THE DIRECTIONAL STABILITY OF AUTOGYROS ILLUSTRATED WITH THE EXAMPLE OF I-28B EXPERIMENTAL AUTOGYRO

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OVERVIEW

I-28B is a new concept of autogyro designed in the Institute of Aviation. Contrary to standard solutions it has a unique upside-down v-tail that fulfils additional role of rear landing gear support. First flights revealed that this design cannot obtain a satisfying, secure level of directional stability, which forced the test pilot to land in a field near the airstrip in the third flight. The authors of this paper try to answer three questions – what happened, why it happened, and how the design needs to be improved. During work on this subject, we elaborated general rules that should be followed to obtain sufficient level of directional steadiness.

1. INTRODUCTION

By definition, the autogyro, also known as gyrocopter, gyroplane or gyrodyne is an aircraft where a free spinning rotor generates lift, turning by autorotation. [1]

Unlike helicopter, forward thrust must be provided by a pusher or tractor propeller configuration. [2]

Autorotation is a complex phenomenon involving the balance of opposing aerodynamic forces along the rotor's blades. Gyrocopters are usually operating in forward flight, they aren't capable of hovering, so the component of relative wind striking the rotor blades as result of forward speed must also be considered. The forward speed of the aircraft is added to the relative wind striking the advancing blade, and subtracted from the relative wind striking the retreating blade. [1]

As defined in the regulation [3] the light gyrocopter class considers construction with maximum take-off weight not exceeding 725[kg] (1600[lb]).

Airframe, powerplant, rotor system, tail surface, and landing gear are the minimum components needed for a functional, simple gyroplane.

Typically designed structure of the fuselage, hanging like a pendulum under the rotor, consists predominantly of composite materials, and usually a steel frame constituting a support for the engine and the rotor mount.

The powerplant, mostly combustion engines, provides the thrust required for forward flight. On the ground, the engine may be used as a source of power to prerotation system. The lightest structures do not have a prerotation of the rotor, in more sophisticated gyrocopters an electric or pneumatic system is usually used.

2. I-28B EXPERIMENTAL AUTOGYRO

Autogyro I-28B was developed in the framework of the 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 the ground tests of components and the research about a start-phase called "jump start", which is also under development in this project. Version I-28B (Figure 1) is a flying prototype built as an experimental solution and it was tested on the airfield when lack of directional stability was detected, which forced pilot to carry out an emergency landing.

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

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 is combined with high compression and tensile strength of carbon composite. Central truss carrying engine is made of steel. The power source is a modified compression ignition engine M47-TU (so called “aero diesel”) with motor power of 150 [HP] at 4000 [rpm/min] and 2000 [cm^3] (122 [cu in]) displacement. It is a liquid-cooled motor. Cockpit has two side-by-side seats and it is fully enclosed. Rear stabilizer is an inverted vee-tail instead of the horizontal and vertical tails, replacing three surfaces with two, and also supporting rear undercarriage as the connected torque tube. Control surfaces constitute about 70% of tail plane area. 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.]) and is equipped with blades using 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.]).

3. IN-FLIGHT INCIDENT

All test flights were performed in Sochaczew airfield. It is surrounded by forest, which is located close to the airstrip on the south side while on the north side wide area for emergency landing is prepared. Figure 2, with flight path during the incident, shows also that location. Flight path is based on the data acquired by flight data recorder, that was installed on the I-28B.

Figure 2. Satellite image of Sochaczew airfield with the incident flight trajectory

Flight profile in isometric view is shown beneath (*Figure 3*).

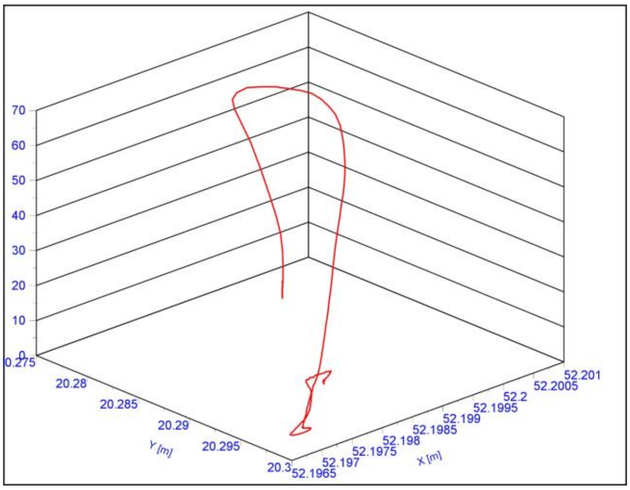

Figure 3. Isometric view of the flight trajectory

The incident took place in the third flight. First stage after take-off proceeded correctly, so as first turn performed in left direction. During second turn, pilot decided not to fly over the forest, so he tried to tighten that turn. In this moment autogyro lost flight direction with tendency to even tighten the turn coupled with loss of altitude. Pilot decided to land (applying emergency procedure) on the grass near the airstrip. Pilot did not suffer any harm, but unfortunately this part of the airfield had lots of small holes and construction of the main undercarriage was slightly damaged.

In order to get full data analysis, the synchronisation of data and video files was done, as is shown in Figure 4.

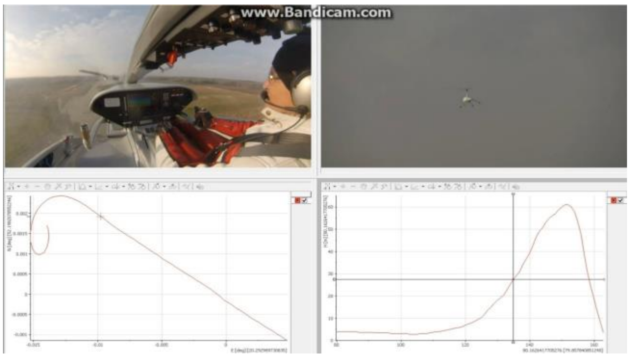

Figure 4. Flight data synchronisation

This flight incident took place on 27 November 2013 about 2:00 pm. At this time maximum wind speed was 5 [m/s], the wind was blowing from SW direction. This data (showed in Figure 5) was acquired from weather station located 35 [km] in east direction from the airfield.

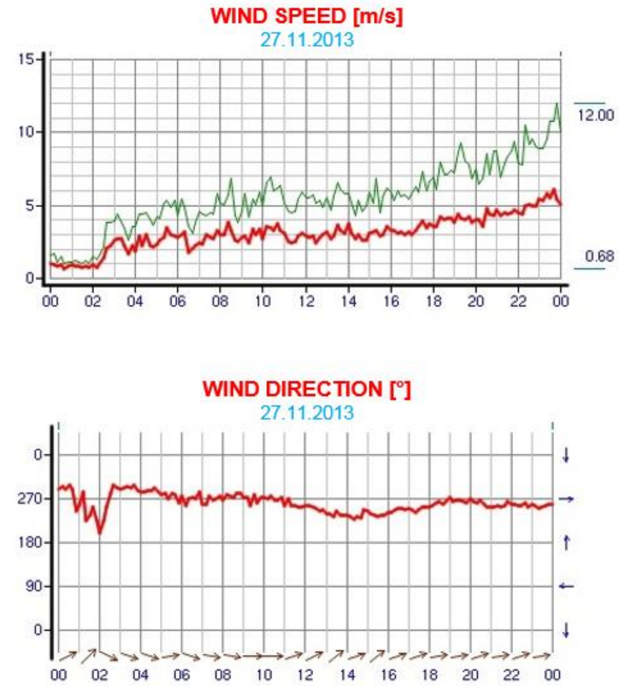

Figure 5. Speed and direction of the wind in the day of the incident [LAB-EL, http://meteo.waw.pl, English version not available]

Flight path, that shown in Figure 2, confirms that pilot decided to do a left turn in order to continue flight with forward wind during altitude gaining. But in this case the forest on the south of the airstrip was dangerously close to the aircraft. This is why pilot decided to do a sharp left turn and lost stability of the aircraft, that should be carefully investigated in a series of test flights. The weather had not direct influence on the incident, but it was a reason of decision to choose left airfield traffic pattern.

4. AUTOGYRO STABILITY

'*Stability is designed into aircraft to reduce pilot work-load and increase safety*.' [1]

Autogyro is neither an airplane, nor a helicopter. Therefore stability of such air vehicle cannot be investigated as for above mentioned construction. Moreover I-28B is also not an ordinary autogyro, because the construction of tail plane is a uniquely reversed v-tail (for theory, see [4]), control surfaces have big areas, comparing to the stabilizers and it is not a pusher-type autogyro, where direct airflow from propeller downwashes tail plain and raises its effectiveness. These three features of I-28B are reason for lack of information about how the empennage, in such configuration, should be designed in order to obtain satisfying directional stability level. The directional stability of the fuselage is completely dependent on aerodynamic forces.

Because in flight, static directional stability was small (first turn was successfully completed) and there was no dynamic directional instability (tendency to tighten the spiral flight), but requirements were met, decision of checking them again was made. Few hypotheses were proposed and verified, as stated in chapter 5.

Table 1. Requirements concerning stability - comparison

Requirements	English	Metric
BUT [5]	BUT 447: $S_V = 0{,}033 * S_{main\_rotor}$	
	24,65 [ft^2]	**2,29** [m^2]
	BUT 447: $l_V = 0{,}22 * D_{main\_rotor}$	
	6,79 [ft.]	**2,07** [m]
CAP 643 [6]	**Paragraph T177** - tendency to correct automatically for moderate disturbance in yaw **Paragraph T181** – no dangerous behavior for all range of speeds by 5 seconds	
ASTM F2352-09 [3]	**4.5.5.1** no tendency to sudden growth of angular velocity	
CS-VLR [7]	**CS VLR.177** in-flight test, clear tendency must be shown, so that pilot is warned, that he is close the limit for sideslip angel	

Certification documents, with requirements concerning stability, are shown in Table 1. Only the BUT provide some information, of how the empennage should be designed. The rest of those papers requires tests, that are performed during flights and the test pilots opinion is the key to meet the regulations.

Problems mentioned earlier, as lack of data and imprecise requirements, had to be resolved. To obtain realistic information about directional stability of autogyros, the large comparison of tens types of autogyros were made. This data was used to construct new configuration of the tail, that should secure appropriate stability level. Full list used for calculation contains 25 positions (44 was chosen, but not for all constructions the data was available), for which data could be achieved via internet along with scaled drawings. Of course, surface values of empennage and dimensions of tail arms had to be calculated manually from scale prospect views. This work was done and finally we could start to do the comparison of different types of autogyros.

None of the selected autogyros meets the requirements for vertical surface of empennage according to BUT. In case of I-28B vertical surface should have at least 2.29 [m^2], but for non-modified gyro it is 0.526 [m^2] which definitely is to small value. Requirement for length of the tail arm is met. 2.07 [m] is required and the true length is 2.73 [m]. Those values suggest, that vertical surface is too small, but do not give information about how big should it be.

That is why we modified the equation for calculation the vertical tail volume to form, that can be used for autogyro. Because in autogyro the main wing is replaced with the main rotor, hence it is in the equation 4.1 and the chord of wing is replaced with the chord of blade.

(4.1) $$K_V = \frac{S_V * l_V}{S_{MR} * c_{prof}}$$

K_V – vertical tail volume

S_V – vertical tail surface

l_V – vertical arm length

S_{MR} – main rotor surface

c_{prof} – chord length of main rotor blade

Equation (4.1) was used for calculation of vertical tail volume for 23 autogyros in order to get trend line, that was used to calculate new vertical tail surface value for modification of I-28B. Same approach using statistic data can be found in [8]. This is shown in Fig. 7.

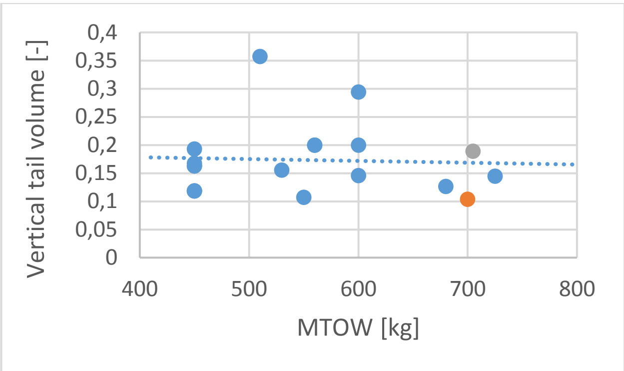

Figure 6. Vertical tail volume in function of MTOW

Orange square on the Figure 6 represents non-modified I-28B vertical tail volume and the grey mark represents modified construction. Those two values were not included for the calculation of the trend line. Change of the trend line is small with rise of MTOW and it is given with the equation 4.2.

(4.2) $$K_V = -3.2 * 10^{-5} MTOW + 0.1912$$

MTOW – maximum take-off weight in kilograms

In case of I-28B, the required vertical surface is S_V=0.86 [m^2] by K_V=0.169.

Equation (4.1) and (4.2) can be easily used to obtain required vertical fin surface and vertical arm values even during a preliminary design stage of a new autogyro. In chapter 6 results of those calculations are presented.

5. MODIFICATION

Modifications presented in this chapter where prepared simultaneously with works (collecting and processing data of autogyros to gain some statistic information) presented in chapter 4. This is the reason, why a few hypothesis were checked before we get full analysis of the previously mentioned data. Several modifications have been tested with CFD model:

- reduction of deflection of the tail surfaces from 18 degrees to 10 degrees,
- raised length of the v-tail stabilizers to get 50/50% length partition (30/70% for I-28B with a predominance of rudder surface),
- raised length of the rudder surfaces in order to get higher responses from steering system,
- added separated vertical tail fin to stabilize the path of flight.

Modification of the structure, which added 'tail fin' (vertical stabilizer) due to the need to increase directional stability of the current structure of I-28B gyroplane, without interfering significantly with the construction approved by the Polish Civil Aviation Authorities was the best solution. The additional 'tail fin' is designed as a classical vertical tail, without rudder. In order to avoid collision of the rotor blade, additional surface has to be located at the bottom side of the fuselage. [9], [10]

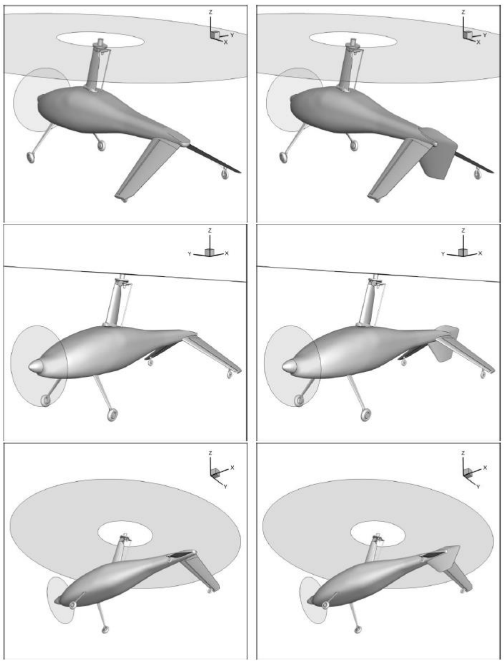

Figure 7. Comparison geometry autogyro I-28 B (left) with the geometry of a modified version I-28 B mod.1 (right)

The aim of the calculations was to assess the aerodynamics of the modified version of the gyroplane including all aerodynamic factors that may affect the quality of the flow around the tail, such as the impact of the rotor or propwash.

Autogyro yaw moment characteristics are essential because any instability in this control channel can lead to the fact that the gyrocopter set sideways to flight direction and flow separation will appear on the rudder. The only way out of this dangerous situation is to try emergency landing in a spiral. Spiral such know in the literature about gyrocopter called 'uncontrolled spin', occurs in particular on the tractor configuration autogyro. The aim of the modification was to improve stability at low angles slip (Figure 8) and that was achieved by the additional 'tail fin'.

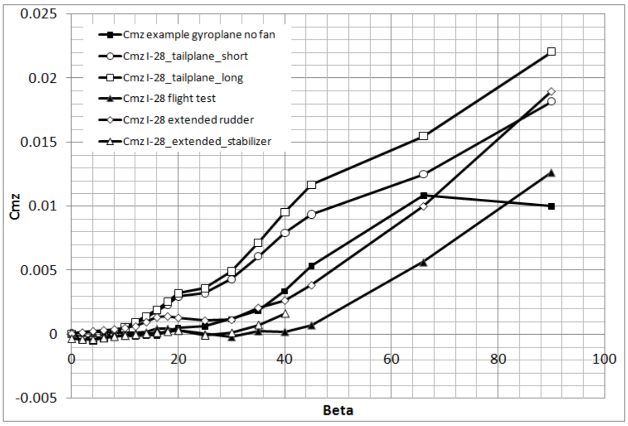

Figure 8. Yaw moment function of sideslip angle for analyzed configurations [9]

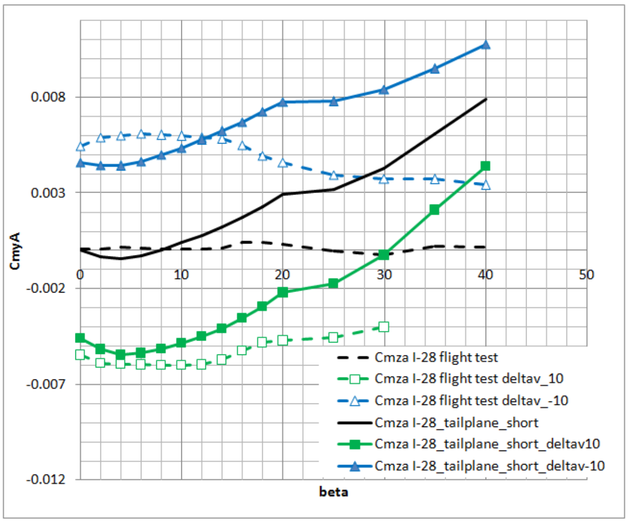

Figure 9. Influence of rudder deflection (δv=+/-10°) difference between equipped with tailplate and flight test configuration [9]

The results of numerical analysis (Figure 8, Figure 9) confirm that after the introduction of this change directional stability of the gyroplane will significantly improve. The use of 'tail fin' causes 'nose up' motion as further deepening of the slip. [11]

6. SIMULATION FLIGHT TESTS

An extremely important aspect of the certification process of the aircraft is the correct execution of the flight test. The aim of the tests is to assess the flight properties, in the case of our gyroplane, over the entire range of operational flight envelope. [12]

Figure 10. I-28B flying over Sochaczew airfield [P. Gliga]

6.1. I-28B flight simulation

Data collected during flights and analysis has to be confronted with the new construction configuration. In reality, there it is impossible to do new flights without proving, that it can be done safely. The only option, to show flying capabilities of the new solution, was to use simulator. Researching the stability problem, we found, that Carter PAV was designed and tested, inter alia, with X-PLANE code, which is stated in [13] and simulators based on X-PLANE are approved by FAA, what is described in [14]. This software has also one colossal advantage – it uses geometry and airfoil data to predict, how the object will be behaving. Standard simulator only realizes aerodynamic characteristics, that are computed outside and also may be flawed.

Versatility of the software allows verification of various types of aerodynamic cases, which resulted in the ability to perform calculations in real time. This approach to the problem of aerodynamic calculations resulted in various methods for various elements of the aircraft. Aerodynamics properties for fuselages, nacelles, deflectors, landing gear and other non-bearing aircraft structures elements are the first group of the calculation method which uses a panel method. The main sections of an aircraft, tail and wing, struts are calculated using the Lifting Line Theory while the rotors and propellers Blade Element Theory is used (Figure 11).

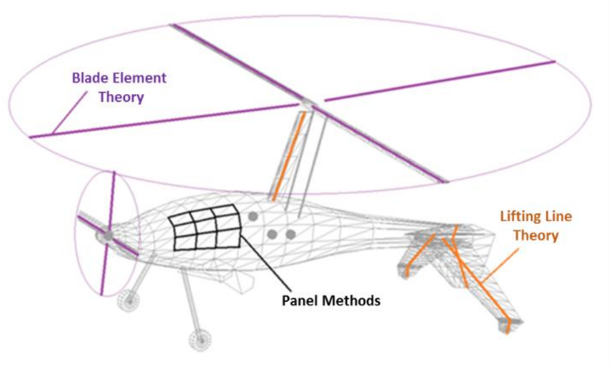

Figure 11. Different methods for simulating the dynamics of the autogyro flight

This method is of course simplified and ignores a lot of the phenomena occurring in a real flight, but the most important information about the behavior of the object in flight can be achieved at a very early stage of the project. This virtual model allows us to identify the most important problems and enables the search for optimal solutions without costly structure modifications. This is achieved by calculating the performance characteristics for each computational step. X-PLANE determines the aerodynamics of the forces generated on all surfaces of the aircraft in different flight conditions.

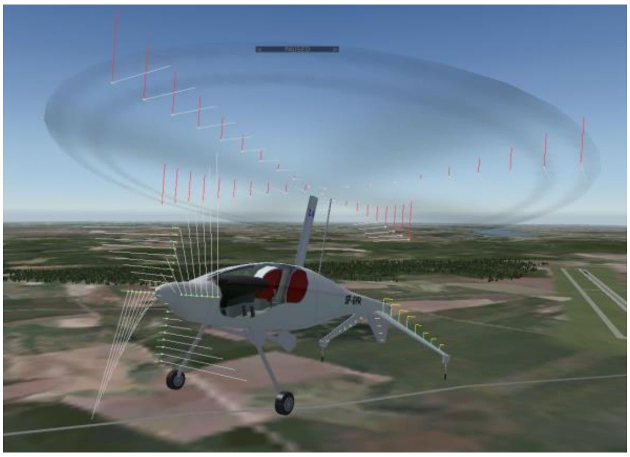

Figure 12. Modified I-28B, X-PLANE testing model

This methodology has been adopted as a result of examining records of the flight test gyroplane I-28B dated on 27 November 2013 over Sochaczew airfield. The flight profile and analysis of the incident are shown (Figure 3), based on data from the onboard flight recorder and data available on the Internet.

First of all virtual models had to be verified in order to check, if it can be used for verification of other changes. Virtual model, that is copy of real I-28B was tested to see, if it is behaving in the same manner, as the real autogyro. Test began with take-off and then left turn was performed during gaining altitude, as it was in the investigated incident.

Flight path of the virtual model was recorded in X-Plane and it is shown on Figure 13.

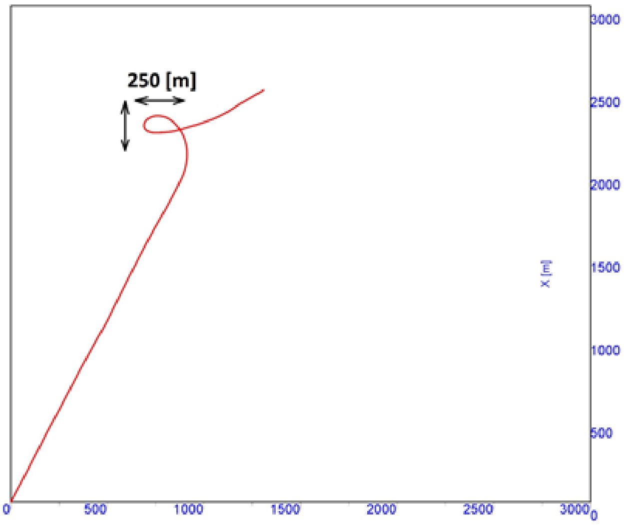

Figure 13. Flight path of virtual model of I-28B

Behaviour of the virtual model was the same, as the real auto gyro. Any attempt to do sharper turn, than turn with diameter of 300 [m], is ending with uncontrolled spin with tendency to lose altitude and problems with retrieving control. It looks the same as in video from the flight with incident. Also right turn cannot be done with small diameter.

6.2. Reduction of rudder deflection

The simplest modification is to reduce angels of rudder surfaces deflection, because first hypothesis assumed, that angels are too large, which leads to air stream detachment on stabilizer and consequently to lose stability. Because uncontrolled spin occurred when pilot was trying to tighten the left turn and first turn was performed correctly, this was the first idea to be checked.

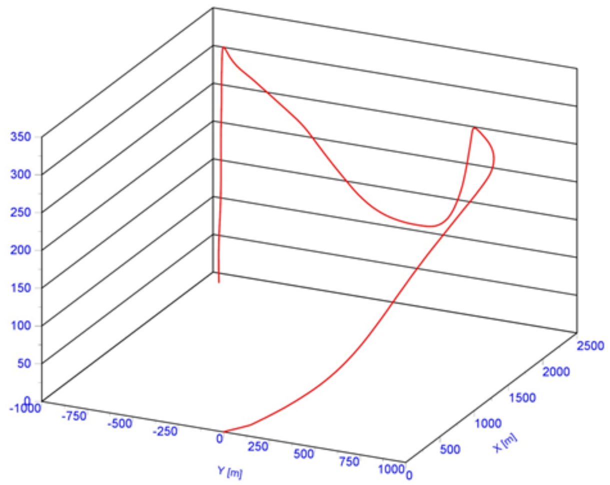

Figure 14. Flight path of virtual model with reduced angels of deflection

In this case the only improvement was that transition from controlled to uncontrolled flight took a little bit longer. Generally the effect was the same, as in previous case, and tight turn always ended with uncontrolled spin.

6.3. Additional surface – version 1

As the data collected in previous chapters showed, the best solution will be to add extra surface to get bigger area of vertical tail stabiliser. This way the first version of this hypothesis was checked. Designers recognized that the easiest way to add extra surface will be adding two small fins – one under the fuselage and second one on the fuselage. The top surface however, could not be too big in order not to collide with the main rotor. Proposed solution is shown below, along with flight path.

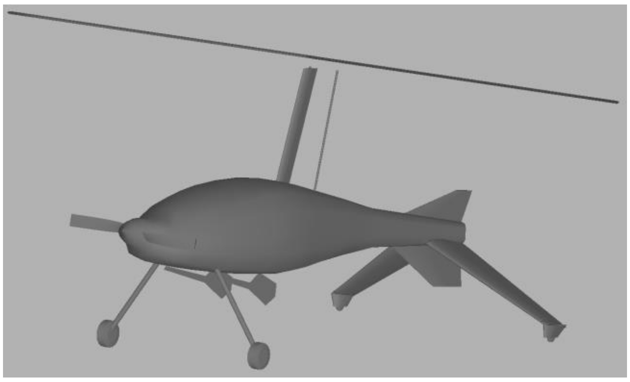

Figure 15. Additional surfaces added to construction

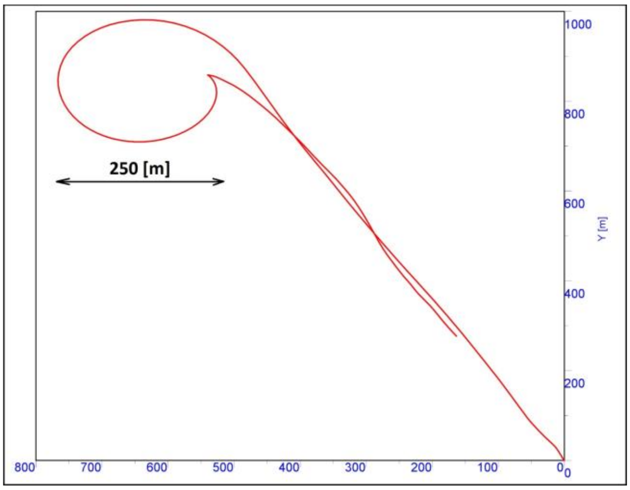

Figure 16. Flight path of virtual model with additional surfaces

This modification give significant improvement. Full circle diameter of 250 [m] can be performed easily and even after spin, control is maintained. Lose of attitude in this manoeuvre is 50-60 [m] which is similar for spin of a glider for example. Those parameters of spin are securing the possibility of a safe flight, but decision was made to reduce height of the top plate and so a second version was elaborated.

6.4. Additional surface – the final version

The final version of the modified I-28B is shown in Figure 17. Vertical surface is now one part, that is moved away from the main rotor to the rear of the fuselage.

Figure 17. Final version of I-28B modification

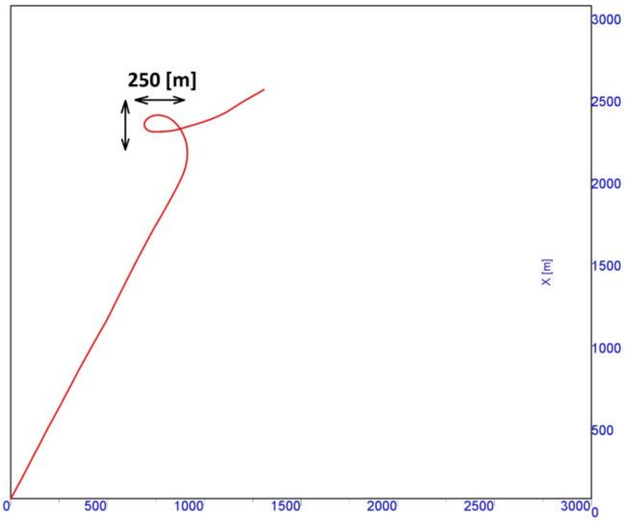

Figure 18. Flight path of final version I-28B

This flight path shows clearly, that this is the best solution, and it works very well. It was possible to do a turn with diameter of 100 [m] while gaining altitude with no tendency to lose control. The autogyro is stable and fully controllable in any state of flight. Spin can be performed only after brutal steering and it is very easy to level up the aircraft.

Based on both CFD and flight simulator analyses, this configuration has been recognized as the final solution and for such vertical surface all the documentation is elaborated.

7. CONCLUSION

The characteristics of yaw moment are proving much lower efficiency of the rudder than in the base case, but increased the stability of the gyroplane, so with the increase of the angle of slip is running low of the rudder to keep the deviation of gyroplane from the path in the flight direction, which is a positive sign, because careless manoeuvring using rudder can lead in adjust the gyro sideways to the flight direction.

Use of simulation methods in the process of creating new structures, at the stage of preliminary design allows to work out the optimum gyroplane concept. Part of the flight conditions, particularly transient, is very difficult to test in the wind tunnel model and very difficult or even impossible to research during flight tests because safety of the test pilot is the first concern.

This type of phenomenon as the interaction of jets of air generated by the rotor and propeller propulsion, the impact of these jets to tail surfaces, or flow separation, which may appear on the control surfaces can be knowingly modelled and tested by simulation.

Summarizing the work and results:

- simulation model of I-28B in X-Plane was tested and verified by comparison with the data collected in the real flight,
- the design team gained ability to check in a safe way different configurations,
- simulator model behaviour was compared with CFD analysis [3] and both approaches give similar results,
- the team achieved a reliable approach to get proper vertical surface and arm length values using simple equations,
- designed modification improves directional stability of I-28B,
- the tool is very useful during preliminary stages of a design process,
- it can be used to verify the new construction before a maiden flight by the test pilot, with restriction that this is simulation model only and fly performance can be avoided,
- the model can be used for test pilot training, if a new feature (for them at least) has been introduced in design.

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