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Planetary transmission for propeller propulsion in the new generation of flying models

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The article presents a planetary gear design, which in combination with an electric motor will allow to obtain an increased torque enabling the propulsion of large, high-performance propellers of modern flying models. The proposed solution allows the use of standard high-speed DC or brushless motors. In addition, the innovative design of the transmission provides high stiffness of the mechanism necessary to counteract the gyroscopic effects generated by the large propeller. The use of high-strength aluminum alloy ensures low weight of the entire mechanism.

KEYWORDS: *planetary transmission, design of planetary gear, engine, aluminum alloy*

Introduction

Man has always been fascinated by the possibility of flying, as evidenced by large variety of flying machines created during technical development of humanity. Large flying structures were built, as well as small devices used for practical checking of new ideas. At the same time, models designed exclusively for fun were constructed, which, however, for a long time were complicated constructions, requiring a lot of technical knowledge and experience - both at the stage of construction and subsequent flight operation. Recently, the development of technology has significantly simplified the construction of flying models and thus their popularizing. This was reflected in the range of devices that allow to play with flying, and above all, drones.

Modern electric flying model consists of several basic elements. The most important of them are: the frame - most often made of light materials, highly integrated control electronics, modern light batteries that store large amount of energy, and a drive motor (and often several drive motors). Modeling engines have also recently undergone a major evolution. This applies especially to the introduction of brushless motors, i.e. synchronous DC motors, which have the ability to develop high power with extremely low weight and small construction dimensions. Unfortunately, engines suitable for use in small models are usually high-speed and as such are not suitable for efficient propeller drive - in this respect, low-speed engines would be preferable, but they are too large [2]. Therefore, it would be necessary to connect the electric motor with a small gearbox

that reduces the revs and thus increases the torque driving the propeller. Currently, such gears are found almost exclusively in helicopter models. They use cylindrical, angular or belt gears [1]. They have many disadvantages, such as: inability to transfer high torque, low rigidity of bearing nodes or high weight.

A partial solution to these problems may be the use of a planetary gear, in which the torque is distributed to several satellite wheels [4]. Such a construction, enriched with new technical solutions and made of lightweight aluminum alloys, can contribute to the creation of a new generation of flying models.

The paper presents an innovative design of a planetary gearbox connected to an electric motor, free from defects typical of currently used gears.

Construction description

The mechanism was designed in Autodesk Inventor Professional. It is a parametric program that allows three-dimensional design of parts, which can then be virtually assembled into components and ready machines. This program has many functionalities facilitating the design process, such as collision analysis of components, kinematics and dynamics - to control the cooperation of components, as well as strength analysis and modal analysis, carried out by the finite element method [5, 7].

Fig. 1. Planetary gear: a) general view, b) cross-section, c) cross-section rotated by 45°. Designations: 1 - electric motor, 2 - external body, 3 - cover, 4 - internal body, 5 - engine cover, 6 - ring wheel, 7 - satellite, 8 - sun wheel, 9 - axle, 10 - bearing, 11 - spacer, 12 - screw, 13 - planetary gear cage, 14 - main bearing, 15 - screw, 16 - main bearing, 17 - screw, 18 - pin, 19 - nut, 20 - special fields for mounting propeller blades, 21 - special box for attaching the gear to the flying model

The mechanism (fig. 1) includes a planetary gear and an electric motor 1, which is the drive of the gear, screwed to the internal body 4 with screws 15. The internal body 4 is completed by the engine cover 5 and the ring gear of the planetary gear 6, forming the internal body assembly. All three elements are bolted together with pins 18 and nuts 19. The internal cover of the main bearings 14 and 16 are mounted on the engine cover 5 and the internal body 4. The engine cover 5 has a special field 21, enabling the gearbox to be attached to the flying model. The outer race of main bearings 16 and 14 are based on cover 3 and planetary gear cage 13. Cover 3 is screwed to external body 2 with screws 17. Planetary gear cage 13 is also screwed to external body 2 with screws 12. Cover 3 connection, the external body 2 and the planetary gear cage 13, forming the external body assembly, allows them to rotate around the internal body 4, while at the same time transmitting the drive moment of the planetary gear to the external body 2 [6].

The external body 2 has special fields 20 for attaching the propeller blades of a flying model. The planetary gear includes the sun gear 8 cooperating with satellites 7 and the ring wheel 6. The sun gear is mounted on the drive shaft of the electric motor 1. Satellites 7 are based on axes 9 through bearings 10. Bearings 10 are held in the correct longitudinal position on axes 9 by spacers 11. The axles 9 are mounted in the planetary gear basket 13 and the external body 2. The ring wheel 6 is bolted to the internal body 4 by means of pins 18 [6]. The 14 and 16 main bearings are extremely important structural components. Their large spacing ensures rigidity of the entire transmission mechanism. The proposed placement of bearings also allows the use of heavy load bearing units. These two properties are important especially in the context of tasks assigned to the whole mechanism.

Principle of operation

Fig. 2 shows a view of the planetary gear used in the described construction. The drive torque from the motor 1 is transferred to the sun gear 8. Satellites 7 mesh with the sun gear 8 and the ring gear 6. This ensures the driving torque rotating the axles 9 around the sun gear 8. The torque is transferred from axis 9 to the planetary gear basket 13 and on the external body 2 connected to it. As a result, the external body 2 is rotated

by the driving torque of the motor 1, multiplied by the planetary gear ratio. These gears allow for a high gear ratio exceeding 8:1. After attaching the propeller blades of the flying model to the external body 2, it is possible to propel the propeller with high drive torque [6].

Fig. 2. View of the planetary gear subassembly without the external body

Material used

The proposed mechanism has slightly larger dimensions than the electric motor itself, and also has additional mechanical elements, which causes an unfavorable increase in the weight of the entire structure. To remedy this, an attempt was made to create a new material that would at least partially eliminate these drawbacks. The aluminum alloy presented below was developed with a view to using it in light machines, with particular regard to flying models. Due to the operating conditions of the gearbox, the tests also included behavior of the material at a reduced temperature. For the construction of the planetary gear, an aluminum alloy EN-PN 2024 was used, which was subjected to a patented hybrid treatment, consisting of a combination of two-stage aging T6I6 with subsequent plastic treatment SPD-ECAP [3]. The use of heat treatment leads to an increase in the hardness of the alloy from 132 HV10 to 156 HV10. In addition, plastic machining after the T6I6 process reduces the alloy grain from 450 μm to approximately 30 μm (fig. 3) and, as a consequence, improves mechanical properties of the alloy.

Analysis of EN-PN 2024 alloy strength changes after the ECAP process was based on a static compression test according to PN-57/H-04320 at room temperature and $-80\text{ }^{\circ}\text{C}$. During the tests, the highest strength was obtained for deformed samples according to scheme B ($R_{plc} = 630\text{ MPa}$, $\Delta l = 1.2\text{ mm}$), while the highest plasticity - for deformed samples according to scheme BB ($R_{plc} = 432\text{ MPa}$, $\Delta l = 4.6\text{ mm}$) and BC ($R_{plc} = 444\text{ MPa}$, $\Delta l = 4.7\text{ mm}$). Results of the strength tests are shown in fig. 4.

Fig. 3. Image of the EN-PN 2024 alloy structure after plastic deformation by the ECAP method

Fig. 4. Tensile strength of EN-PN 2024 alloy after T6 and T6I6 machining at room temperature (RT) and -80 °C

Fig. 5. Fatigue strength of EN-PN 2024 alloy after T6 and T6I6 machining at room temperature (RT) and -80 °C

Fatigue strength tests were carried out at room temperature (RT) and -80 °C. Samples were frozen in LN_2 and then tested in a thermal chamber isolating from external conditions, in accordance with PN-67/H-04326 (pendulum cycle). Fatigue strength was determined for the number of $N_G = 107$ cycles with 0.01 mm deflection. It was found that T6I6 machining increased fatigue strength Z_G by 10÷15% - both at RT and -80 °C ($Z_{G\ T6\ (RT)} = 132$ MPa, $Z_{G\ T6I6\ (RT)} = 145$ MPa, $Z_{G\ T6\ (-80\ ^\circ C)} = 152$ MPa, $Z_{G\ T6I6\ (-80\ ^\circ C)} = 162$ MPa). Results of fatigue tests are shown in fig. 5.

Construction data

Described construction uses a 5580 W brushless motor at 6350 rpm shaft speed. It is an engine designed to drive large flying models, e.g. airplanes and drones. In the case of such large engines, the manufacturer does not offer a gearbox enabling reduction of the rotation of the shaft, on which the propeller is mounted [2]. The engine weight is 1.45 kg, and the weight of the entire structure - 3.2 kg.

Presented planetary gearing has a 6:1 ratio, therefore the engine shaft speed is reduced to about 1050 rpm, with which the gear body rotates. The gear ratio was selected on the basis of information on the offered gearboxes combined with the engines of flying models - most often it ranges from 4:1 to 6.7:1. With current construction dimensions, the transmission theoretically ensures that 6300 W power is transferred from the engine to the propeller. Such excess power is necessary because of the impossibility of a perfect dimensional gearing, which means that it is not possible for each of the four satellite wheels to fully transfer the assigned part of the propulsion engine power.

For drones, constructions containing four, six or eight propulsion engines (and sometimes even 10, 12 and 16) are most often used to obtain greater load capacity [8]. Currently, the largest drones are agricultural

machines with a load capacity of 10÷20 kg, designed for spraying fields [9]. This is due to regulations restricting the use of large transport drones in urban areas. High load capacity, possible to achieve by the proposed structure, predestines it for the use in drones with even greater payload, and in the future - even in machines for transporting people.

Summary

Proposed propeller head design opens new possibilities in the construction of large flying models that will have a significant load capacity with low energy demand. The use of high-performance, low-speed propellers will also significantly extend the life of the model on one set of batteries. This is very important for drones, working time of which is closely related to the capacity of a battery.

Due to the compact design of the gearbox and the use of modern, light materials, the low starting weight of the model will be maintained. High rigidity of the propeller bearing system will ensure trouble-free operation under heavy loads resulting from maneuvers, e.g. quick changes of direction. Appropriate location of the gearbox mounting points will allow it to be installed in the place provided for the electric motor - without the need for structural changes in the frame of the drone, helicopter or aircraft.

Slow-rotating propellers will significantly reduce the noise generated by the flying model, which is important when used for recording movies.

Described advantages of the propeller head mean that it can be used in modern drones, models of planes and helicopters.

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