MODELING OF DYNAMIC BEHAVIOR OF LATTICE COMPOSITE AIRCRAFT STRUCTURES

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Abstract: Development of lattice composite aircraft primary structures have been formed during recent years as a novel and promising direction of research aiming to create the next generation of lightweight composite airframes. The application of composites within the frames of lattice/frame layouts, based on unidirectional composite elements, shows high potential in weight saving up to 15% and more for such composite primary structures in comparison with conventional semi-monocoque metallic and composite analogues [1].

The lattice composite structures are substantially different by their topology, layouts and the functions of their main structure elements from conventional laminated composite airframes based on thin stiffened skin. According to that, the creation of lightweight lattice composite airframes requires a proper study of the main questions of strength, including the question of dynamic behavior of composite structures with lattice layouts. The experience shows that the conventional methods of strength analysis are as a rule not correct as applied to the novel lattice composite structures. Hence, these methods should be adapted for the new type of structures or the new special methods for these structures should be developed in order to provide confident solutions of the main tasks of structural dynamics.

In the presented paper the main special features of some lattice airframes from the viewpoint of structural dynamics, including eigen frequencies, mode shapes and frequency response, have been formulated. These special features should be taken into account as basic requirements for the development of methods for modeling of dynamic behavior of lattice composite airframes.

1 INTRODUCTION

During several recent years the development of lattice composite aircraft structures have been formed as one of the perspective and promising directions of research in aviation aiming to create the new generation of composite primary aircraft structures having high weight excellence. The appearance and development of this new direction can be explained by the two main reasons.

The first one is a negative experience of application of composite materials in frames of conventional (traditional) (so-called “black metal”) primary aircraft structures based on thin load-bearing skin stiffened by thin-walled frames and stringers. Such composite structures have demonstrated almost no weight saving in comparison with metallic prototypes. Furthermore, the designing of composite airframes on the basis of “metallic” approaches gave a bunch of the principally new and very complicated problems most of which have not been solved so far. Experience of development of conventional composite structures have shown that a number of problems of strength that are not critical for metallic structures, turned out to be extremely decisive for composite structures. This is caused by the principal differences in physical properties of metallic alloys and composite materials, that are not taken into account within the conventional design methods.

The second reason is a wide and successful application of composite structures based on lattice/frame layouts in space industry. For a number of load-bearing composite structures developed and manufactured by CRISM, Hotkovo, Russia [2] (see Figure 1), real weight saving from 25 to 50% (in comparison with metallic analogues) was obtained. It is worth to mention that such impressive results have been obtained for structures under serial production. There are also excellent examples of development of lattice composite structures in European space industry: demonstrators of lattice composite adapters developed in CIRA (Italy) have shown up to 40% weight saving [3].

Figure 1: Lattice composite structures in rocket industry (CRISM, Russia)

The promising results obtained for space structures have formed a background for a number of researches on application of lattice composite structures for various load-bearing structures in aviation industry, including fuselage sections/panels, wing caisson, helicopter tail boom, and also various beam structures, e.g. passenger floor beams.

For some of these structures, such as helicopter tail boom or aircraft wing structures the main problems of strength defining their weight effectiveness are the problems of structural dynamics. Unfortunately, at the moment there is almost no experience of practical solving of such problems for this novel type of composite airframe structures. That means that the application of traditional methods and models for analysis of dynamic behavior of lattice structures requires a certain validation. At the first step of such validation the main special features of lattice composite structures from the viewpoint of dynamic behavior should be investigated.

2 LATTICE COMPOSITE STRUCTURE CONCEPT FOR PRIMARY AIRCRAFT STRUCTURES

The main specific feature of the unidirectional (UD) composite structures (particularly, lattice structures) as compared to conventional semi-monocoque structures is the layout and functions of the main structural elements. Within the frames of conventional structures the main load-bearing elements are thin skin and the stiffeners (stringers and frames) supporting the skin. Such skin serves both for taking external loads (forces and moments) and provides pressurizing of the cabin (if it is needed, i.e. for fuselage structures). This conventional layout had been developing during the long evolution of metallic aircraft structures with account of the main advantages and disadvantages of metallic alloys, but this layout is absolutely "indifferent" to the special features of physical properties of non-isotropic composite materials.

Unlike the conventional analogues, the lattice structure concept was developed with the focus on physical properties of the current composite materials aiming to enhance their main advantages and minimize their shortcomings. According to that, the lattice structure concept is based on the following principles [1]:

- Unidirectional layout of high-loaded structure elements: main primary structure element – grid of UD-composite ribs, that allow to provide higher level of loads for high-strength carbon fibers.
- Principle of division of primary structure into two main elements: 1.High-strength grid of composite ribs – for taking external forces and moments. 2.Elastic internal skin – for pressurizing and transferring loads from pressurizing to the grid.
- Principle of protection of load-bearing composite elements from impact and environmental factors: Due to the topology of the grid it is possible to protect the ribs with slight weight penalty and thus to provide safe and long-term operation of the structure.

These principles can be illustrated by a simple example (Figure 2) of comparison of the nature-driven evolution of a bird skeleton and the results of the topology optimization of composite fuselage section performed by Leeds University within the frames of FP7 ALaSCA project. As shown on the picture, the optimization process leads to the composite primary structure having skeleton-like topology. At the same time, the functions of protection of the fragile skeleton in the bird's body are realized by such "structure elements" as skin, muscles and feathers. The same idea became the basis for the lattice structure concept, consisting of composite "skeleton" and protective elements.

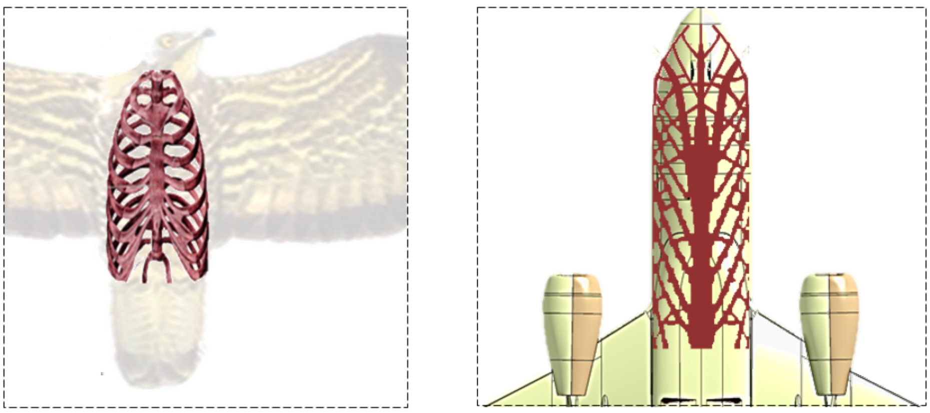

Figure 2: Skeleton of a bird (left) and results of topology optimization for a fuselage primary structure (right)

According to the principles described above, the lattice structure has the following main elements (Figure 3):

– stiff lattice grid on unidirectional composite ribs acting as the main primary structure element responsible for bearing moments and forces;

– elastic waveform inner skin acting for pressurizing and transferring the loads from pressurizing to the lattice grid (for structures with internal pressure);

– smooth outer skin forming aerodynamic shape;

– protective layer to prevent degradation of strength properties of the lattice grid under environmental factors during long operation.

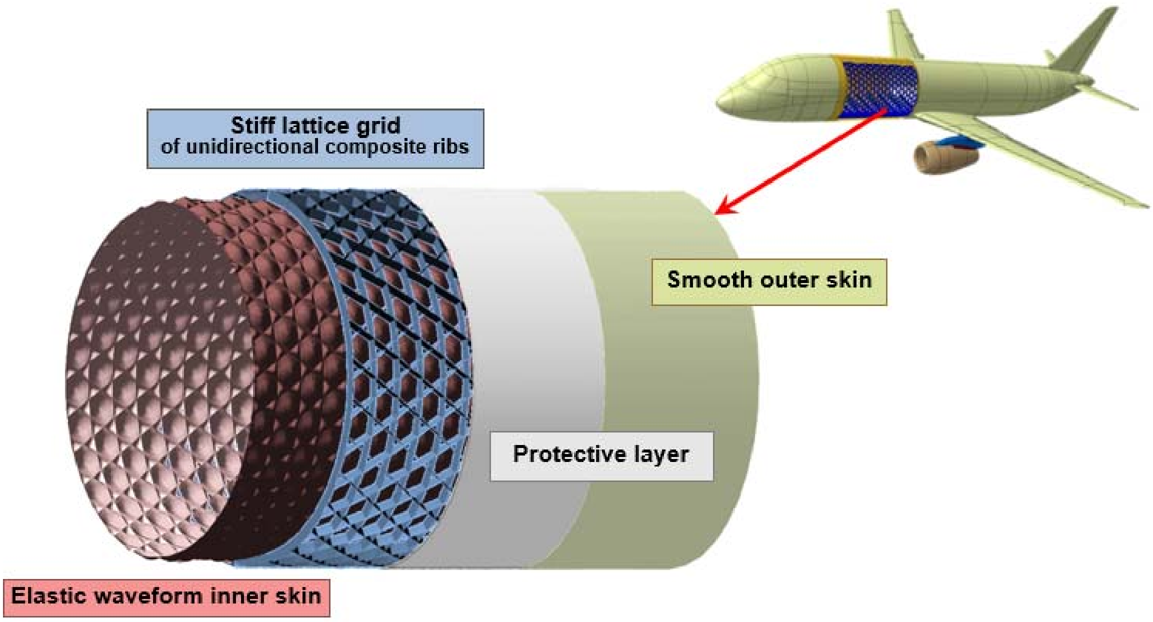

Figure 3: Lattice composite structure concept (as applied to a fuselage structure)

The proposed lattice structure concept has the following main advantages (in comparison with conventional composite structures with laminated skin and stiffeners):

- force flows in the lattice structure are directed mainly along the direction of carbon fibers that allow to realize higher levels of loading in the composite primary structure elements;

- enhanced durability of structure, as the lattice grid of ribs (i.e. the primary structure) can be reliably protected from external factors (e.g. impacts, environment, hot/wet etc.) with a slight weight penalty;

- lattice structure allows to realize small cut-outs without “cutting” primary structure elements and thus avoid additional stress concentrators.

Currently, the main direction of research of lattice airframes is devoted to adaptation of the lattice technology for fuselage structures of up-to-date civil aircrafts. During last 5 years a number of projects on this topic have been launched, including EU Framework projects FP7 ALaSCA [4], FP7 PoLaRBEAR, Russian projects Karkas, CM-Aggregates – Renaissance and others. The results of the FP7 ALaSCA project launched in 2010 and successfully finished in

2013 have shown weight benefits up to 18% (compared to metallic and composite “Black metal” analogues) for lattice composite fuselage section of the perspective middle-range aircraft. These results were confirmed by the investigations in frames of a number of Russian and International projects on the related topics.

The success in application of lattice structures in space industry and the proven potential of such application in aircraft fuselage structures has inspired to search for a new applications of lattice composite structures for various aggregates of aircrafts and helicopters.

3 APPLICATION OF LATTICE COMPOSITE STRUCTURES TO AIRCRAFT AND HELICOPTER PRIMARY STRUCTURES

The technology, which is currently available for manufacturing of lattice composite structures, is based on wet winding method. This technology was developed by CRISM (Hotkovo, Russia) and it is widely used for manufacturing both large-scale structures of space rocket adapters and smaller structures for aerospace and aircraft applications. Technological constraints for wet winding cause significant limitations of the feasible shapes of lattice structures, so the current lattice composite structures have, as a rule, cylindrical or conical shapes. According to that, the applications described below are based on cylindrical/conical shapes of lattice structures.

One of the promising applications of the lattice composite structures is wing caissons of regional aircrafts. Implementation of one or several conic-form lattice caissons to the wing primary structure can allow to obtain higher weight efficiency of the wing and provide durability for this composite primary structure (Figure 4).

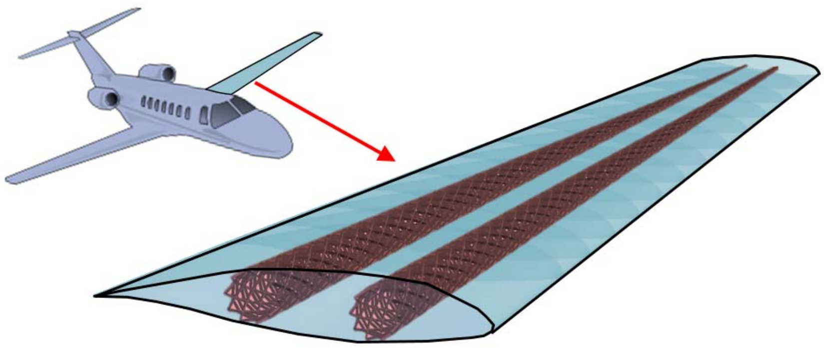

Figure 4: Lattice-caissons concept for a wing structure of a regional aircraft.

The method of keeping the strength characteristics of lattice airframe structures during long-time operation is based on the principle of full and reliable protection of the main primary structure elements (ribs) from environmental factors, i.e. impacts, hot/wet etc. Such protection can be created on the basis on new lattice structure concept akin to the one for a fuselage structure described in the previous chapter. Unlike the fuselage structures, wing structures of regional aircrafts have no requirements of pressurizing, so the lattice wing structure concept will have the following main elements:

- Stiff lattice grid of unidirectional composite ribs;

- Elastic composite outer skin for aerodynamic shape;

- Protection system for the lattice grid.

In frames of this concept only the lattice grid of lattice caissons is responsible for strength and stiffness characteristics of the wing structure, while the other two elements are secondary and have other functions, including the function of protection of the lattice structure from external factors. It is worth to mention that the protection system for such type of structure can be very lightweight, due to the topology of the lattice grid, when the main primary structure elements (ribs), that should be protected, have a lot less surface area as compared to the load-bearing skin within the frames of "black metal" concepts.

The other possible application of the lattice composite structures having cylinder or conical form is the tail boom of a helicopter (Figure 5). This structure has the same three main elements as for the wing concept described above.

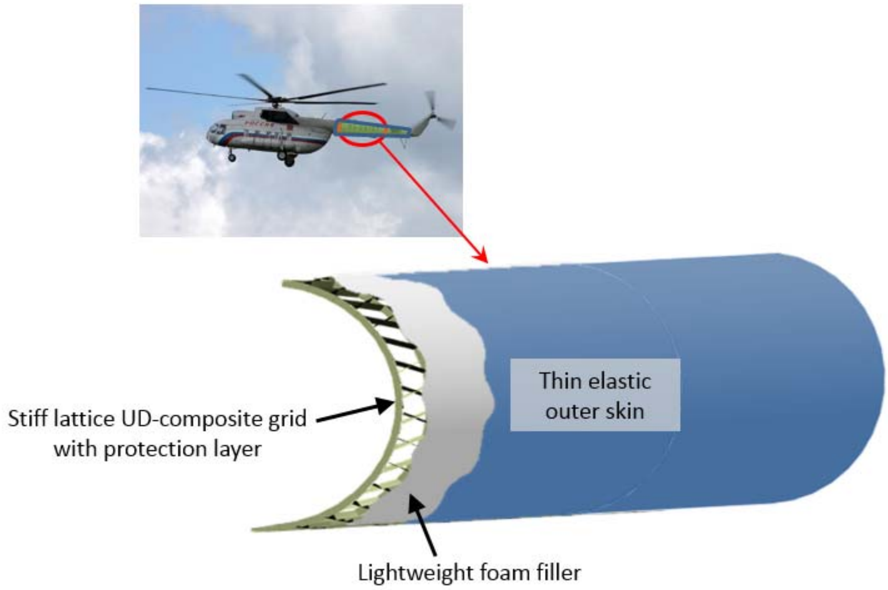

Figure 5: Concept of lattice structure for a helicopter tail-boom

The manufacturing technology for the tail boom structure can be developed via upgrading of the existing winding technology (existing for lattice grid) by implementation of the new structure elements to the manufacturing process. It is significant to note that the entire structure, including all main structure elements, can be manufactured within the frames of one production cycle. The manufacturing concept for the lattice structure of helicopter tail boom is described on Figure 6.

The concept consists of five main stages. At the first stage of manufacturing the "inner" part of protection layer is manufactured and put onto the cylindrical/conical mandrel. This inner part here serves as a preform for winding of the lattice grid which is carried out at the second stage of manufacturing. The use of the protection layer as a preform allows both to reduce the manufacturing costs and provide better quality of the lattice grid, as the stage of removing the preform and mechanical processing (typical for the current lattice technology) is not needed in this case.

After these two stages the autoclave forming is carried out. At the third stage, after the forming, the lattice grid is "closed" by the outer part of protection layer. The two parts of the protective layer are fastened (or glued) together and also the joints are formed for attachment of wiring and the equipment, located inside the tail boom. At the forth stage of manufacturing the foam filler is added to the structure. This can be made using various methods, including spreading or installing pre-manufactured plates of foam.

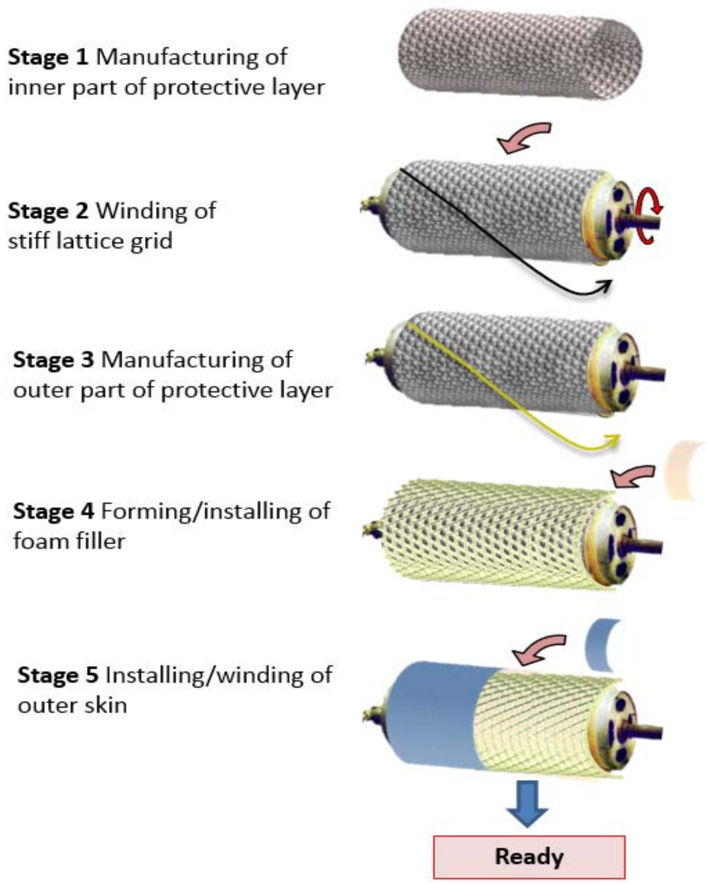

Figure 6: Manufacturing of lattice structure for a helicopter tail boom

Finally, at the fifth stage, the outer skin is manufactured. Here is also a variety of available methods of performing this procedure: installing of curved panels of skin, winding/prepreg layup/braiding (preferably, using out-of-autoclave technologies).

The proposed manufacturing technology allows to perform fast and cost-efficient manufacturing of the bulk-type lattice structures such as helicopter tail boom. Currently, such technology can be developed and realized but this requires a more detailed study of technological issues.

4 DYNAMIC BEHAVIOR OF LATTICE COMPOSITE STRUCTURES

In the development of lattice composite fuselage structures carried out in frames of a number of projects during recent years, the tasks of dynamic behavior haven't been considered so far. The main reason is that the weight efficiency of fuselage structures is not defined by their dynamic strength properties. Unlike fuselage structures, weight parameters of wing and tail boom structures are as a rule determined by their stiffness characteristics.

According to this assumption, the conic lattice structure with geometrical parameters close to a part of a tail boom of a civil helicopter have been considered. The conic lattice tube had helical ribs (directed at a certain angle α to the longitudinal axis) and circular ribs.

For searching of rational parameters of the structure, the parametrical investigations including static strength numerical analysis, analysis of stiffness characteristics, eigen frequencies and mode shapes of the lattice structure were carried out. The numerical analysis was performed using parametrical FE model based on 2D shell elements (Figure 7, right), which have been validated and used in frames of a number of projects devoted to the development of lattice composite fuselage structures [5]. This model allows to perform fully automated static strength and buckling analysis of cylindrical and conical lattice structures with any feasible combination of design parameters.

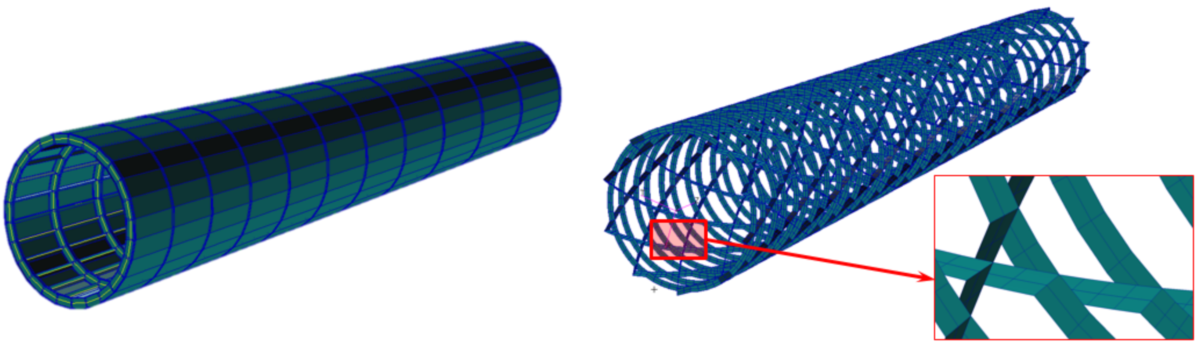

Figure 7: FE modeling of lattice composite (right) and metallic (left) tail boom primary structures

The loads on structure for estimation of strength margins were taken corresponding to FAR Sec.29.351-Yawing conditions. For the preliminary estimation of weight of the lattice tail boom various variants of the lattice structure were compared by their stiffness and weight characteristics to the metallic tail boom of a real civil helicopter, which have been also analyzed using FE model (Figure 7, left).

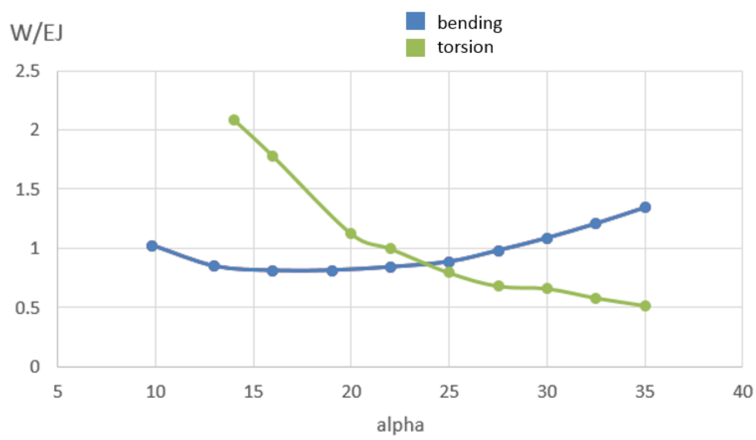

Figure 8: Reduced weight/stiffness ratios to the angle of orientation of helical ribs

The first calculations have shown that the strength and local buckling margins for the considered load case are more than two and the main active constraints for the lattice structure are bending and torsional stiffness. For these two constraints the parametrical investigations of lattice composite have been carried out. The calculation have shown that the main driven parameter defining the weight/stiffness ratio is the angle of orientation of helical ribs to the longitudinal axis. The graph on Figure 8 shows the dependences of the ratios weight/stiffness (for torsional and bending stiffness) on the angle of orientation of helical ribs. The graph shows that the optimum values of the angle of orientation are significantly different depending of what stiffness requirements (bending or torsional) are more decisive. The further investigations have shown that in order to get good enough weight efficiency for the lattice structure in comparison with the metallic analogue, it should be a compromise between stiffness and weight characteristics. At that, the strength and buckling requirements for the lattice structure are satisfied.

At Table 1 the results of parametrical investigation are shown on example of 4 lattice structures having different combinations of design parameters. The design parameters for variants 1-3 were chosen as a result of searching rational parameters of the structure and they are very close to each other. The variant 4 has lower constructional depth (i.e. lower height of ribs) that allows to provide better margins for buckling and bending stiffness.

The results have shown that the potential in weight saving for the lattice structure mostly depends on the stiffness requirements to the structure. Also, the decisive constraint for variants 3 and 4 is local bucking of circular ribs, which margin is close to 1 for these two variants.

Variant, #	Weight saving (%)	Bending stiffness, %	Torsional stiffness, %
1	4	125	97
2	10.6	103	88
3	17.5	87	77
4	23.8	91	76

Table 1 – Parametrical investigation of weight and stiffness parameters

According to these results the analysis of mode shapes and frequencies have been carried out. The relative values of eigen frequencies for different modes for the considered variants of the lattice structure are presented in the Table 2. The eigen frequencies for the “base” variant (variant 2) are taken as 100%. The main mode shapes of the lattice composite tube are shown on Figure 9.

Mode shape	Freq._V1, %	Freq._V2, %	Freq._V3, %	Freq._V4%
B1	106	100	97	102
B2	104	1.00	97	101
M1	99	100	102	72
M2	100	100	101	74

T	101	100	98	100
CT	100	100	99	98
M3	99	100	103	75
M4	103	100	99	88
B3	102	100	97	101

Table 2 – Frequencies for main mode shapes of lattice tube

The results show that the slight change of rational design parameters (variants 1-3) has a slight response on the values of frequencies. At the same time, reducing of constructional depth of the lattice structure reduce the frequencies of membrane mode shapes and thus does not allow to get more weight benefits.

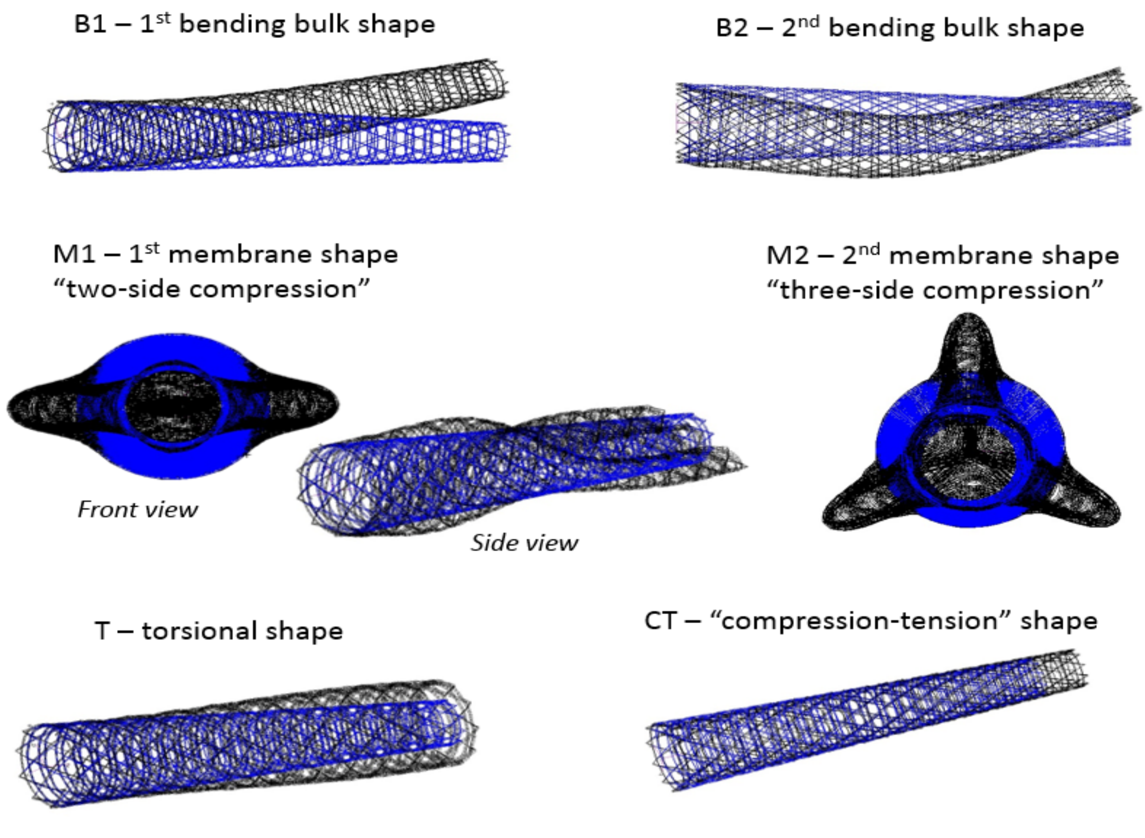

Figure 9: Mode shapes of lattice composite conic tube

The results of parametrical investigations of the angle of orientation of helical ribs (α) to the longitudinal axis on eigen frequencies of the lattice structure are shown in Table 3.

Mode shape	Freq. α=20	Freq. α=30	Freq. α=40	Freq. α=45
B1	177	149	100	72
B2	110	123	100	76
M1	85	96	100	102
M2	83	97	100	99
T	65	88	100	96
CT	164	136	100	79
M3	88	99	100	101
M4	89	110	100	92
B3	79	103	100	81

Table 3 - Parametrical investigation of frequencies for various angles of helical ribs

A number of lattice structures having the same running weight with various values of the angle α. The base variant with α=40 degrees corresponds to the base variant 2 on Tables 1-2. As seen on the table, at low values of α, the lattice structure has significantly lower frequencies of membrane shapes (M1-M2) and torsional (T) shapes. At the same time the 1st and the 2nd bending shape (B1 and B2) and compression-tension (CT) frequencies are considerably higher. For the angles higher than 40 degrees the torsional and bending shape frequencies are lower.

In order to mark out the main special features of lattice composite structures from the viewpoint of mode shapes and eigen frequencies the comparison of the selected variants of the lattice tube with the metallic prototype having the same geometry parameters have been performed. The results of the comparative analysis for some mode shapes are shown on Table 4. The four considered variants are the same as on the Tables 1-2. The 100% value corresponds to the eigen frequencies of the metallic prototype.

Mode shape	Freq._V1, %	Freq._V2, %	Freq._V3, %	Freq._V4,%
B1	85	80	78	82
B2	107	104	101	105
M1	87	88	90	63
M2	98	98	99	72

M3	98	99	101	74
B3	122	119	116	119

Table 4 – Comparison of frequencies for lattice composite and metallic analogues

The analysis have shown that the lattice bulk has slightly lower frequencies of membrane (M1-M3) modes and lower frequencies of torsional modes. Also, the frequency of the first bending mode (B1) significantly drops. Frequencies of the other bending modes are higher.

It is worth to notice that the frequencies highly depend on ratios of geometry parameters of ribs. For the ribs with the ratio “height/width” lower than 2 the membrane mode frequencies are significantly lower (Var. 4 in the table).

5 SUMMARY

The numerical investigations have shown the main features of lattice composite structures from the viewpoint of stiffness characteristics and dynamic behavior. Lattice structure can be considered as a bulk structure, having a number of differences from typical metallic prototypes:

- Frequencies of first bending mode shape are up to ~20% lower due to lower bending stiffness;
- Frequencies of membrane mode shapes are close;
- Frequencies of most of other possible mode shapes are considerably higher.

Preliminary estimations of weight efficiency of the lattice structure for a part of a helicopter tail boom have shown that weight saving up to 10-15% in comparison with metallic prototypes can be obtained.

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