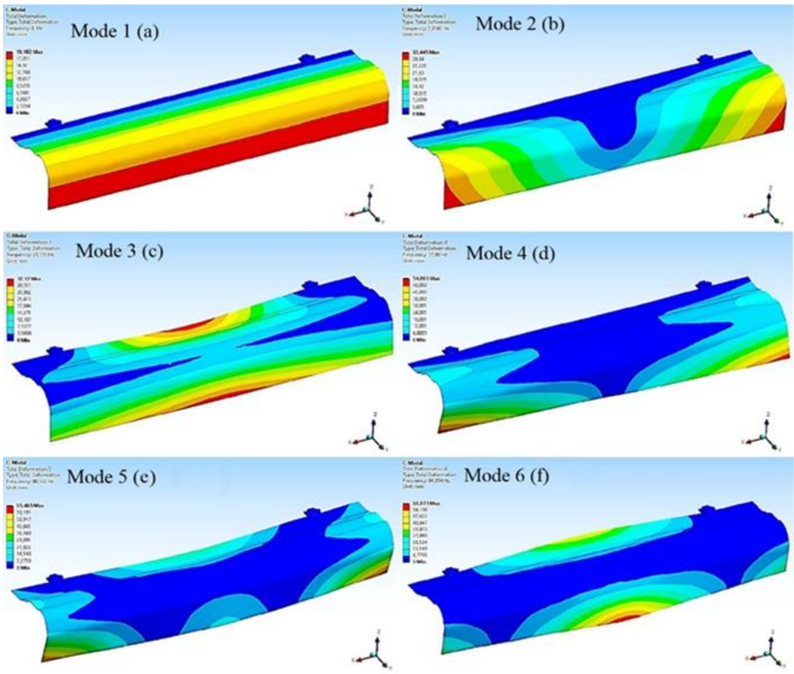

Figure 16 Modal analysis results of optimized cover design in different modes

Table 4 Analysis results of design geometries (natural frequency value-Hz)

	Initial Design (Non-Ribs)	Alternative Rib Geometry	Optimum Design Geometry
Mass (kg)	4,8	6,4	6,4
Mode 1	0	0	0
Mode 2	4,3262	6,4135	7,0165
Mode 3	23,832	28,476	29,131
Mode 4	29,995	37,891	37,66
Mode 5	39,003	47,115	48,122
Mode 6	47,763	59,349	64,954

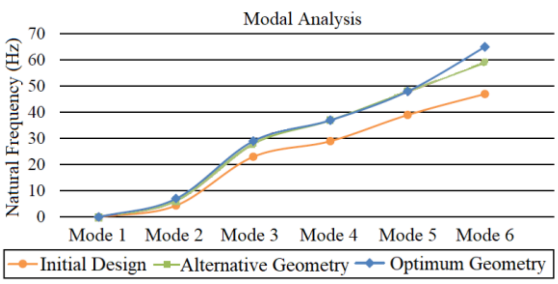

Figure 17 Modal analysis results for all geometries

According to the analysis results, the mode 2 frequency of the alternative rib geometry was found to be 6.4135 Hz. The optimum design geometry has a mode 2 frequency 9.4% higher than the highest alternative rib geometry. After optimization, the weight of the composite cover increased by 33.3% with the rib attachment, and consequently, its natural frequency increased by 62.2% compared to the initial design, so when the weight is critically important, it should be decided by evaluating whether or not to make rib attachment.

In order to support the optimization results conventional rib geometries were modeled and compared after optimization to be the same weight (6.4kg) and volume. The only difference between these caps is the rib shape. These shape changes will directly affect the center of gravity and mass moment of inertia values of the part. The reason for examining moments of inertia is that the structure directly affects the natural frequency value. In the cover design used in the alternative rib geometry, the distance between the center of gravity of the part and the axis of rotation (x-axis) is 238.17 mm and in the cover design with optimum design geometry it is 232.32 mm. The distance from the rotation point to the center of gravity is shown in figure 18.

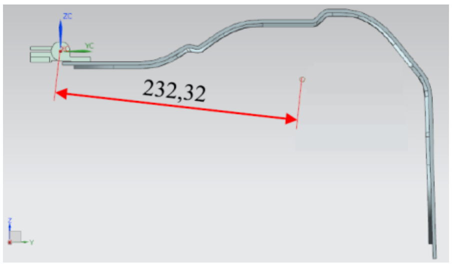

Figure 18 Distance from rotation point to center of gravity

In the cover design used in the alternative rib geometry, the moment of inertia of the part is 486034.17 kg.mm^2 and 469608.67 kg.mm^2 in the cover design with optimum design geometry. The lowest moment of inertia value has been obtained in the cover design with optimum design geometry. According to these values, as the distance of the center of gravity from the axis of rotation increases, the moment of inertia also increases. If we evaluate the natural frequency formula according to the working system of the composite cover, the value of the moment of inertia with respect to the turning point is inversely proportional to the natural frequency. According to the results obtained, the natural frequency decreases as the moment of inertia increases. Analysis results of design geometries are given in Table 5.

Table 5 Analysis results of design geometries

	Alternative Rib Geometry	Optimum Design Geometry
Mass (kg)	6,4	6,4
Distance of Center of Gravity to Rotational Axis (mm)	238,1723	232,3263
Moment of Inertia (kg.mm^2)	486034.17	469608.67
Mode 2 Natural Frequency (Hz)	6,4135	7,0165

The long and flexible cover design with structurally optimized base that emerged as a result of all studies is shown in Figure 19.

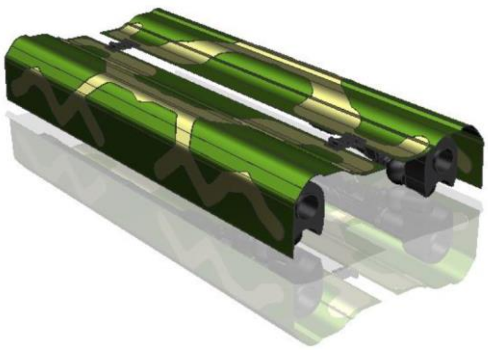
Figure 19 Final cover design

4. CONCLUSION

In this study, the effects of design variables on the weight, dynamic characteristics, and stiffness of the product were revealed by using GENESIS and ANSYS software for a long and flexible composite cover design. The following results were achieved in the study;

• According to the analysis results, the mode 2 frequency of the alternative (conventional) rib geometry 1 was found to be 6.4135 Hz.

• With the rib attachment after optimization, the weight of the composite cover has increased by 33.3%, whereas its natural frequency has increased by 62.2% compared to the initial design.

• The natural frequency of the ribbed cover created by topography optimization was obtained as a result that the mode 2 natural frequency value was 9.4% better than the traditional ribbed cover design with the same weight. It was concluded that topography optimization improves the natural frequency value in composite cover design.

• In the cover design using alternative rib geometry 1, the moment of inertia of the part is 486034.17 kg.mm^2 and in the cover design with optimum design geometry it is 469608.67 kg.mm^2. The lowest moment of inertia value has been obtained in the cover design with optimum design geometry.

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Authors' Contribution
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The Declaration of Ethics Committee Approval
This study does not require ethics committee permission or any special permission.

The Declaration of Research and Publication Ethics
The authors of the paper declare that they comply with the scientific, ethical and quotation rules of SAUJS in all processes of the paper and that they do not make any falsification on the data collected. In addition, they declare that Sakarya University Journal of Science and its editorial board have no responsibility for any ethical violations that may be encountered, and that this study has not been evaluated in any academic publication environment other than Sakarya University Journal of Science.

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