The use of composite materials in load-bearing elements of an adaptive wing

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Abstract. The article discusses methods for manufacturing power elements of an adaptive wing from composite materials, as well as various principles for changing the configuration of an adaptive wing. A comparison is made of the aerodynamic characteristics of an adaptive wing and a wing with traditional high lift devices.

1 Introduction

The high lift devices of the wing, which includes many devices, such as flaps, slats, spoilers, ailerons, hinges and guide rails, allows you to change the lift and drag of the wing of the aircraft. At the same time, during the operation of these devices, gaps are formed that worsen the aerodynamic properties of the wing. In addition, the devices have a significant weight.

As an alternative to a wing with traditional high lift devices, an integral adaptive wing with a profile shape that changes depending on the flight mode can act. The use of an adaptive wing will make it possible to get rid of many devices that change lift and drag, thereby reducing the mass and the likelihood of wing failure. It will also allow you to get rid of gaps that worsen the aerodynamic characteristics of the wing.

Efficient flight in the atmosphere requires the apparatus to have different aerodynamics depending on the flight speed and flight mode. The classical approach to the design of new aircraft at the moment allows only a slight (no more than 1-2%) improvement in the aerodynamic quality and improve take-off and landing characteristics. The high lift devices of the wing in the form of simple deflected noses and tails of the profile or a change in sweep does not allow obtaining high values of the maximum lift coefficient under changing operating conditions.

Therefore, in recent years, in connection with the development of the technical base and the emergence of new aviation materials, more and more attention is paid to the possibility of improving the aerodynamic properties of the aircraft by changing the geometry of the wing in flight mode - the use of an adaptive wing.

The use of composite materials in the design of the load-bearing elements of the adaptive wing will also make it lighter. Due to the properties of composite materials, it will be possible to implement the concept of an adaptive wing.

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A problem for many types of products made of composite materials is the low automation of their production, or its complete absence. In addition, for most types of production of products from composite materials, there are no opportunities for manufacturing optimized designs. Also, composite products made by conventional manufacturing methods often lose their mechanical properties in the vicinity of holes made by various types of machining due to damage to the reinforcing material. These negative effects can be offset by using 3D printing of a composite material reinforced with continuous carbon fibers as a manufacturing method for various structures.

The production of composite structures reinforced with continuous carbon fiber using additive technologies opens up new opportunities for the automated and cost-effective manufacture of highly loaded structures. This is achieved through a great deal of freedom in the design process, allowing the placement of the fibers to be adapted and thus taking full advantage of the anisotropy and strength of the composite material.

A contribution to the study of adaptive structures was made by I. K.-V. Kuder, U. Fasel, D. Keidel, L. Baumann, B. Vermes, T. Czigany, W. Hufenbach, M. Gude, L. Kroll, E. R. Abrahamson, M.S. Lake, N.A. Munshi. Of these, I.K.-V. Kuder, U. Fasel, D. Keidel, L. Baumann conducted a study of adaptive structures in the context of their application in aircraft, U. Fasel, D. Keidel, L. Baumann also demonstrated the benefits of using 3D printing in the production of load-bearing elements of an adaptive wing. Zi Kan, Daochun Li, T. Shen investigated the increase in the aerodynamic characteristics of an adaptive wing compared to a traditional wing.

The Anisoprint team made a great contribution to the study of 3D printing of composites and its application in practice. So, in the work of A.V. Azarova (et al.) [1] describes the process of manufacturing a quadrocopter frame sample using composite 3D printing, as well as testing the finished product. At the same time, tests were carried out on the resulting product, which showed that it can withstand loads up to 30 kg without any signs of destruction or delamination of the material. Mark G.T., Gozdz A.S. also explored the technology of 3D printing of a composite material.

2 Materials and methods

2.1 Principles for changing the configuration of an adaptive wing

Various concepts of adaptive constructions were considered in [2]–[15]. Adaptive mechanisms in such constructions are studied in detail in [16]–[18].

There are several principles for changing the configuration of an adaptive wing. For example, the use of adaptive materials, special mechanisms, semi-active methods and multi-stable materials.

The use of special adaptive materials allows you to purposefully change the configuration of the structure. Shape memory materials deserve special attention.

Quite a lot of research is devoted to materials such as various alloys, ceramics and polymers, in which the shape memory phenomenon can be observed. For example, the phenomenon of shape memory was studied in [19]. In the context of the use of special materials in the design of load-bearing elements of an adaptive wing, it is shape memory polymers that are most interesting due to their significant reversible deformation ability in combination with the possibility of additional improvement of their properties by reinforcing and, as a result, the formation of composite materials with shape memory or so-called memory elasticity.

Comparing alloys and shape memory polymers in terms of applicability in adaptive designs, we can conclude that polymers are superior in their mechanical characteristics to alloys, since they have a lower density, large reversible deformations, and better adaptation of thermomechanical characteristics to individual conditions. Also, polymer structures are more economical to manufacture, and the effort to put them into action is an order of magnitude lower compared to alloy structures. On the other hand, one should take into account the risk of damage to structures made of polymers on a microscale at an insufficient operating temperature, and, consequently, the risks of reducing their reliability and durability.

When polymers are used separately, the structures obtained from them have a significant potential for reversible deformation, reaching 200%. However, polymers have a number of disadvantages, such as high temperature sensitivity, which makes it difficult to control the configuration of an adaptive design, low stiffness at elevated temperatures, and a high linear thermal expansion coefficient.

Improving the stiffness properties can be achieved through the use of reinforcement, which will reduce the reversible deformation by a factor of 10. In order to eliminate these limitations, composite materials based on shape memory polymers, called shape memory composites or elastic memory composites, have been developed. Such materials make it possible to combine sufficient rigidity with a controlled high deformation capacity.

It is accepted that the term composite material with elastic memory is associated with the use of a thermosetting matrix, since it provides the composite with the best mechanical characteristics, durability and manufacturability.

Through experimentation with CTD-DP-5.1 thermosetting resin, Abrahamson et al. found that shape memory effects can be induced not only in a standard temperature loading process, but also by applying exceptionally high mechanical loads without the need for heating. This fact indicates that elastic memory composites should be considered when choosing a material for load-bearing structures of an adaptive wing.

The traditional method of changing the configuration of a wing is to use devices based on mechanisms with separate control surfaces, such as flaps, slats, spoilers, ailerons. Variable wing sweep is also a similar method. The disadvantages of such systems are a large mass, a significant number of parts and increased design complexity.

Semi-active methods involve the use of electricity to change the stiffness of power elements by inserting electrodes into them and using piezoelectric materials. However, the volume of research in this area is small, which does not allow making predictions of the necessary accuracy to assess the viability of applying these technologies to the power elements of an adaptive wing.

Among multistable materials, it is worth considering separately the so-called bistable (two-stable) laminates.

A bistable or multistable laminate is a type of composite structure that exhibits many stable static configurations. The presence of multiple stable equilibrium configurations makes bistable laminates extremely attractive candidates for adaptive wings. Non-symmetrical composite laminates exhibit two stable configurations at room temperature after curing at elevated temperature. The bistability of multilayer laminates with transverse layers is due to the presence of residual deformations that occur during the curing process. The loss of stability can be the reason for the transition from one stable form to another. The amount of force required to achieve another stable shape depends on the total strain energy of the laminate in its original cured shape. By adjusting the energy levels of stable shapes, such as square shaped laminates, one can vary the force required to achieve another stable shape and the return force.

2.2 The use of additive technologies in the manufacture of load-bearing elements of an adaptive wing

The latest developments in the additive manufacturing of continuous carbon-fiber-reinforced composite materials make it possible to automate the manufacturing process and produce very complex composite parts without the use of special molds. Compared to automated fiber lay-up with limited maximum tow curvature or modern manual processes, more complex geometries can be realized with additive manufacturing at a lower cost. The first calculation of the cost of continuous fiber-reinforced additively manufactured composite parts suggests a potential reduction in manufacturing costs by up to ten times using the presented 3D printing technology.

2.3 Aerodynamics of the adaptive wing

In [20] Z. Kan (et al.) presented an aerodynamic calculation of an adaptive wing and compared the obtained aerodynamic characteristics with those of a conventional wing. For numerical simulation, a two-dimensional NACA 0012 airfoil with a flexible leading edge was taken. The shape of the deformation is parabolic, and the deformable region is located in the front quarter of the profile chord. A conventional rigid leading edge and a flexible leading edge are shown in fig. 1. The leading edge deflection angle γ is defined as the angle between the chord line and the line from the deflection axis to the leading edge, with the downward direction being positive. The angle of attack α is defined as the angle between the chord line and the direction of the flow velocity.

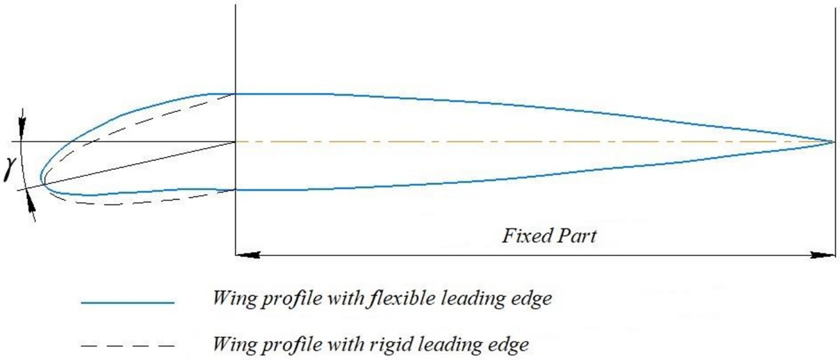

Fig. 1. NACA 0012 Wing Profile with Conventional Rigid Leading Edge and Flexible Leading Edge

To model the aerodynamic characteristics of adaptive wings, the Reynolds-averaged Navier-Stokes equation with the Spalart-Allmaras turbulence model was used. The boundary of the computational domain was set as a pressure field, and the profile was set as a non-slip static wall. To update the mesh, the method of local permutation of cells and the method of smoothing based on springs were applied due to the change in the leading edge with a large amplitude. To be applicable to this method, triangular cell types were adopted and the mesh was refined near the profile to improve the accuracy of the results.

The aerodynamic characteristics of the adaptive wing and conventional wing were studied numerically. The Mach number and Reynolds number of the flow were 0.2 and 4.6×106, respectively, and the deflection angle γ was 16°.

3 Results and discussion

3.1 The choice of material for the load-bearing elements of the adaptive wing, the method of their production

Adaptive or so-called morphing mechanisms, which use the elastic properties of a material to change the shape of a structure, show great potential in improving the flight performance of aerospace structures. Such structures have a complex internal topology, which makes them prohibitively expensive to fabricate using traditional methods. The combination of additive manufacturing technologies for composites and morphing mechanisms has the potential to simultaneously reduce manufacturing costs and significantly improve the flight performance of aerospace structures.

Thus, in further studies, composite materials with elastic memory or bistable laminates should be considered as a material for the load-bearing elements of an adaptive wing.

3.2 Study of adaptive wing aerodynamics

The aerodynamic characteristics of an adaptive wing were studied in [20]–[22].

On fig. 2 shows the lift coefficient curves for conventional and adaptive wings. It can be seen that the slope of the lift curve of an adaptive wing is almost identical to that of a conventional wing. An adaptive wing has a higher lift coefficient than a conventional wing, especially near the critical stall angle. In addition, the stall angle of attack and the maximum lift coefficient of an adaptive wing are greater than those of a conventional wing. The maximum lift coefficient of an adaptive wing is about 8% greater than that of a conventional wing.

On fig. 3 shows the characteristics of the lift-to-drag ratio (Cy/Cx). The lift-to-drag ratio of the two wings first increases to a maximum and then decreases as the angle of attack increases. The adaptive wing is clearly superior to the conventional wing in terms of lift to drag ratio. The adaptive wing achieves a maximum lift-to-drag ratio of 75.2 at α = 10°, which is 10.3% more than that of a conventional wing - 68.2 at α = 12°. In addition, as shown in Fig. 4, moment coefficient curves near a quarter chord show that the adaptive wing has a lower nose-down moment coefficient than the conventional wing, improving control surface efficiency and aerodynamic performance.

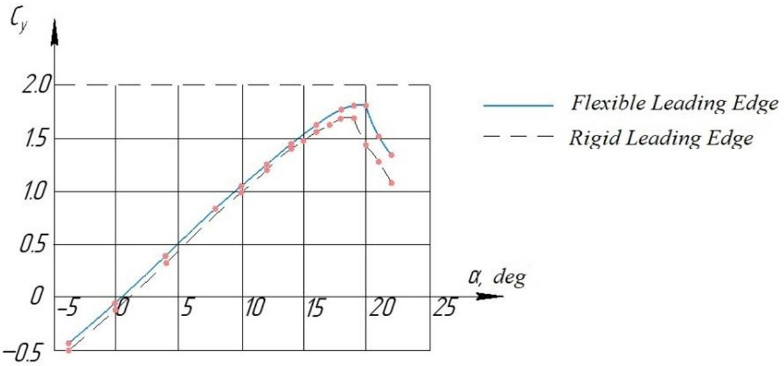

Fig. 2. Lift coefficient curves for a wing with a flexible leading edge and a wing with a rigid leading edge

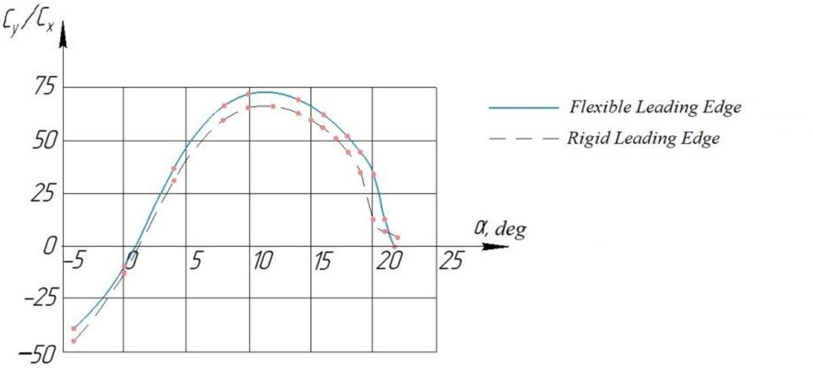

Fig. 3. Lift-to-drag ratio curves for a flexible leading edge and a rigid leading edge wing

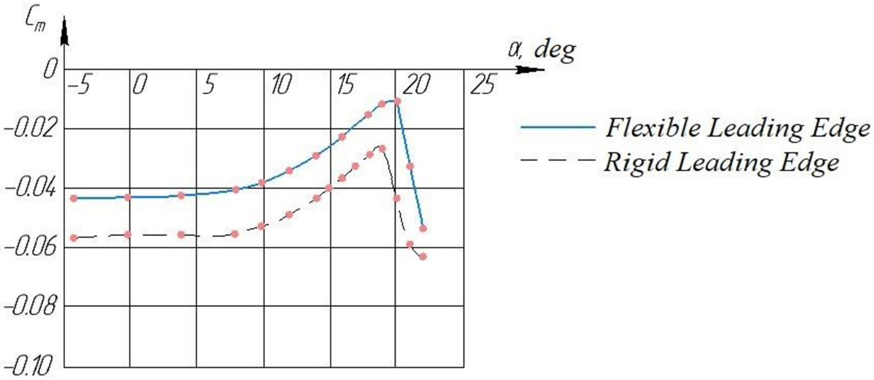

Fig. 4. Curves of the coefficient of moment of the wing with a flexible leading edge and a wing with a rigid leading edge

To explain the differences in the aerodynamic coefficients, the flow fields and pressure distributions of the adaptive and conventional wing were extracted at α = 20°. On fig. 5 shows that the pressure coefficient on the upper surface of a conventional wing has a sharp change around the deflection position of the rigid leading edge, while the pressure coefficient of an adaptive wing changes gradually. As a result, the area covered by the pressure coefficient curves of an adaptive wing is larger than that of a conventional wing, resulting in a higher lift coefficient.

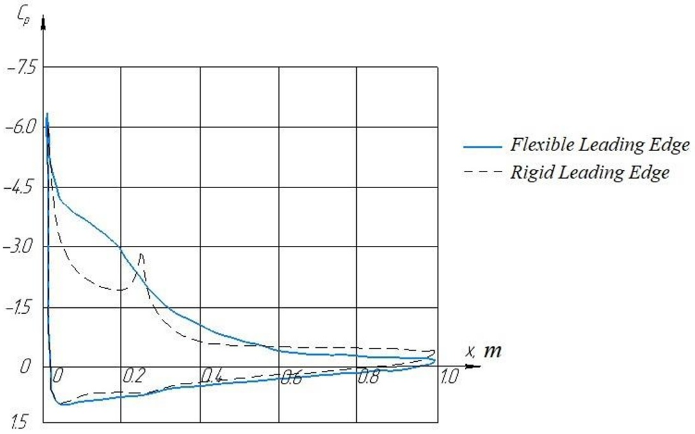

Fig. 5. Curves of pressure coefficients on the surface of a wing with a flexible leading edge and a wing with a rigid leading edge

4 Conclusions

1. Composite materials with elastic memory or bistable laminates seem to be the most suitable materials for the manufacture of load-bearing elements of an adaptive wing.
2. As a method for producing load-bearing elements of an adaptive wing with a complex topology from composite materials, it is worth considering the method of three-dimensional printing of a composite material reinforced with continuous carbon fiber.
3. An adaptive wing has improved aerodynamic characteristics compared to a wing with traditional high lift devices.

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