Methodology to Provide Strength and Service Life of Composite Hingeless Rotor Elastic Elements

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Introduction

The hingeless main and tail rotors are widely used as standards in the present-day helicopter design. Although the production costs somewhat rise, such structures are justified at the expense of lower operation costs (change to operation by condition) and simpler maintenance procedures.

High qualities of such structures are provided by the application of modern composite materials, by a high level of design and improved analytical and experimental methods; these methods can be used for solving problems of structure parameter optimization and realization of specified characteristics of static strength and service life with respect to fatigue strength.

In accordance with the standard documentation existing in Russia for helicopter certification (FAR-29, FAR-27), not only helicopter flight performance, but also composite materials produced by the developer must meet the certification requirements.

In addition to the certification requirements for environmental conditions of helicopter operation in Russia, specifications to a helicopter under development involve its flight within a range of ambient temperature variation (±50°C), at high humidity and impact of hostile media.

Since 1993 Kazan Helicopters has been developing a family of light single-rotor helicopters.

The certification tests of the “Ansat” helicopter with takeoff weight to 3.3 ton are scheduled to terminate in 2003, and we hope to obtain a type certificate in accordance with the certification requirements of FAR-29. The “Ansat” helicopter is equipped with a hingeless main rotor and composite blades of main and tail rotors. These structures of different design versions are today subjected to numerous kinds of tests to ensure basic strength and service life parameters.

Special Features of a Structural Design of the Ansat Helicopter Hub with Torsion-Type Elastic Elements

In selecting an optimal solution for the main rotor (MR) hub structure, the most important criteria among many variants were the structure mass, operational manufacturability (and hence – cost), reliability and failure safety.

The main rotor hub is designed as a hingeless one with an elastic torsion that performs the functions of flapping, lag and feathering hinges (Fig. 1).

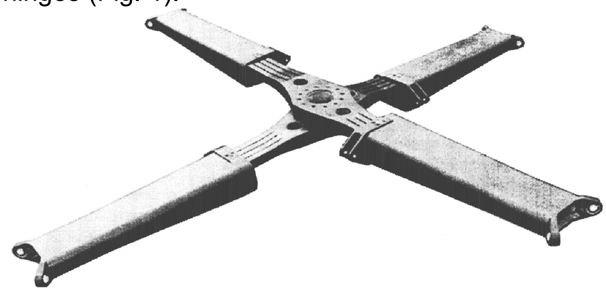


Fig. 1. General view of MR hub

The main rotor hub torsion is designed as a composite beam. An elastic deformable section is made as a rectangular beam and consists of compacted packets and interlayers; packets of high-modular fiber-glass plastic and interlayers of lowmodular viscoelastic and plastic material alternate in height. To reduce torsional rigidity, the beam has longitudinal slots; therefore, this torsion section can be used as a feathering hinge of the main rotor hub.

The rigidity and geometrical parameters of the torsion packets on the elastic deformable section are so selected that they provide the necessary frequency characteristics for the system “MR hub–blade” in the flapping and rotation planes, as well as strength and required service life. Unlike other elastic elements of the beam type, the low modular plastic materials with viscoelastic properties used in the torsion afford certain damping of blade vibrations in two planes.

The low-modular viscoelastic material interlayers between the high-modular fibre-glass plastic packets allow these packets to operate under a variable load in the flapping plane with “tensile–compressive” strains and a small bending. This is due to the shear strains in the interlayers resulting in higher parameters of the torsion service life.

The torsion axis displacement from the shaft axis in the rotation plane Δ provides for bending moments relief of the torsion root in the rotation plane M_{rot} (Fig. 2). A cone angle provided by the torsion reduces its bending loads in the flapping plane.

Fig. 2.

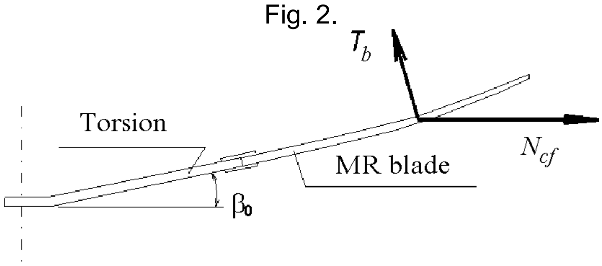
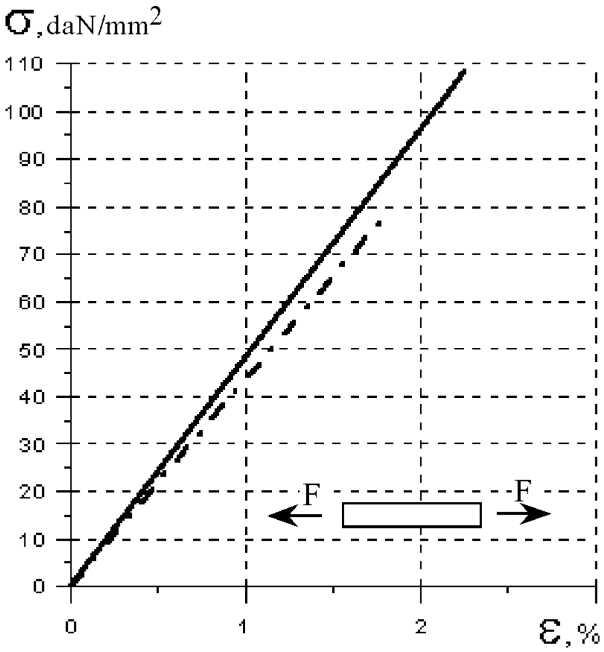


Fig. 3.

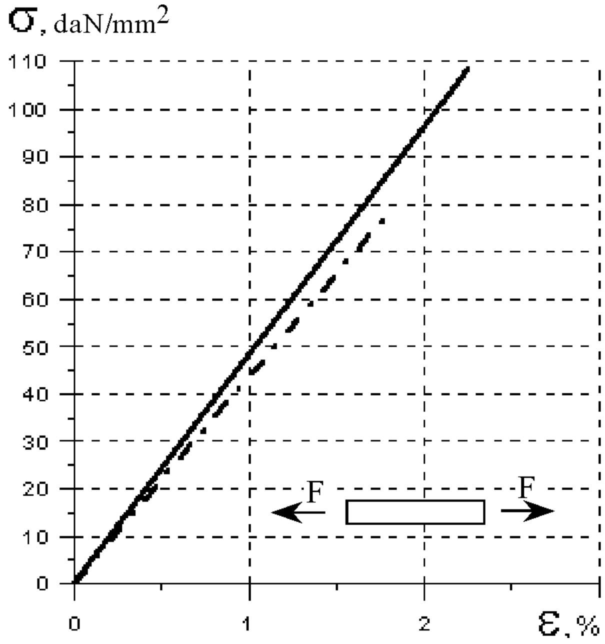
A special feature of the hub structure is the fact that the torsion housing which transfers a torque and controlling actions from the blade to the wobble plate bears no tensile and bending loads owing to the kinematic scheme of torsion attachment.

Determination of Mechanical Characteristics of Materials Used for Torsion Manufacture

To create a data bank on the physical and mechanical properties of composite materials used in manufacture of an elastic element, tensile (rupture) and bending (fracture) tests were conducted in accordance with the certification requirements.



a) – tension



b) – bending

Fig. 4.

Standard specimens were used for the tests. The experimental σ – ε diagrams for the variants of tensile and bending tests are shown in Fig. 4. Figure 4, a gives comparison of the σ – ε relations for the specimens exposed and not exposed to a radiation action. As is seen from the diagrams presented, the relation σ – ε retains its linear character to the point of failure. To meet the specification requirements, the physical and mechanical properties of composite materials were in addition tested at increased (to +80°C) and decreased (to –50°C) temperatures. Not only standard specimens but also fragments of the elastic element structure were subjected to environmental tests.

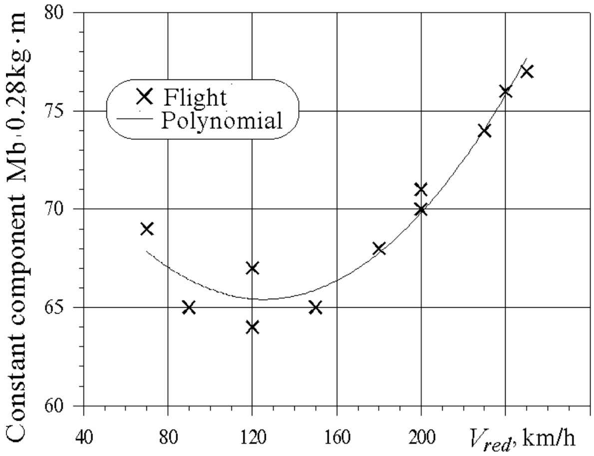
Analytical and Experimental Determination of Helicopter Main Rotor Loads

Since the Ansat helicopter being developed is a totally new helicopter of this class in rotorcraft production of Russia, prediction of loads on its lifting system was a rather labor-intensive problem. The reliable flight data on loads were first obtained only in 2000, but the bench tests of elastic element specimens have been conducted since 1997.

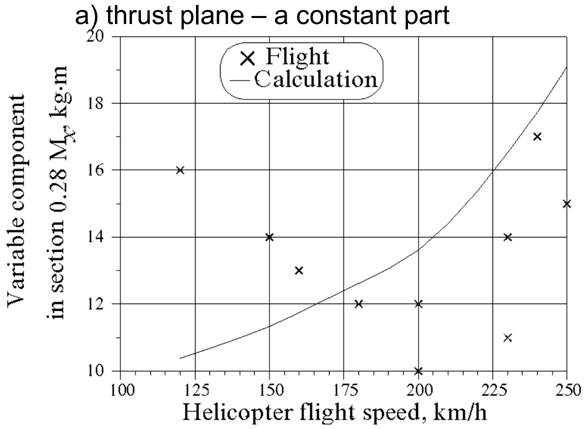
In this situation a demand arose for design methods to predict loads, and for their creation we had to solve a number of problems associated with the operation characteristics of the hingeless main rotor [1, 3]:

1. Development of a model of helicopter spatial aeroelastic trimming using a geometrically nonlinear model of blade deformation;

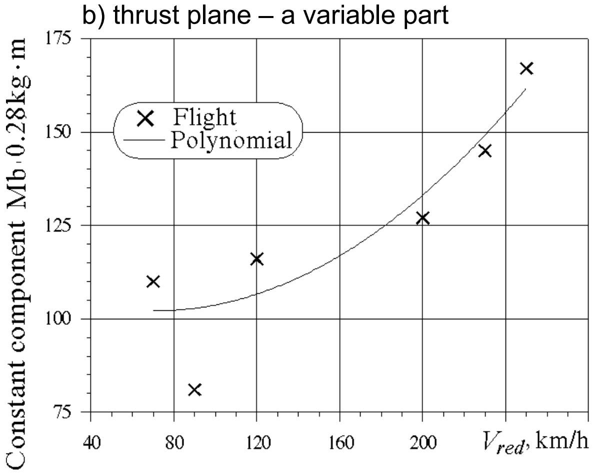
2. Development of a simplified model of torsion deformation on the basis of a beam multilayer composite structure. A design model of this type is intended to create a torsion compliance matrix in the zone of blade articulation. The model takes into account a blade root space position under load in the problems of aeroelastic calculation.



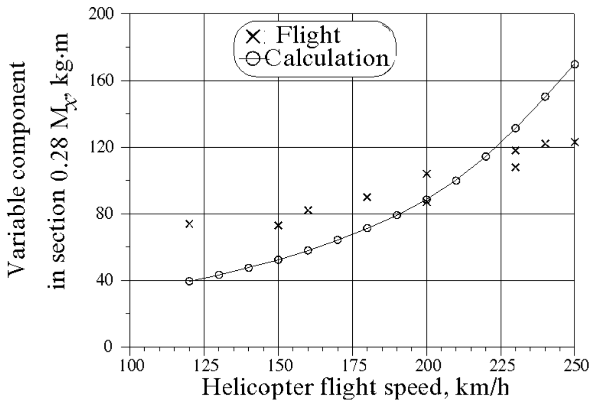
a) thrust plane – a constant part



b) thrust plane – a variable part



c) – rotation plane – a constant part



d) rotation plane – a variable part

Fig.5.

Figure 5 presents the standard calculation and experimental data on bending moments in the flapping plane (a) and rotation plane (b) depending on flight speed.

Such loads were simulated for all flight conditions (including flight with maximal overload); they make it possible to provide the torsion loading in the static and dynamic bench tests. These loads are also used to evaluate local torsion strength under service loads with the aid of the finite element method.

Analytical and Experimental Evaluation of General Static and Local Strength under the Action of Equivalent Design Loads

A torsion is a beam of a complex shape with the complex rectangular cross-section; it has openings and three longitudinal slots dividing the working section into four “grooves” (Fig. 6). The beam model makes it impossible to determine the torsion stress-strain state with a required accuracy; therefore, the design scheme was based on the finite-element method in the three-dimensional statement.

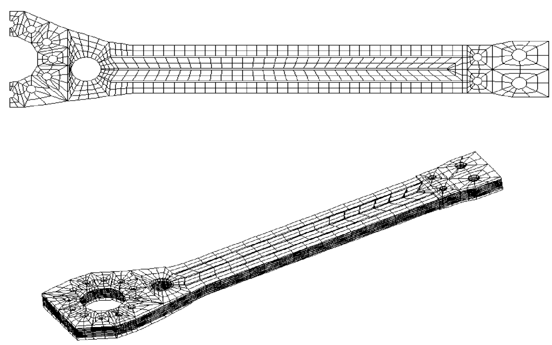


Fig. 6.

A grid of finite elements was used which makes it possible to adequately represent all geometric features (cutouts, adapters, fillets, and others).

The structure cross-section under study is a 24–26 layered packet consisting of variously oriented fiber glass plastics and rubber. The pattern of material placement in the separate zones of the MR torsion is different. This packet is characterized by a small thickness of rubber inserts, which are of significant importance in reducing torsional rigidity. In this case, the mathematical modeling of the stress-strain state becomes complicated since the unified kinematic hypotheses make it impossible to adequately present the stress-strain distribution across the thickness.

Therefore, a three-dimensional model with a set of finite elements across the thickness is used in the calculation; the number of finite elements is equal to the number of layers of significantly different materials. Since the number of layers is great, but each layer is small in thickness, the use of linear approximation in the transverse direction is quite justified. For the exact representation of the geometry features and displacements, quadratic approximation was used in the plane of layer placement (in the direction of two other coordinates). As a result of mathematical modeling, an algebraic problem with 145296 unknowns was obtained. Its solution was based on the finite-element technique with the use of the grid described in plan and according to the placement pattern (each layer is a finite element). The mathematical model is described in detail in [2]. The calculation results for basic loadings (bending, tension, torsion) well agree with the experimental data.

Experimental Determination of the Elastic Element Service Life by Fatigue Strength Conditions

Two elastic elements (torsions) are the base of the “Ansat” helicopter MR hub; the elements are attached to the main reduction gear shaft through a splined joint of the hub central part. The test objects are the following:

1. The central part of the hub (metal).
2. The torsion (a half of the torsion with a hub part is tested on the benches).
3. The housing (is made of high-modular composite materials; is subjected only to torsional loads).
4. The adapter (a mating element between the blade and the torsion; it is metal).
5. Hinges (provide kinematics for housing displacements) are subjected only to wear tests.

During development of the “Ansat” helicopter lifting system, the design elements of torsions and mating elements were tested in order to perform design and technological analysis of the units and to confirm the proper conceptual design principles selected. The main objectives of bench tests in performing the research and development works are the following:

– selection of materials and study of strength and workability parameters of different-modular materials and their joints using standard specimens;

– check of technological processes in the units and their joints;

– check of static strength margin of the units and development of design models to study general and local strength of elastic elements and their joints;

– running for preliminary service life of the most critical elements for the helicopter flight tests;

– study of the quality check methods to select the most optimal ways of nondestructive check for the rotor elastic element quality.

The static tests of the elastic element structure as an assembly with the central hub part, adapter and a blade section serve to evaluate the general strength margin of the unit, to determine limiting displacements of an elastic element and possible failure zones, as critical loads are applied.

A specimen of the elastic element (with one arm) as an assembly with the adapter and blade section is subjected to fatigue tests. The loads on the specimen are applied on the automated hydraulic bench by six loading channels (Fig. 7) [4].

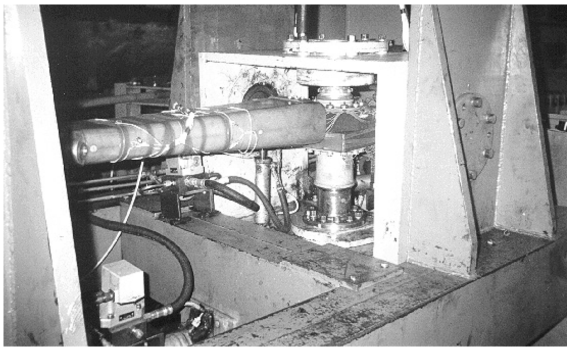


Fig. 7.

The specimen was subjected to service loads equivalent to those in the standard helicopter flight. Each subsequent regime duplicates increased loads on the specimen under test. The test process is automated, and the test conditions can be checked both visually by the loading channels, and the measurement results over entire test period can be archived. The scheme of strain measurement allows the parameters to be checked both by external loads and strains in the elastic element sections.

From the results of testing the given number of specimens a conclusion can be drawn regarding the initial assigned service life of the elastic element for flight and certification tests.

For the specified type and level of MR torsion loading there are local stress concentration zones, in which fatigue failure may occur during service; therefore, the torsion strength will be evaluated by fatigue strength of the material at a dangerous point. A fatigue process in the composite material starts when there appear nonelastic (microplastic) deformations accompanied by heat release. The parameters of thermal field dynamics at the specified type of loading depend on the load level and are a function of material life. In this case, the fatigue characteristics of a part can be predicted using dynamics of the thermal fields that appear in cyclic loading.

The quantitative evaluation of a thermal field on the torsion surface, the surface temperature gradient and heating rate can be used to select loading conditions during the bench tests and to predict the sites where failure starts. In addition, the scheme of loading on the bench can be specified by means of a thermal imager, so that the local zone of maximum loading coincide with that detected during service.

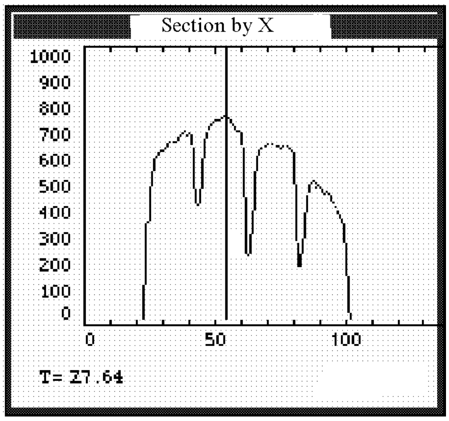


Fig. 8.

The MR torsion heating under cyclic tests was studied with the aid of a thermal imaging radiometer. The temperature values in the torsion transverse direction are presented in Fig. 8.

Providing for Design Service Life of the Unit Followed by Conversion to Service by Technical Condition

This problem is still under development for the Ansat helicopter main rotor. No sufficient statistical data on service of main rotors of the type under consideration are available.

In this paper we consider only the lines that can be conceived for solving the problem stated.

To ensure the specified characteristics of reliability and service life of an elastic element, the following problems must be solved.

1. To provide for design operation of the elastic element material within a fatigue range on the fatigue curve under all kinds of variable loads possible in service.

2. To provide for safe operation of the lifting system under conditions of local failures in the torsion material.

3. To develop a system of service monitoring over the elastic element condition.

The service life of the elastic element is evaluated by stresses measured during flight and fatigue tests in the most loaded torsion section. The design service life is determined by the formula

$$R = \frac{N_{redI}}{3600 \cdot f \cdot \eta_{\Sigma}} \left(\frac{\sigma_I^V}{\sigma_{eq}^V \eta_{\sigma}} \right)^m ,$$

where N_{redI} is the operating life reduced to the first test conditions under fatigue tests (cycle); f is the frequency of load action in flight; n_{Σ} is the reliability factor for the application of the hypothesis on linear summation of damages; $\eta_{\Sigma} = 2$ is the value of variable stresses under tests in the first conditions; σ_I^V are the variable stresses over flight that are equivalent in damageability; σ_{eq}^V is the reliability factor by stresses; m = 8 is the exponent on the fatigue curve.

Since the stresses under bench tests exceed flight stresses and the level of equivalent flight stress variables amounts to 3–5 kg/mm^2, the service life of the elastic element of the type under consideration may be 6000–8000 flight hours at the beginning of helicopter certification. As the extent of the helicopter flight tests increases, the number of the elastic element specimens after the bench fatigue tests grows, the service life characteristics of the most important element of the helicopter main rotor will increase.

The safe operation of the Ansat helicopter when local failures of the elastic element occur is ensured by two characteristics:

1. The elastic element in design is a multiply statically indeterminate structure with a multichannel system of load transfer. The operation of this multichannel system in the transverse direction is provided by the technological slots along the torsion axis and by the multilayered packet across the section height.

2. The materials of a fabric and a binding substance used in the torsion packets ensure the structural redistribution of the load transfer into the torsion zones that are not subjected to local failure.

The results of the bench tests have shown that partial failure of the upper packets in the elastic element makes it possible to retain the bench loads without changing the displacement amplitude.

The Ansat helicopter is today being subjected only to flight tests, and the development of a service monitoring system according to the program available in Kazan Helicopters is the nearest task. In the first turn, it is a part of the onboard measuring system in the program instrumentation module that provides for the check of flight loads on the lifting system and summation of damages that occur in the lifting system units over each flight. This system makes it possible to monitor the use of the elastic element service life under conditions of stationing at an operator. The software of this kind is being developed and will be a part of the onboard complex.

The instrument evaluation of the magnitude of the blade overhang at a station is a lower level of service monitoring. When local failure of one of the layers occurs or the cross section is separated, the blade end overhang increases and can be monitor by means of ground equipment.

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