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# DESIGN SOLUTION AND STRUCTURAL OPTIMISATION OF FEATHERING HINGE ASSEMBLY OF TEETERING ROTOR HEAD FOR TIP-JET HELICOPTERS

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***Abstract:*** *If one compares the tip-jet helicopters to the conventional ones, one of the most important disadvantages are the much heavier blades, due to the massive inner channel for operating fluid transport through its structure. This increased blade mass causes a significantly larger centrifugal force that loads the construction of the rotor head, especially the feathering and teetering hinge. The case study of this paper is feathering hinge assembly of teetering rotor head for ultra-light tip-jet unmanned helicopter. The new design solution and structural optimization for such engineering problem is presented in this paper. The described construction solution is developed for a new project of unmanned helicopter Hussar based on the experience and knowledge achieved on the previous helicopters ATRO-X and Hornet.*

***Keywords:*** *tip-jet helicopter, feathering hinge, rotor head, structural optimization, design solution.*

## 1. INTRODUCTION

The tip-jet helicopters are very rare and specific in design. This concept is based on the propulsion force on the blade tips, which causes the rotation of the blades. These propulsion forces, one on each blade, are directed tangential to the rotor disc and can be created in several different ways, by rocket engine, by exhaust gasses of the turbo jet engine, by high pressure compressor etc. ([1],[2]).

In each of these cases a fluid must be transported through the blades to their tips, so the structure of the blade has to be hollow. This has a negative effect on the load capacity of the structure, if compared to the conventional structure of the blades, with ribs, stringers, spars, skin etc. For blades of the tip-jet helicopter, which are driven by some turbo jet or turbo shaft engine, a large amount of space (cross-section) is needed for the transport of the operating fluid due to the large mass flow.

During the past several years, the EDePro company has been developing and testing conventional and tip-jet types of helicopters. The first developed, produced and tested concept is ATRO-X tip-jet helicopter [3] which uses a turbo-jet engine as a generator of hot gasses, combustion products, Figure 1. This operating fluid, at high speed, pressure and extremely high temperature of 700°C is transported through the blades which are made by welding of Inconel sheetmetal. This concept of tip-jet helicopter is called "hot" cycle tip-jet. It implies much heavier blades compared to the light aluminum or composite blades of the conventional helicopters. On the other hand, tip-jet helicopters require a larger diameter of the rotor disk and larger speed of rotation than the conventional helicopters. These facts lead to very high centrifugal forces that load the structure of the helicopters' rotor head.

The new design of the Hussar tip-jet involves the turbo shaft engine [4], which spends all its power to drive the compressor which creates a high pressure of relatively "cold" operating fluid – compressed air. Due to lower temperature, the blades could be made from aluminum alloys but it requires an even longer blade. The effect of the centrifugal force of blades is almost the same as in the previous design concept.

The most affected parts of the helicopter rotor head, due to the large centrifugal force, are the assembly of the feathering hinge and, in our case, the central part of teetering hinge ([5],[6]).

The case study of this paper is the feathering hinge of Hussar tip-jet helicopter, **Figure 2**. In order to enable the rotation of the feathering axis due to continual blade pitch change, the most usual design uses several angular bearings installed in set. But this solution has its own limits, in terms of dimensions and number of required bearings. In case of the tip-jet helicopters, if very high centrifugal force is reached, we propose the usage of a thrust bearing in combination with two deep groove bearings.

**Figure 1.** ATRO-X tip-jet helicopter

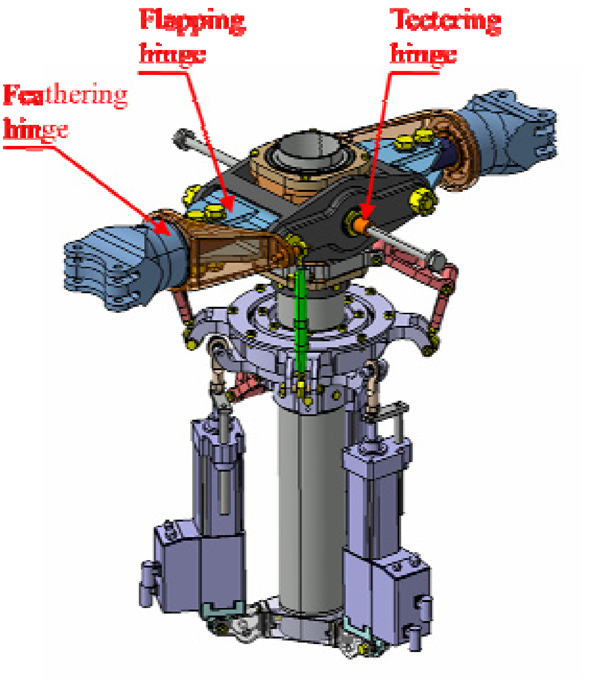


**Figure 2.** Rotor head and position of feathering hinge

The design solution for the feathering hinge subassembly for the tip-jet helicopter rotor head and structural optimization of the most loaded part are presented in this paper.

## 3. DESIGN SOLUTION

The most common feathering hinges, for the light helicopter and therefore light blades, are comprised of several angular bearings combined in one set in order to provide the ability to rotate around the pitch axis of the blade and to withstand the centrifugal force of the blade. The feathering hinge of the rotor head of the Hornet helicopter has this kind of construction of bearing arrangement installed in it, **Figure 3**.

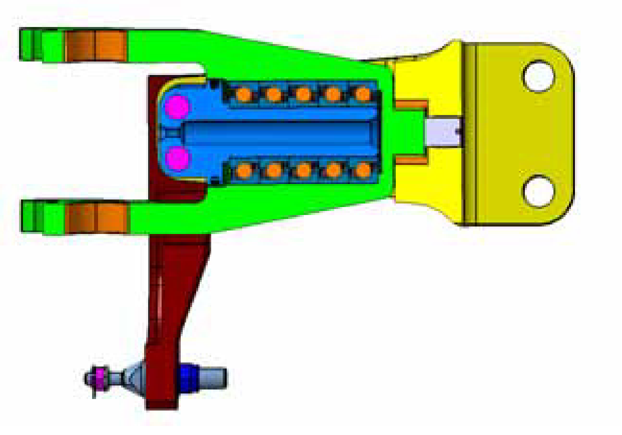


**Figure 3.** Bearing arrangement of the feathering hinge on Hornet helicopter

The blades of the Hussar helicopter are much heavier and longer than Hornet's blades and create an at least 2-3 times larger centrifugal force. This implies that much more than five angular bearings for each set of the blade are needed, which leads to an increase in length as well as in weight of the assembly. The alternative solution is to use bearings that are larger in diameter with more load capability, but it also leads to higher diameter and more mass.

Based on the previous facts, we chose the combination of one thrust bearing with high load capability for axial force – centrifugal force, and two deep groove bearings for the radial position of the assembly and for radial loads. As there is a flapping axis of the blades, there is no significant radial load. But when the helicopter is on the ground and the blades do not rotate (there is no lift force), there is a static radial load on these bearings due to the blade weight. As the center of mass of the blade is on the large arm, the weight of the blade creates significant amount of momentum that loads the radial bearing of the feathering hinge. This static force must be taken into account for calculation. On the other hand, thrust bearing withstands all of the axial force due to the centrifugal effect of the blade rotation. As pitch change of the blades is relatively small, only a few degrees over time, the static load capability of the thrust bearings corresponds to the calculation of the bearing.

The proposed design solution for the feathering hinge of tip-jet helicopters is shown in the following **Figure 4**. This construction is already installed in the ATRO-X helicopter and it proves to be satisfying during the hovering test of the helicopter. For the Hussar tip-jet helicopter this solution is used as verified.

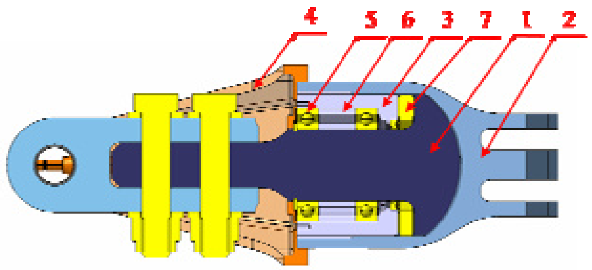


**Figure 4.** Feathering hinge of the rotor head for Hussar helicopter

## 4. STRUCTURAL OPTIMISATION

The feathering hinge of the Hussar helicopter consists of the hinge support (1), blade grip (2), bearing nut (3), pitch control horn (4), radial bearings (5) with distancing bushes (6), thrust bearing (7), and etc.

The most loaded part of the feathering hinge assembly is the hinge support **Figure 4**, (1). Apart from having to withstand the high longitudinal load, it also has to satisfy more rigid demands of deformation in order to keep the surface flat for the thrust bearing. The permissible axial deflection of this flat surface for normal thrust bearing operation and life estimation is 0.01 mm.

The structural optimization of the feathering support part is presented through the following figures. Structural calculations were performed by using the Finite element numerical model. Optimization refers mostly to the right side of the part, where the thrust bearing should be installed. The left side of the part is not to be optimized since it can be easily calculated and predicted by analytical methods.

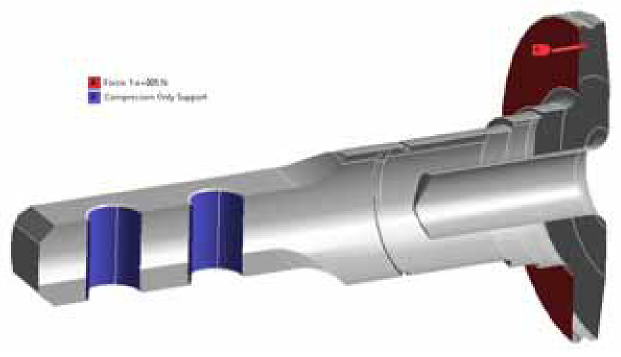


**Figure 5.** Part shape in the first iteration

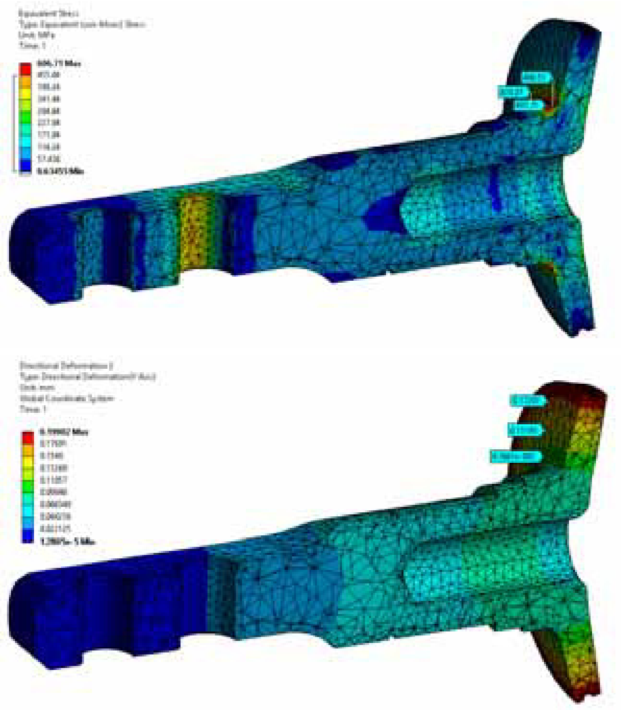


**Figure 6.** Stress and longitudinal deformation distribution on the part in the first iteration

The first part has a shape of a flat disk on the right side where the thrust bearing should be installed, **Figure 5**. Load, due to centrifugal force, is 100,000 N, and there are two holes for adjusted screws where the reaction forces act. A "Compression only support" boundary condition is used for these cylindrical surfaces.

The results are not satisfactory from both points of view, **Figure 6**. Equivalent (von-Mises) stresses are above the permissible limits, but much more critical are the deformations of the flat surface for the thrust bearing which are 16 times bigger than the permissible value 0.01 mm.

The second iteration was performed to increase the rigidity of the right side of the part by adding ribs, as shown in the **Figure 7**. The idea is to create better support from the right side which will increase the rigidity of the surface where the thrust bearing should be placed.

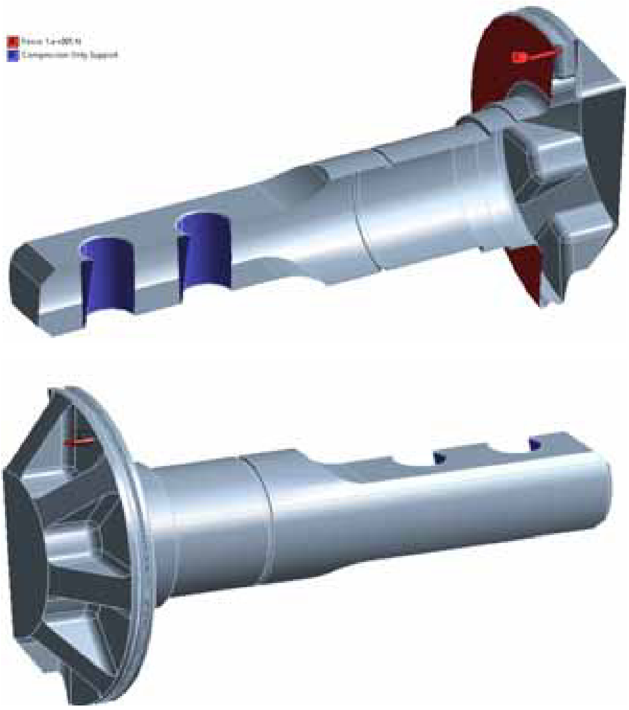


**Figure 7.** Part in the second iteration

The boundary conditions and longitudinal load were the same for the second iteration. The results are presented in **Figure 8**.

Stress values for the shape of the part in the second iteration were two times lower than the previous and within acceptable limits. The deformation of the flat surface is significantly lower but still 2 times bigger than the required value of the 0.01 mm.

In the third iteration, the part on its right side has the shape of a hemisphere, so it is very massive on this side, **Figure 9**.

The boundary conditions and the longitudinal load were the same as in the previous iterations. The results are presented in **Figure 10**.

The stress values for the shape of the part in the third iteration were much lower than previous and within acceptable limits with higher degree of safety. The deformation of the flat surface of 0.006 mm is below the limiting 0.01 mm which achieves the demand for rigidity. Based on the results, this part and its hemisphere shaped right side have the ideal form for the lowest stresses and deformation.

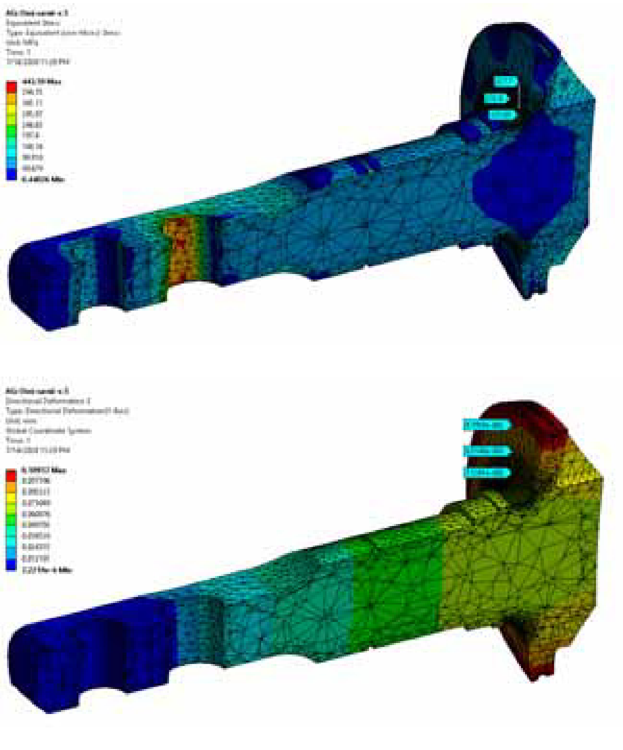


**Figure 8.** Stress and longitudinal deformation distribution on the part in the second iteration

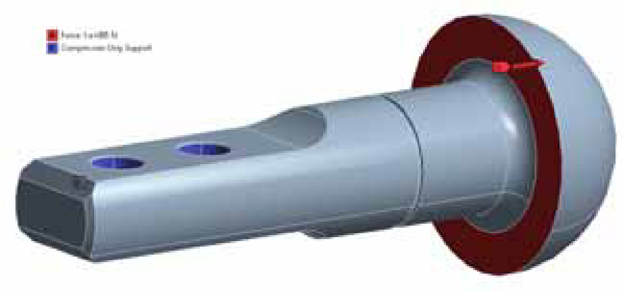
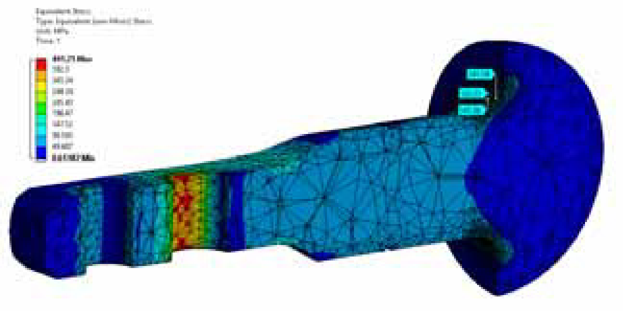


**Figure 9.** Part shape in the third iteration

But as the part is used in aerospace engineering, its massive shape is not desirable. So, some compromise should be made in terms of increasing the stresses and deformation on the limit values while the mass should be significantly decreased.



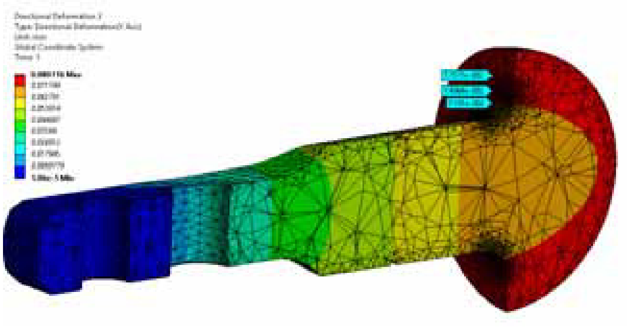


**Figure 10.** Stress and longitudinal deformation distribution on the part in the third iteration

The shape of right side of the part in the last iteration is changed to a partial sphere (less than hemisphere). The following **Figure 11** shows the geometrical model for this iteration. The numerical model has the same boundary condition and load value.

**Figure 11.** Part shape in the last iteration

In the last iteration, the equivalent stresses on the radius below the surface on which the thrust bearing should be placed are larger but acceptable with safety factor above 3. The deformation of the flat surface is around 0.012 mm which is near the permissible limit for normal bearing operation **(Figure 12).**

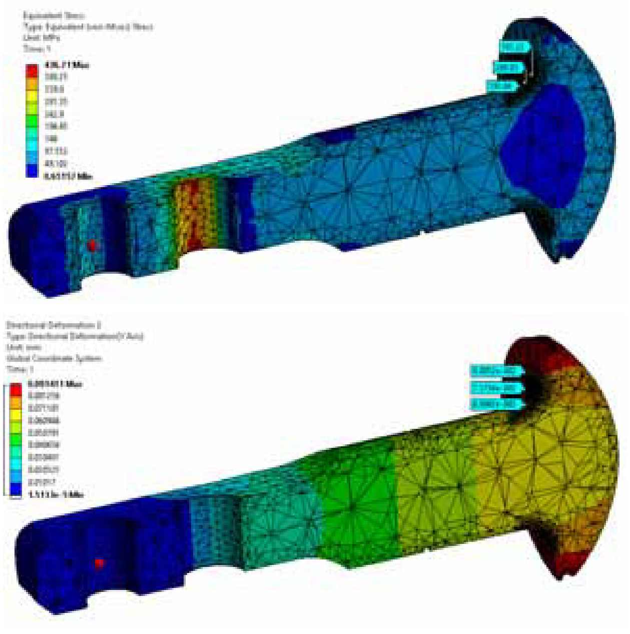


**Figure 12.** Stress and longitudinal deformation distribution on the part in the last iteration

## 5. CONCLUSION

The proposed design solution that consists of the thrust bearing in combination with two deep groove bearings is used and proved to be satisfying on the previous tip-jet helicopter ATRO-X. This design has smaller longitudinal dimension with the same diameter as the conventional design solution with several angular bearings. Especially for tip-jet helicopters this solution meets all requirements and is more suitable than the conventional solutions.

Based on the result from last iteration of the structural optimization, it was concluded that the last shape with the part of sphere on the right side of the feathering hinge support part is optimal from the point of demanded stress and deformation as well as of minimal mass.

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