INVESTIGATION OF 'JUMP TAKE-OFF' POSSIBILITY FOR THE NEW CONCEPT OF MODERN AUTOGYRO

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Keywords: *autogyro, jump take-off, technology demonstrator, rotor model, data analysis*

Abstract

I-28 is the new construction of autogyro designed in the Institute of Aviation. Contrary to standard solutions, it has a unique upside-down v-tail, that performs additional role of rear landing gear support. The target design is planned to be high speed construction with low fuel consumption thanks to diesel engine and retracted main landing gear. The main feature, that will be comprehensively described in the full paper, is the ability to perform a manoeuvre called jump take-off. Normally, an autogyro need some runway to get proper rotation speed of main rotor in order to get airborne. In this case, the main rotor blades pitch angle is constant and rise of lift force is generated by rise of the rotation speed of the rotor. To perform jump take-off, more sophisticated main rotor hub is needed. Some aspects concerning main rotor design and test of this new construction are presented with detailed description about problem of jump take-off calculation.

1 Construction overview

Autogyro I-28B was developed during European project "Technology of implementing in the economic practice of a new type of rotary-wing aircraft". Two versions have been built. I-28A is a static demonstrator used for ground tests of components (for example – retractable main landing gear, what is unique in this class of aircraft) and new start-phase called "jump start". Version I-28B (Figure 1.) is a flying prototype built as an experimental solution and it was tested on the airfield.

Figure 1. Autogyro I-28B in test rotors stand at the Institute of Aviation [IoA materials]

I-28B has mixed construction. The cockpit compartment and tail boom with vee-tail are made of hybrid fabric combinations – high resistance and tensile strength of the aramid fibre combines with high compressiveness and tensile strength of carbon composite. Central truss carrying engine is made of steel. The power source is modified compression ignition engine M47-TU (so called "aero diesel") with motor power of 150 [HP] at 4000 [rpm/min] and 2000 [cm3] (122 [cu in]) capacity. It is a liquid-cooled motor. Cockpit has two side-by-side seats and it is fully closed. Rear stabilizer is inverted vee-tail instead of the horizontal and vertical tails, replacing three surfaces with two, and also supports rear undercarriage by the connected torque tube. Four-point landing gear has its main wheels on the front and, as mentioned previously, rear wheels integrated with the vee-tail. Main rotor has diameter of 9.4[m] (30.84 [ft.]) equipped with NACA-9-H-12-MOD airfoil. The airfoil chord is 0.2 [m] (7.87 [in]) and blades do not have geometrical deflection. Main rotor maximum RPM is 554 [rpm/min]. The direction of rotation is counter clockwise from the pilot's point of view. Maximum take-off weight is 700 [kg] (1545[lb.]).

2 Jump take-off

In order to explain "jump take-off" procedure, differences between helicopter and autogyro have to be listed. Although both machines looks quite similar, helicopter have main rotor connected with the fuselage by drive shaft that is transmitting power from engine continuously and main rotor generates both lift and trust force by having variable blade pitch rotor hub. Autogyro have bearing, free spinning main rotor, that is unpowered by the engine and its rpm and lift force is maintained only in forward flight, whereas helicopter can perform hover. Thanks to that, rotor hub of autogyro is much less complicated and there is no need to have swash plate, because whole rotor with hub is tilt able but propeller to maintain sufficient thrust is needed. As this solution is quite simple, so it is also a lot cheaper than standard helicopter solution. More information can be found in [1],[2].

Figure 2. Rotor hub with pre-rotation and parking break [http://wiatrakowce.com.pl/gyroplane-rotor-head/]

More sophisticated autogyro, that can perform jump take-off, have rotor hub with variable pitch and main rotor is powered in some way. But it is not similar to helicopter, because swashplate can only realize two pitch angles. One for pre rotation and normal flight conditions and second used only during jump take-off in order to get boost of lift force from over speeded main rotor. Also power to spin the main rotor is supplied only to get proper level of rpm and then is disengage before the classic start, that need some runway to get speed.

There are two ways to distribute power to main rotor. It can be delivered by the main engine that is connected by a clutch or by the separate, usually electric, motor that can be turned on and off. In case concerning jump take-off, rpm of main rotor have two regions of values. First one, nominal, is used only during flight and classic take-off. Second one, over speed rpm, is only for jump take-off and permitted to use only on the ground. Before take-off, power is disengaged and excess of lift force, in order to get some height, is available for a few seconds. In this short period of time after vertical start (as helicopter), aircraft have to get some horizontal speed in order to maintain main rotor speed above minimal value, that is needed to perform horizontal flight **[3]**. Next chapters will describe, what requirements are necessary to obtain permission to fly and how to calculate performance of main rotor at that stage of flight.

3 Regulations regarding the design of the jump take-off

Autogyro I-28B was built based on requirements ASTM F2352-09 [4]. This gyroplane standard was developed by a dedicated ASTM subcommittee comprised of numerous gyroplane manufacturers, designers, users and regulators from around the world, also in conjunction with the other ASTM standards. The regulations define the basic conditions and design features to which they apply. This means that all deviations from them are subject to definition by the supervisory body (in this case Polish CAA) and then additional arrangements regarding the conditions that must be complied. These technical conditions apply to light gyroplanes of orthodox design. These technical conditions apply to light gyroplanes construction orthodox and more specifically:

- the rotors are either solid angle setting blade pitch controls, or is not regulated in flight,
- a single engine has a propeller with a fixed pitch or set on the ground,
- passenger seats are no more than two,
- the maximum Gross Weight (MGW) is 725 kg (1,600 pounds) or less.

Due to the fact that the design of the I-28B deviates significantly from the standards adopted in the regulations by the possibility of jump take-off, a number of tests and calculations have been carried out. A lot of attention has been paid to an important condition regarding the testing of rotors in the stand. The complete rotor can and should be tested for prerotation speed. The process of performing a jump take-off is pretty straight-forward. The prerotation consists basically of a drive shaft and a gearbox, connecting the rotor to the engine through a clutch. The prerotation system of the I28 gyrocopter rotor consists of a friction clutch, a flexible shaft and a Bendix type toothed clutch. The purpose of the system is to transfer torque from the drive unit to the rotor in order to pre-spin before it start gyroplane. Prerotation is activated by the pilot and turned off as soon as the rotor is accelerated to the desired rotational speed. This allows a significant reduction in the length of the runway.

Tests involving higher speed of the rotor without the appropriate calculation head proof should not be performed at the stand - driving the rotor through the torque applied to its head is not a natural way of driving it. The forces from rotation are transferred by and onto the blades and connecting elements, not through the rotor axis and the head. For stationary tests, it is therefore necessary to use heads that are able to safely transfer the equilibrium resistance torque propelling the rotor and the blades.

Due to new technologies and construction solutions, the availability of equipment and the ever-increasing popularity of this type of air transport, one should expect significant changes in regulations and requirements, especially in the area of maintaining high flight safety. Compliance with the ASTM gyroplane standard, especially on the important issues of stability and control, will provide gyroplanes with safety, stability and performance strongly comparable with the safest fixed-wing aircraft.

4 Lift force calculation

For safe performance of jump start, knowledge about generation of lift force must be obtained during primary stage of design process. This information is crucial, because with lift force, there are sized various numbers of other parameters, so as speed of main rotor, aerodynamics characteristics of blades profile, diameter, rotor hub dimensions, blade chord, swash plate movement range and so on. All of them have to be obtained before structural design as an input for dynamic loads calculations. In this case we used combined blade element theory and Rankin and Froud stream theory [5]. Such solution was validated in works over several projects.
In every case calculated values were close to measured values during tests of working prototypes designed in Institute of Aviation.

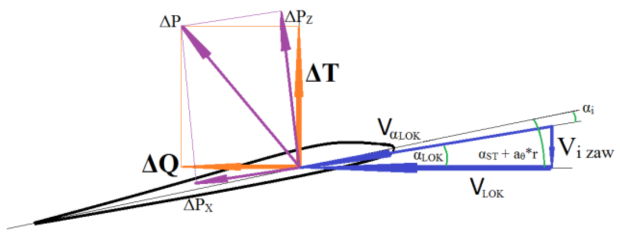

Figure 3. Distribution of forces and velocity vectors on profile [IoA materials]

The main advantage of this approach is that we were able to get quick primary values and also quick check other combinations of parameters.
The flow is calculated separately for every blade element in that way, that vortex ring, which is responsible for losses of energy, is represented by induced velocity ($V_{i\,hov}$ on fig.3). This correction of local velocity results in changing the trust and drag in such way, that local lift force vector is smaller and local drag force is higher.

That way all calculation are simple and linear, but give good results. Tip losses are included by coefficient according to [6], that is 0.96 of overall main rotor trust. Of course this solution for calculating lift force of main rotor can be considered by assumption, that main rotor is a planar disc and induced velocity is doubled after passing main rotor disc (fig. 4). In this case induced hover velocity can be calculated according to (4.1)

$$v_{i\ hover} = \sqrt{\frac{m*g}{2*\rho*A_d}} \qquad (4.1)$$

where:
m – mass of autogyro
ρ – atmosphere density
A_d – main rotor disc area

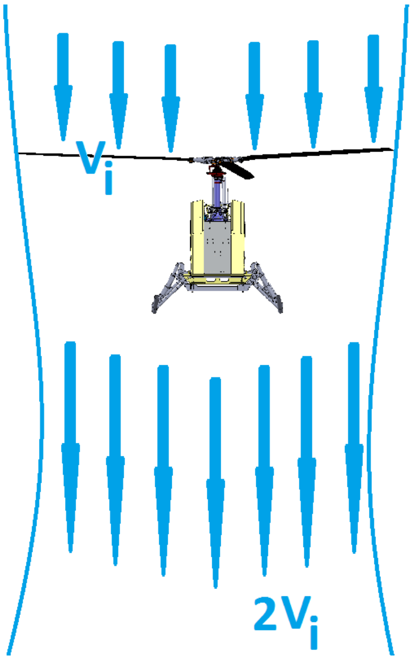

Figure 4. Induced velocity profile - visualisation [IoA materials]

This equation is really easy to use, but it is representing one of the most complex phenomena, that is occurring during flight of rotorcraft. Real airflow of rotor have a shape of spiral line with rotation in normal plane. It is shown schematically on fig. 5.

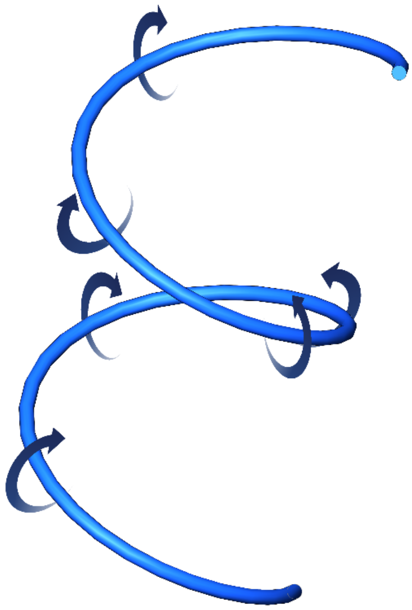

Figure 5. Schematic airflow generated by main rotor [IoA materials]

Thanks to previous assumptions, this complicated airflow is replaced by single correction of main rotor thrust and drag using induced velocity.

$$\Delta T = \Delta P_Z \cos\alpha_i - \Delta P_X \sin\alpha_i \qquad (4.2)$$

$$\Delta Q = \Delta P_Z \sin\alpha_i + \Delta P_X \cos\alpha_i \qquad (4.3)$$

where:

$$\alpha_i = arctg\frac{V_{i\ hov}}{V_{LOC}} \qquad (4.4)$$

$$\Delta P_Z = \frac{1}{2}\rho V_{LOK}^2 b\Delta r C_{Z\ LOK} \qquad (4.5)$$

$$\Delta P_X = \frac{1}{2}\rho V_{LOK}^2 b\Delta r C_{X\ LOK} \qquad (4.6)$$

Local lift force (ΔP_Z) and local drag force (ΔP_X) are calculated for every blade element. The last thing is to sum up all results in to main rotor thrust and drag according to (4.7) and (4.8).

$$T = 0.96 * k\sum_{i=1}^{i=n}\Delta T_i \qquad (4.7)$$

$$Q = k\sum_{i=1}^{i=n}\Delta Q_i \qquad (4.8)$$

where:

n – number of blade element

k – number of blades in main rotor

Results of calculations are compared in chapter 6 with test results.

5 Ground tests of technology demonstrator

The A version of autogyro was planned as a demonstrator of various solutions that have to be checked before use on flying model. Especially for engine mount, performance and endurance tests. Because regulations about jump take-off are very limited, so only a proof of possibility to perform such manoeuvre was considered.

In order to do this, variable pitch main rotor hub was designed. Also few solutions of power distribution was considered and checked. More information about this problem can be found also in [1]. For jump take-off test, after detailed analysis, a stiff shaft was chosen, that was connected with the engine by friction clutch. Measure equipment was chosen carefully in order to obtain all the data from the test. Because jump take-off is quick event, it was necessary to use high speed devices, that can write large amount of data fast. This data also have to be synchronized in one file to get all needed information. For measure main rotor trust a force sensor, that can sample up to 100 [Hz], was chosen. Pitch angle of main rotor blade was measured using linear transducer also with sample rate 100 [Hz]. Main rotor revolution speed was obtained by contactless, optical sensor and vibration sensor was used to compare different rotation speeds and to monitor, that every state of the test have safe, similar condition. It is very important, especially when changes of test parameters or parts are done and there is a need to be sure, that those changes did not affect construction by rise of vibration level.
The other thing to do was to calibrate sensors, because main rotor thrust and blade pitch angle could not be measured direct way.

Figure 6. I-28A demonstrator during sensor calibration [IoA materials]

The demonstrator was mounted (fig. 6) as it was during test and known range of forces was applied to the rotor hub while recording values from force sensor. That way, although force was measured in different place, results during test where showed and recorded for the thrust generated by main rotor.
Tests of jump start were performed in a special test facility "Rotunda" designated for tests of rotorcrafts and isolated rotors (fig. 7).

Figure 7. I-28A demonstrator prepared for tests [IoA materials]

First stage of test was focussed on functional checking of all components and proof, that ground resonance will not occur. It was done during series of runs with staged rotor speed rising. The main goal of this event was to obtain information about starting and running the engine, clutch working and balancing main rotor blades. After smooth completing and proving, that everything works fine, final test could be performed. Data collected during test is presented in next chapter.

6 Test results and comparison

In chapter 4 the mathematical model of main rotor was presented. The goal was to obtain mathematical model, that can be used for fine tuning. For I-28 parameters it was calculated that by rotation speed 370 [rpm/min] and blade pitch angle 5,5 [deg] the maximum thrust force of main rotor is 11741,59 [N] (1196,9 [kg]).

Results from tests are presented beneath on fig. 8 and detailed view on fig.9.

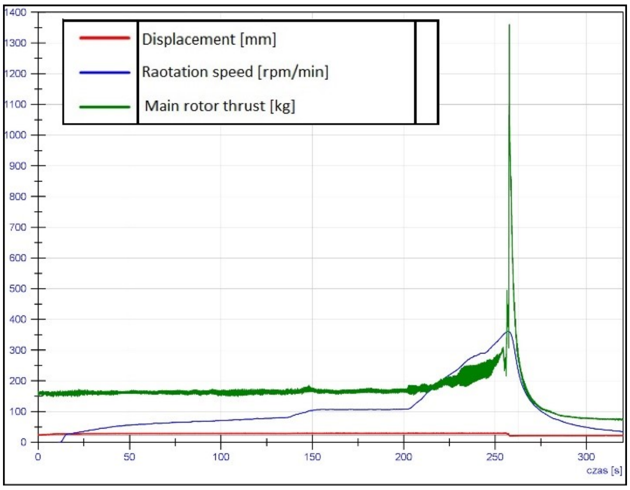

Figure 8. Jump take-off test data [IoA materials]

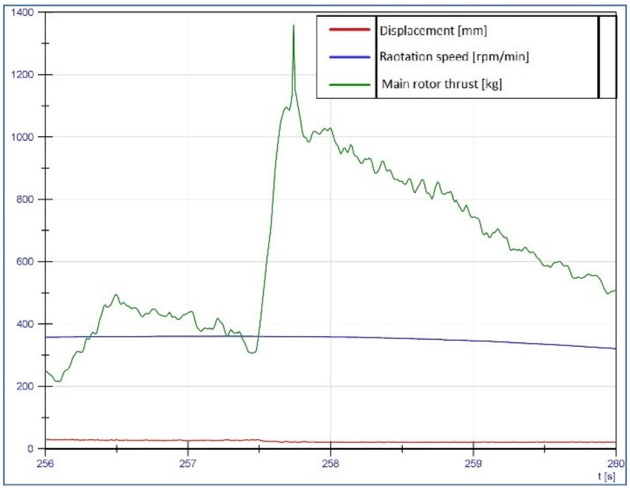

Figure 9. Main event details from 256 [s] to 260 [s] of the test [IoA materials]

Fig. 9 is showing, that maximum thrust value is 1360,6 [kg]. It was achieved by rotation speed 361 [rpm/min] and blade pitch angle 4,5 [deg]. So it looks like the calculations from chapter 4 are not correct. This is due to one fact, that was not considered. The aircraft stays on the ground, so ground effect have to be taken into account. Literature says [6], that it influence the maximum trust by factor 1,1 on the ground to 1 on height of one rotor diameter. With this factor, calculated thrust is 1316,59 [kg] and the difference between calculated and measured value is 44 [kg], which is 3,3%. Calculations, that are made for measured values, differ much more, because calculated value of thrust is 1150,75 [kg]. In this case the difference is 210 [kg] and it is 15,4% of measured value. It necessary is not bad result, because when fig. 9 is carefully analysed, it can be seen that maximum force is generated in short period event and value around 1150 [kg] can be treated as average maximum value.

7 Conclusions

Test proved, that it is possible to obtain main rotor thrust, that will allow to perform jump start. All mechanical parts, as engine, clutch, shaft and hub were working normal. Measure equipment also worked good and allowed to collect all needed data. Analysis software NI DIAdem was capable to provide detailed information about timing of events and perform mathematical operations needed for calculations. So it was possible to obtain information, that maximum thrust was achieved in 0,2 [s]. For autogyro, that would not be connected to the ground, separation from the ground would started at 257,58 [s] of the test (thrust value passed 700 [kg]). Maximum height would be achieved at 259,19 [s], when lift force again hit the 700 [kg] border, but when it was fallen. Time of climb is 1,61 [s]. Time of touch down was estimated by integrating force curve above 700 [kg] and then checking, when areas will be the same by integrating force curve after point 159,19 [s] – height lowering start. Touch down was estimated after 1,57 [s]. So whole time of jump take-off from lift-off to touch down is 3,18 [s]. This time is sufficient to perform safe jump take-off procedure [4] but pilot should be well trained. Nevertheless it is proved, that for heavier autogyros jump start is also possible. Rise of mass and complexity of whole construction have to be considered, but for heavier construction reduction dangerous behaviour during start is more important. Future for such construction will be vertical or short (few meters) accelerating before lift-off.

Acknowledgement

The work has been accomplished under the research project No. UDA-POIG.01.03.01-14-074/09-00 co -financed by the European Union from the Funds of the European Regional Development Fund.

References

[1] W. Krzymień i M. Delega, „Verification of rotor prerotation systems of the autogiro", *Trans. Inst. Aviat.*, t. 3, nr 236, s. 35–40, 2014.

[2] M. Wojtas i M. Trendak, „New gyroplane hub connector with positive coning angle", *J. KONES*, t. Vol. 24, No. 3, 2017.

[3] E. Niemi i B. V. Gowda, „Gyroplane Rotor Aerodynamics Revisited - Blade Flapping and RPM Variation in Zero-g Flight", 2011.

[4] ASTM F2352-09, „Standard Specification for Design and Performance of Light Sport Gyroplane Air-craft." .

[5] G. D. Padfield, *Helicopter Flight Dynamics: the Theory and Application of Flying Qualities and Simulation Modelling.* Chichester: John Wiley & Sons, 2008.

[6] J. P. Bratuchin, *Design and construction of helicopters (in polish)*, 1958. wyd. PWT.

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