INVESTIGATION, DEVELOPMENT AND TESTS RESULTS OF THE VARIABLE GEOMETRY ROTOR

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1. Introduction

It is known that the applied now rotors of various designs do not give the possibility of optimization of all flight process of propeller driven aircraft (A). It has been proved by many scientists that the full solution to this problem is possible only by application of the variable geometry rotor (VGR) due to simultaneous changes: rotor diameter and also setting angle and twist of blades in dynamics [1].

The application of the VGR especially is perspective to propeller driven airplanes with vertical takeoff and landing (VTOL) as on these aircraft the rotor functions in rather different loading conditions of the rotor blade. In the hover mode as the main rotor and in the cruise flight mode as propeller. The flight optimization of the VTOL is possible by providing the maximum diameter and minimum twist of the rotor blade in the hover mode and contrary the minimum diameter and maximum twist in the cruise flight mode. This will give the possibility to increase significantly payload or the flight speed and also decrease fuel consumption for the unit of transported load.

In connection with this the creation of the VGR effective design, which will be characterized by high technological efficiency, reliability, great resource and also will be convenient in exploitation is very actual task of modern aviation.

It must be noted that creation of the rotor with variable parameters in dynamics is also the actual task for other fields of technology, for example, wind energy and ship building. This is explained by the fact that on this problem during the last decades intensively work such famous and authoritative organizations as Sikorsky Aircraft Corporation, the Boeing Company, NASA, Bell Helicopters, ONERA, DLR etc. However, in the developed by them VGR-s the variable parameter is either only diameter or only twist that does not provide the maximum effectiveness of the rotor [2-8].

At the Georgian Technical University (GTU) in 1998 carrying out the International Science and Technology Center (ISTC) Project the Collaborator of which was Mr. L. Dadone, Senior Technical Advisor of the Boeing Rotorcraft Company was created the original VGR with ability of the changing control of diameter, setting angle and twist of the rotor blades in dynamics at the level of the model experiment. In Fig.1 is shown the kinematic diagram and in Fig.2 is shown the external view of the stand for the test of the created VGR in dynamics.

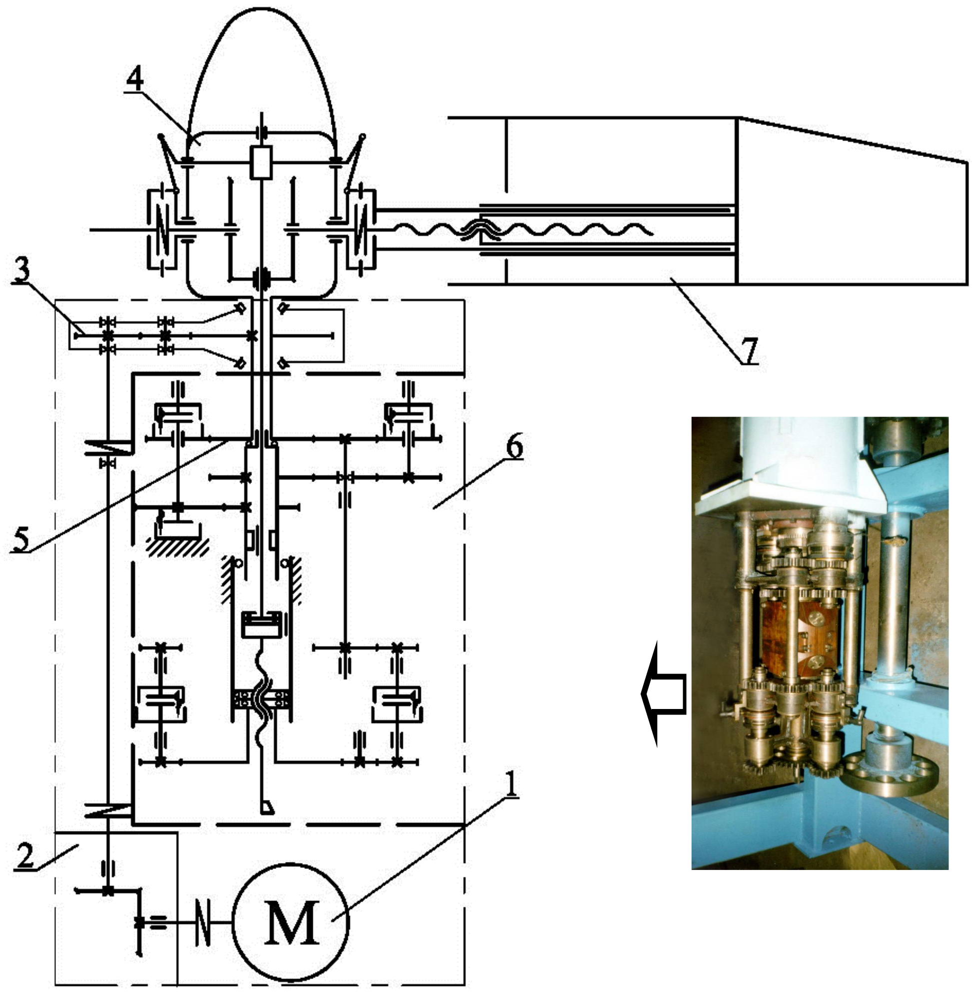

Fig. 1. Kinematic diagram of the test stand of the variable geometry rotor
1- electric engine; 2-conical reducer; 3- cylindrical reducer; 4-hub;
5-central pinion of coupler control, 6-control reducer, 7- blade.

The conducted experiments have shown that the action synchronism of control mechanisms of the VGR developed at the GTU in different cases was complicated and violated by influence of immense values of centrifugal forces to 40-45 tons on the blade movable parts.

That's why the objective of the following, present Project is the investigation and development of the system at least with the partial compensation of centrifugal forces in the control mechanisms of the VGR.

2. Raising of the Problem

The work priority trend is the experimental proof of possibility of the partial discharge of the rotor diameter change mechanism from the influence of centrifugal forces. It is important to note that compensation of centrifugal forces reducing the force influence on the VGR units provides the durability of the VGR design and its safety.

The expected result is the achievement of synchronic, reliable with big resource, stable functioning of the system “VGR – device of compensation of centrifugal forces – stand for dynamic tests” in the model experiment.

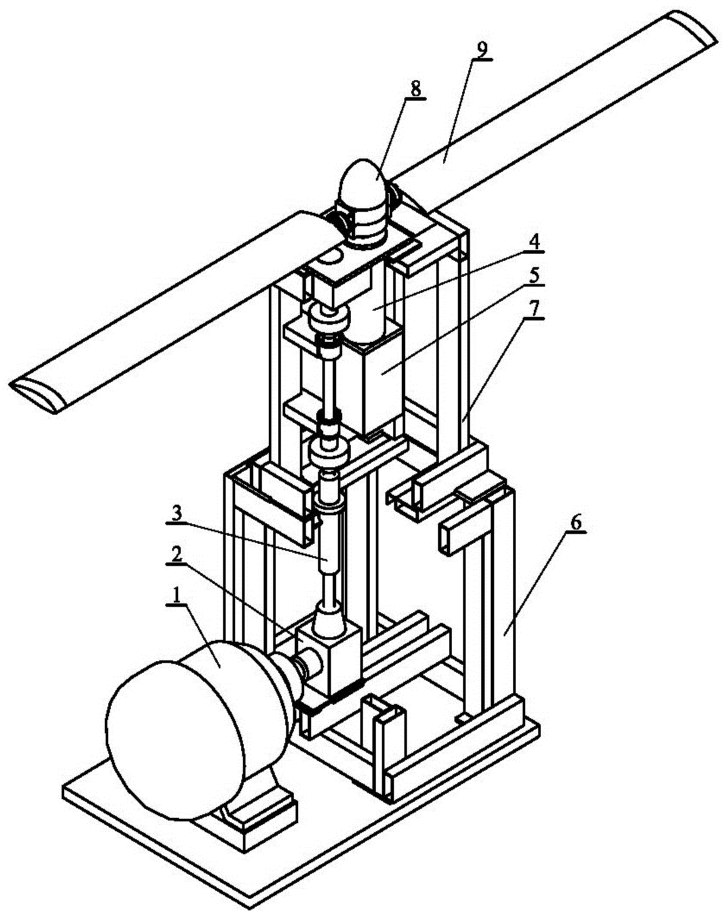

Fig. 2 Diagram of the stand for dynamic tests
1-electric engine; 2-reducer; 3-transmission; 4-spindle; 5-reducer; 6-lower frame; 7-upper frame; 8-hub; 9-blade.

In accordance with the International Standards ISO 9000, ISO 9001, EN9100 the Project is based on the process and system approaches.

The controllable variable geometry rotor with compensation of centrifugal forces is the system of interconnected and interacting elements of the VGR design and the device of compensation of centrifugal forces implementing the change process of diameter, setting angle and twist of the rotor blade in dynamics in relieved conditions as a result of compensation of influence of centrifugal forces.

3. Investigation and Development of the Compensation System of the Arising Centrifugal Forces Negatively Acting on the Functioning Process of the VGR.

The process of investigation and development was implemented on the basis of the model of management quality.

It was possible to use “Plan-Do-Check-Act (PDCA)” system (Plan-planning, Do-implementation, Check-check up, Act-action). However, the model of management quality does not give the possibility of the full review of the implementation process of creation of the planned article.

The input data were determined in the view of developed Technical Task (TT) which includes functional and exploitation requirements and is analyzed on sufficiency. The principal concept is the above-mentioned priority trend-experimental proof of the possibility of partial discharge of the mechanism of the rotor diameter change from influence of centrifugal forces. The alternative versions of compensation of centrifugal forces – mechanical, hydraulic, electric and combined were considered. In the system of compensation of centrifugal forces was used the accumulation of the acting energy of centrifugal forces in the hydro-pneumo-accumulator during extension of blades with subsequent its use for discharge of the diameter change mechanism during retraction of blades when the work conditions of the mechanisms are mostly loaded. Practically in this case we have the heuristic method for use of harm for the use.

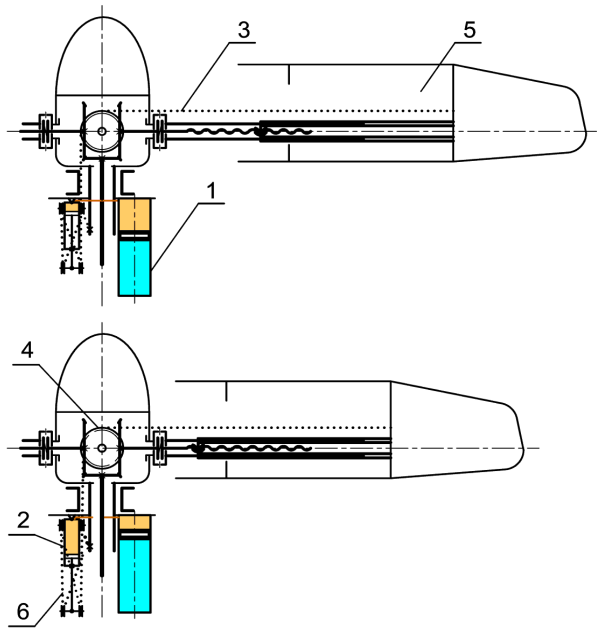

Fig. 3. Diagram of the VGR with located hydro-pneumo-accumulator and hydro-cylinder below the rotor hub.

Several design versions have been developed. Taking into account all the advantages and disadvantages of these versions and also productive capabilities of Georgia and what is the most basic according to the Collaborators Mr. J-J. Philippe and L. Dadone and also employees of

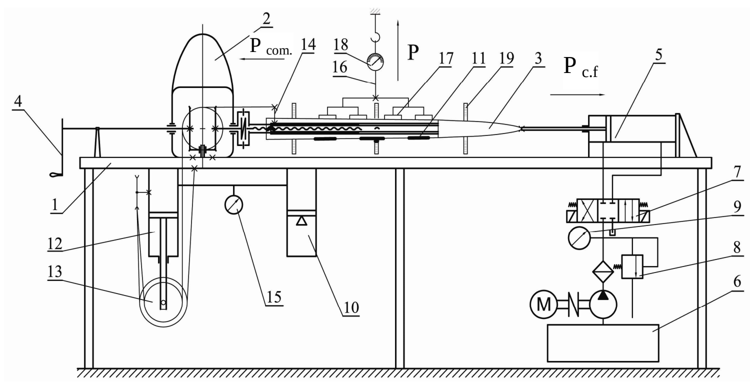

Fig.4. Diagram of the stand for static tests of the VGR. 1-frame, 2-hub, 3-blade, 4–handle, 5–hydro-cylinder, 6–hydro-station, 7–hydro-distributor, 8–reverse valve, 9-mano-meter, 10–hydro-accumulator, 11–spar, 12–hydro-cylinder, 13–pulley-block, 14-corbel, 15-manometer, 16 -rod, 17-lever system, 18-dynamometer, 19-ruler.


Fig. 5. Stand for VGR static.

“ONERA” for fabrication was selected a VGR model with the hydro-pneumo-accumulator and hydro-pneumo-cylinder located below the rotor hub.

In Fig.3 is shown a principal kinematic diagram of the VGR design selected version. One end of the rope 3 is fixed on the movable part of blade 5. With roller 4 the rope is connected with the mechanism of unloading influence of centrifugal forces, consisting of hydrocylinders 2 and pneumo-hydraulic accumulators 1. During the extention of blade 5, under the influence of centrifugal forces piston of hydrocylinder 2 is moved and it creates the excess pressure, which communicates with hydropneumoaccumulator. As a result, the oil overflows into the hydroaccumulator, where the energy is accumulated. With the retraction of blade 5 hydrocylinder 2 at the expense the accumulated energy creates an effort directed against centrifugal forces, which ensures the decrease of an effort on the nut. For decreasing the motion of the piston of hydrocylinder 2 pulley block 6 is used.

The advantage of this design unlike other versions is absence of additional parts and units inside of the rotor blade that excludes its charging. Thus, the blade profile relative thickness does not increase that does not worsen the rotor aerodynamic characteristics. Besides that the location of cylinders, hydro-pneumo-accumulators and elements of the compensation system in the direct nearness from the rotation axis of the rotor decreases the inertia moments of the design and is conducive to the reliable work of the rotor.

Designing of different units and parts is carried out by means of contemporary methods and programs of computer graphics “Auto CAD 2004” and “Mechanical Desktop 2004”.

During fabrication of the selected design were used precise equipment and precision methods of mechanical machining and for assembling the units characteristic for creation of precise articles in condition of individual production.

During conducting of dynamic tests of the VGR the workable stateHi of its units is the significant condition for sfaety guarantee. This caused the necessity of designing and fabrication of the stand for static tests for the safe definition of workability of the VGR parts and units at various conditions of loading (Fig.4 and 5).

The stand consists of frame 1 to which is fixed hub 2 with blade 3. On frame 1 on the left is fixed handle 4 that carries out the rotation of hub differential 2 during the extension and retraction of blade 3. On the right blade 3 is linked with hydro-cylinder 5 which imitates the influence of centrifugal forces. The feeding of hydro-cylinder 5 is carried out from hydro-station 6 with the control from hydro-distributor 7. The value of centrifugal force $P_{c.f.}$ is regulated by safety valve 8 and is measured by manometer 9.

The compensation force $P_{com.}$ is created by hydro-accumulator 10 and is transferred to hydro-cylinder 12 on which are placed pulley-block rollers 13 the rope of which is fixed on the blade spar 3 by means of corbel 14 and is measured by manometer 15.

Thrust P is transferred from the special small pitch strainer via rods 16 with tarpaulin straps 17 evenly fixed on blade 3. The thrust is measured by dynamometer 18.

By means rulers 19 are determined deflections of the blade at the given loads and its elastic line is constructed. It is possible to imitate on the stand the case of break down of the mechanism of compensation of centrifugal forces of the VGR i.e. to investigate reliability of functioning of the rotor mechanism. This can be carried out by disconnection of hydro-cylinder 12 and pulley-block 13.

The experiments have shown that after some finishings the blade design has sufficient stability and rigidity. Failures already were not observed. Experimentally were determined elastic lines at various positions of the blade, in retracted state, in extended state and also in several intermediate positions without compensation and with compensation of centrifugal forces. Various experimental investigations for different load conditions of the blade were carried out the results of which by corresponding analysis will be shown in the Final Report. In Figure 5 as an example is shown the elastic line at the medium position of the blade without compensation and in Figure 6 with compensation with compensation of centrifugal forces. The elastic lines are determined by deflections of the blade along it at the static influence of imitation of increase of the rotational speed. beginning with n=50 RPM to 350 RPM

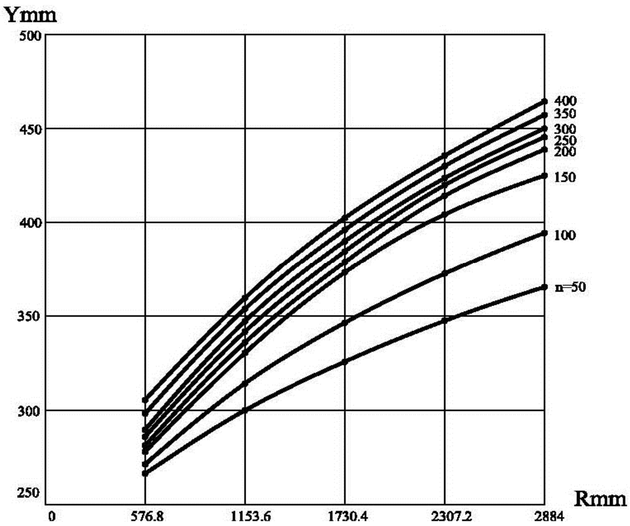

Fig. 6. Elastic line at medium position of the rotor blade without compensation of centrifugal forces.

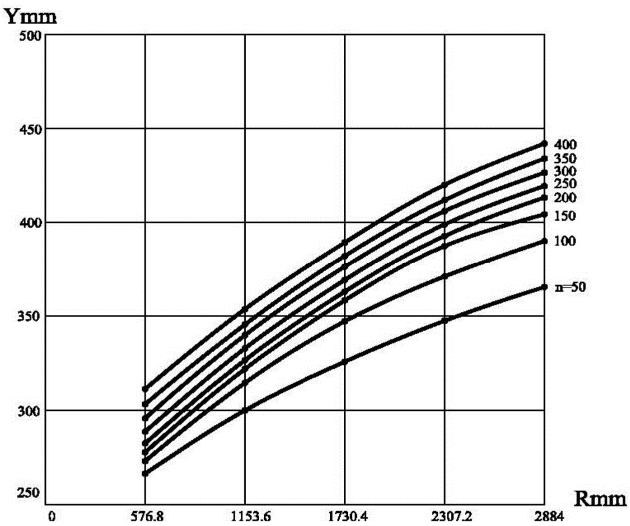

Fig. 7. Elastic line at medium position of the rotor blade with compensation of centrifugal forces.

In view of the fact that workability of parts and units of the VGR was provided it was possible to move to the VGR dynamic tests. For this purpose it was necessary to update the stand for dynamic tests earlier developed and manufactured by the Project team. The basic trend of updating this stand was in the necessity of account in the stand design of the compensation system of centrifugal forces. In Figure 7 is shown the diagram the updated stand for dynamic tests 1 added with block 2 for compensation of centrifugal forces. In Figure 8 is shown the photograph of the added unit of the centrifugal force compensation – a and the whole updated stand – b.

The most significant meaning has the quality value of the system of compensation of centrifugal forces for definition of its effectiveness.

The experiments conducted on the stands for static and dynamic tests have proved the

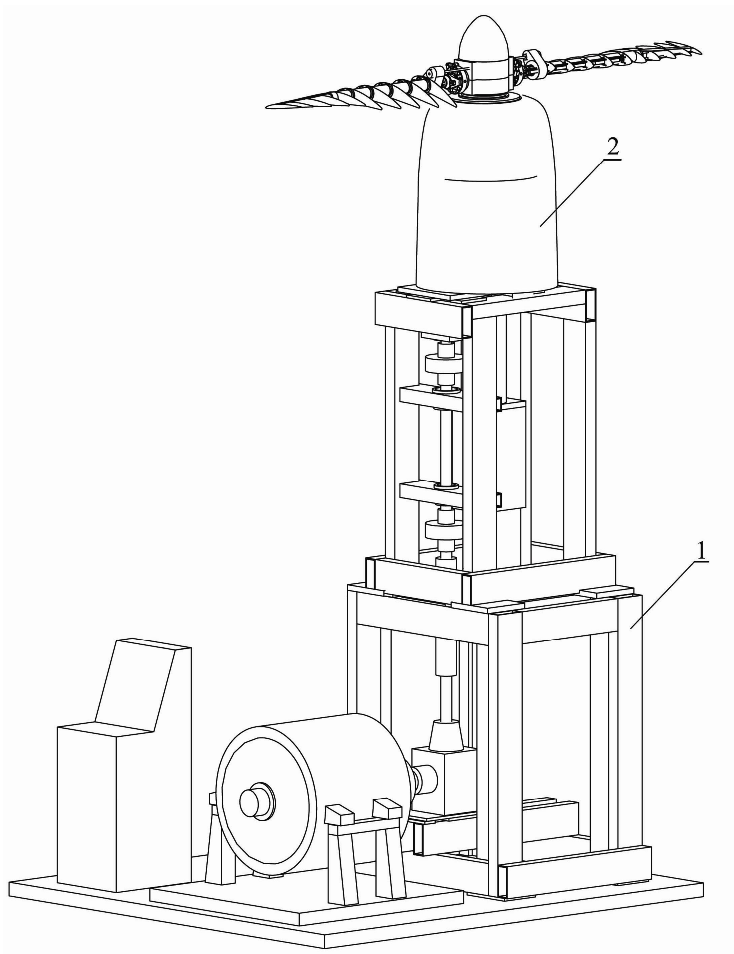

Fig. 8. Diagram of the stand for dynamic tests of the VGR.

a

b

Fig.9. Stand for dynamic tests of the VGR.
a–mechanism of compensation of centrifugal forces.
b–stand for dynamic tests with the mechanism of ccompensation of centrifugal forces.

effectiveness of application of the hydro-pneumo-accumulator in the system of compensation of centrifugal forces. The reduction of the value of compensated force in medium by 40% has been reached (Fig.9).

On the absciss axis are shown changes of the blade length value i.e. of the rotor diameter which imitates loading of the rotor at the imitated rotor rotational speed to n=350 RPM.

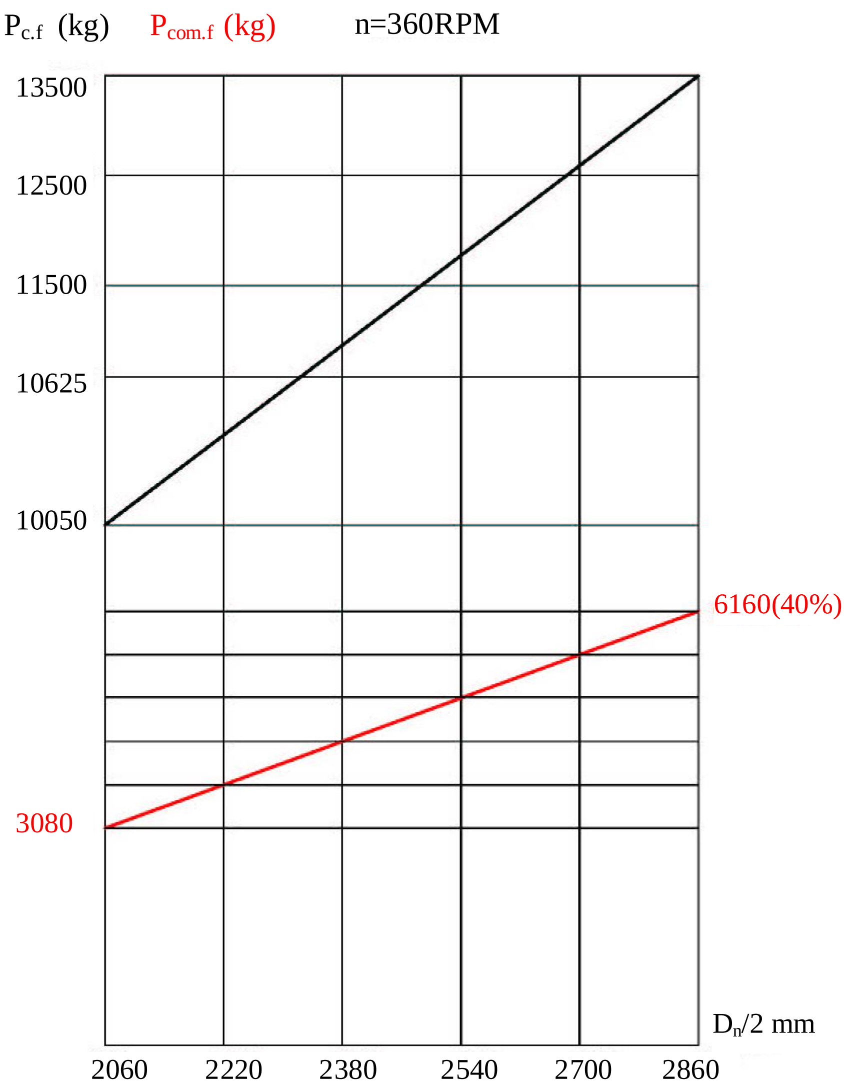

Fig. 10. Illustration of effect of compensation of centrifugal forces.

On the ordinate axes are shown the values of imitated centrifugal forces. Value 3080 kg corresponds to the initial value of charging of the hydro-pneumo-accumulator, 1050 kg is the centrifugal force value at the blade minimum diameter and 13500 corresponds to the centrifugal force value at the rotor maximum diameter.

With the increase of the rotor diameter and growth of centrifugal forces simultaneously increase compensation forces that is preconditioned by the adiabatic process flowing in the hydro-pneumo-accumulator.

In Figure 10 is shown that at the maximum diameter the compensation force reaches the value of 6160 kg. It forms 40% of the maximum centrifugal force. As a result the jack-screw of the mechanism of the rotor diameter change is discharged from the harmful influence of centrifugal forces in extreme conditions of the rotor blade retraction.

The reduction of centrifugal forces by 40% is not the limit. The experiments and theoretical calculations have shown that it is possible to increase the compensation effectiveness to 70-90% by means of increasing size dimensions, selection of the necessary relation of the diameter and length and also the value of the initial charging of the hydro-pneumo-accumulator.

The effectiveness of the compensation system was also proved by the continuous extensions and retractions of the blade in dynamic tests during definition of the thrust-T in all the change range of the rotor rotational speed and diameter.

There are various methods of the thrust definition: Indirect method on measuring of electric engine power, method of dynamometering, method of weighing, method of receiver of air pressure with U-shaped manometer, method of the pressure integrator, method of measurement of the air flow by the revolving-vane analyzer with subsequent definition of the thrust..

Having analyzed the essence of all these methods and also the possibility of conducting experiments in Georgia we have considered that for solution to our problem which is in the qualitative estimation of the thrust force change depending on change of the diameter or the rotor rotational speed the most optimal and sufficiently acceptable is the known in literature simplified method of anemometers.

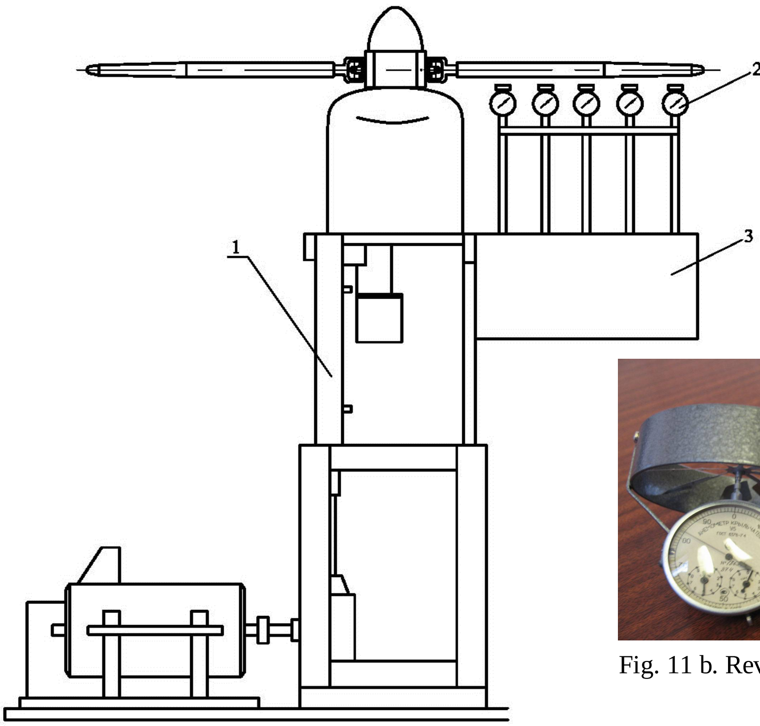

Fig. 11 a. Diag ram of the device for measure of the rotor thrust on the stand by measuring speeds by means of anemometers.
1-VGR stand, 2–anemometers, 3–frame for setting anemometers.

Fig. 11 b. Revolving-vane analyzer ACO-3.

The essence of this method is in the fact that anemometers measure the air flow medium speed in several points along the blade span (Fig.11a, b). The air flow medium speed is being calculated and by the known dependences of aerodynamics via the induced speeds of air flow we determine the thrust.

In Figure 12 is shown the distribution of induced speeds along the rotor blade span.

It is seen that curves have obviously expressed minimums that are located along the rotor blade span depending on the diameter value. At the minimum diameter the minimum is located closer to the hub than at the maximum diameter.

In Figure 13 is shown the dependence of the VGR thrust from the rotational speed at the minimum and maximum diameters determined during dynamic tests. On Figure 13 it is seen that the diameter increase 1,4 times causes essential growth of the rotor thrust. With the growth of the rotor rotational speed the thrust values linearly increases (on the absciss axis are put squares of values of the rotational speed).

As any article of aero-space technology investigations and developments in the field of the VGR must be characterized by the constant improvement of the system of quality management especially in the part of reliability of the mechanisms of change of the diameter, setting angle and widening of the blades twist range.

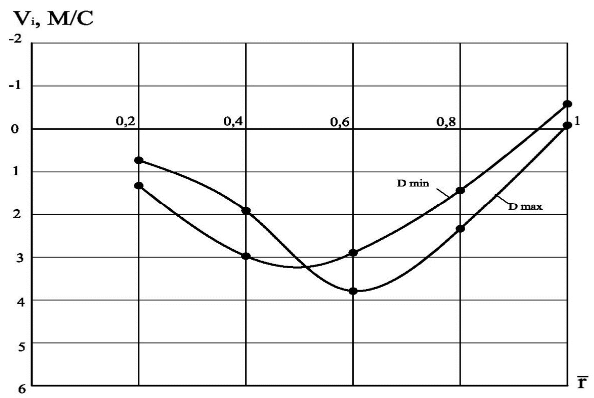

Fig.12. Diagram of distribution of inductive speeds along the blade span for various diameters of the rotor.

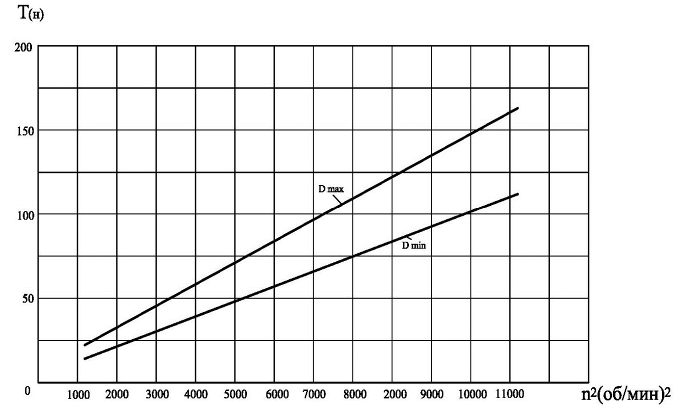

Fig.13. Diagram of dependence of VGR thrust from the rotor rotational speed for the case of the blade setting angle $\varphi_{0,75}=15^0$.

On the first stage it was necessary to prove controllability of the twist change of blades simultaneously with the rotor diameter changes. The principal design solution was reached by angle movements of ribs around the spar at the rigid casing. The experiments have shown the possibility of twist change not more than 15^0. According to the Collaborators' advice the controllability of the twist change is desirable to be taken to $40\text{-}45^0$. For this purpose the Project team suggests new design solutions in a view of deformed casing or different sections of blades with widening of the manipulation range of rib movements. There are also new design solutions of the rotor diameter change and compensation of centrifugal forces. We hope that all these design solutions after agreement with the Collaborators can become the basis of the new international projects.

Conclusion

1. The reliable system of compensation of centrifugal forces arising during work of the VGR and influencing harmfully on the most significant element of the design-jackscrew especially during retraction of blades has been developed and manufactured. The tests have shown that at the maximum diameter compensated power forms approximately 40% of the maximum centrifugal force. As a result the mechanism of the rotor diameter change discharges in the extreme conditions of the rotor blades retraction. The analysis of the developed design shows that at the corresponding selection of parameters by means of the dimensional size increase, selection of the necessary co-relation of the diameter and length and also the value of initial charging of the hydro-pneumo-accumulator is possible to increase the compensation effectiveness to 70-80%.
2. For evaluation of the workability of the VGR units at different loads the stand for static tests has been developed and manufactured. In advance theoretically are determined expected centrifugal forces and thrusts at various VGR rotational speeds. The stand for static tests gives the possibility to carry out imitation of influence of these forces on the blade at various loads and determine deformations of the blades main elements and also workability of the mechanism of change of the rotor diameter and blade twist at the given loads and corresponding deformations. Preliminary tests were conducted, elastic lines at various positions of the VGR were constructed and dependences of forces in jackscrew transmission at various loads with compensation and without compensation of centrifugal forces were determined. These experiments are basic for conducting dynamic tests as they guarantee the safety of experimental work.
3. The existing stand for dynamic tests has been updated with addition of the block of system of the centrifugal force compensation that gives the possibility of comparison of work conditions of the mechanisms of the VGR geometry change with compensation and without compensation of centrifugal forces at various rotational speeds.
4. The distribution of induced speeds of the air flow along the rotor blade span has been investigated by means of the revolving-vane analyzers and by well-known dependences of aerodynamics the VGR thrust is determined depending on the rotational speed and setting angle at various diameters of the rotor.

5. The method of multilateral investigation of the created VGR was developed both on the stand for static tests and the stand for dynamic tests. A number of tests have been conducted and positive results have been obtained.
6. According to the Collaborators' advice the controllability of thrust must be increased to 40-45^0. For this purpose the Project team has got the new design solutions, control systems of the diameter change, increase of the blades twist range and also perfection of the centrifugal force compensation. These solutions after agreement with the Collaborators and other competent specialists can become the basis of the new international projects.

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