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OVERVIEW OF THE INVERTED JOINED WING SCALED DEMONSTRATOR PROGRAMME

Cezary Galiński*, Wieńczysław Stalewski*, Mateusz Lis*, Jarosław Hajduk**
***Institute of Aviation, **Air Force Institute of Technology**

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Abstract

Efficiency is crucial for an airplane to reduce both costs of operations and emissions of pollutants. There are several airplane concepts that potentially allow for increasing the efficiency. A few of them were not investigated thoroughly enough yet. The inverted joined wing configuration, where the upper wing is positioned in front of the lower one is an example of such a concept. This paper presents selected results of a project dedicated to fill this gap. Project consisted of aerodynamic analysis and optimisation, development of the software for multidisciplinary optimisation, development of an electric propulsion system, development of an experimental scaled demonstrator, wind tunnel testing and flight testing. All these tasks were performed by a consortium led by the Institute of Aviation, including also Warsaw University of Technology, Air Force Institute of Technology and small company MSP.

1 Introduction

Joined wing configuration is considered as a candidate for future airplanes due to several potential advantages resulting from mass and induced drag reduction. It is an unconventional airplane configuration consisting of two lifting surfaces similar in terms of area and span. One of them is located at the top or above the fuselage, whereas the second is located at the bottom. Moreover one of lifting surfaces is attached in front of airplane Centre of Gravity, whereas the second is attached significantly behind it. Both lifting surfaces join each other either directly or with application of wing tip plates, creating a box wing.

Application of this concept was described for the first time by Prandtl in 1924 [1]. Concept was further developed by Wolkovitch [2] and many others. Researchers in Poland got interested in this concept in early eighties [3, 4]. Their works lead to the conclusion that front wing of the joined-wing airplane should be designed in high-wing configuration and aft wing in low wing configuration [5, 6].

Joined wing configuration is difficult to design due to the strong aerodynamic coupling [7] and static indeterminacy. Therefore dedicated research programme was undertaken to explore its properties, utilizing previous experiences in optimisation [8-13] and UAV flight testing [14-17]. Institute of Aviation was chosen as a leader of this effort because of its specialization [18] and previous experiences in general aviation [19].

2 Project course

Activities in this programme were divided into two separate streams. First of them was dedicated to the development of the software for multidisciplinary optimisation of the joined wing airplanes. Second was dedicated to the development of scaled demonstrator in joined wing configuration and its testing, both in wind tunnel and in flight. Unfortunately there was no possibility to apply newly developed software in stream one, to design demonstrator in stream two, because programme had to be finished within three years. Development of this software was described in [20-24].

Second stream began from detailed aerodynamic analysis [25] verified with wind tunnel testing. Demonstrator was only slightly aerodynamically optimised, assuming that it should be as large as possible, fit to the wind tunnel measurement volume [26, 27] and be lighter than 25 kg to simplify legal procedures of flight testing. Moreover, quite strict constraints, resulting from previous experiences [6, 28], were imposed on aerodynamic optimisation to ensure safety of flight testing. This approach was taken to ensure safety and maximize amount of information possible to collect during the programme.

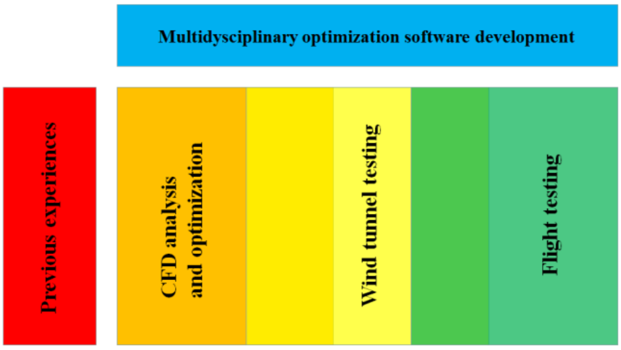

Fig.1. MOSUPS programme organization


Fig.2. MOSUPS demonstrator in the wind tunnel.


Fig.3. MOSUPS demonstrator in flight.

Performance and handling qualities were simulated basing on results of CFD analyses and wind tunnel investigation [29, 30]. Results obtained in this phase of the project were used to prepare the test pilot for the first flight. It was performed successfully on 28th of September 2014 [31]. The following flight test campaign allowed for verification of simulated flight characteristics [32] and introduction of small modifications improving directional stability of the demonstrator.

Simultaneously aerodynamic optimisation was continued to explore possibilities of the airplane improvement, unconstrained by structural issues [27, 33].

Propulsion design created also very interesting challenge in this programme. Effort in this area was described in [34-38]. Demonstrator was to resemble manned large scale airplane for 2-4 persons. Therefore problem of visibility from “pilot seat” had to be addressed. Application of high wing configuration for front wing suggested that “pilot head” should be located below the leading edge of front wing. Joined-wing airplanes usually have CG shifted significantly backwards to obtain positive lift on the aft wing. Therefore pusher configuration was selected for the propulsion system to obtain balance of the airplane with proper stability margin. Unfortunately this configuration always generates a dilemma of the propeller diameter. Therefore it was decided to attempt ducted fan concept to decrease the diameter of the system. Moreover electrical propulsion was applied during wind tunnel testing to simplify maintenance and operations of the propulsion system in the wind tunnel. Electric propulsion system was also applied during first flights.

3 Results of aerodynamic optimisation

Aerodynamic optimisation described in [27] referred to the UAV that could be developed from the demonstrator tested in current programme by application of increased weight and different CG position. This assumption allowed searching for optimal geometry in much broader design space. However, it would require application of different mass distribution if one wanted to build such an UAV. As a result it appeared that aerodynamic design freedom would allow for building an airplane with

17.8% better gliding ratio and 47.1% better power factor. This result encouraged to conduct optimisation also for manned variant of discussed airplane. The same BASELINE geometry was used [Fig.6a], but 10:3 times larger. Genetic algorithm with application of PARADES and PANEL3DBL software [8-10] were used. Assumed design parameters defined the following geometric properties of optimised joined wing:

- areas of front and aft wing
- sweep angles of front and aft wing
- spanwise position of division of front and aft wing on two ruled-surface segments
- taper ratios of ruled-surface segments of front and aft wing
- chords of limiting sections of side wing
- geometric twist of front, aft and side wing
- inclination of front wing and aft wing
- shapes of smooth connection between front, side and aft wings

Additional design parameter was the aircraft airspeed. Values of all assumed design parameters should have been determined during optimisation process, which was conducted for a trimmed aircraft of MTOW of 472.5 kg .

Results of optimisation are shown in Fig.4 presenting the Pareto Set – typical solution of multi-objective-optimisation problems.

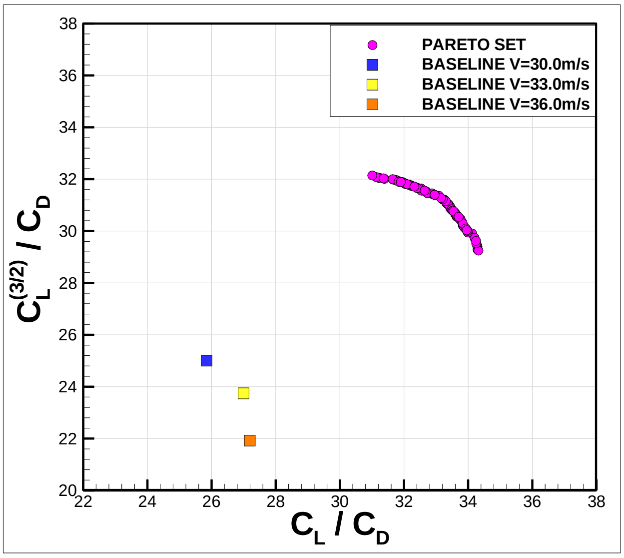

Fig.4. Results of the optimisation conducted for manned version of the airplane.

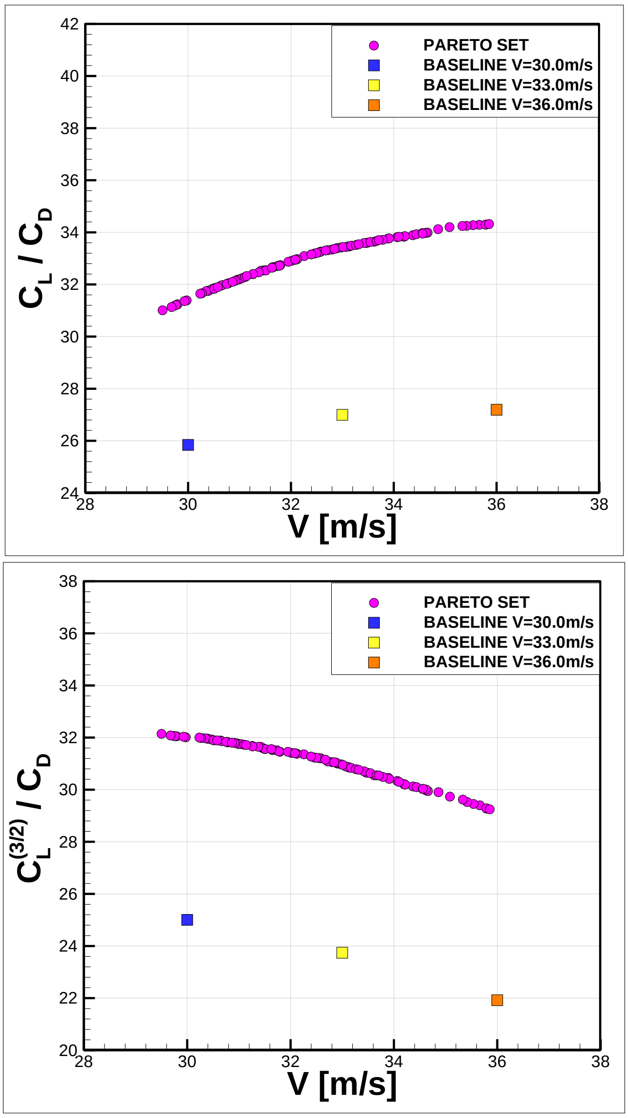

Fig.5. Gliding ratio and power factor as a function of airspeed for Pareto optimal solutions.

Each single, Pareto-optimal solution was optimal for different airspeed (from 29.5 m/s to 36 m/s) which was one of design parameters. Comparing solution optimal for airspeed of 33 m/s with BASELINE (Fig.5) one may observe the following improvement of aerodynamic characteristics:

- about 24% in gliding ratio,
- about 30% in power factor.

The improvement is even greater in the case of solutions of higher airspeeds (e.g. 36 m/s).

Wing sweeps are the most visible difference between BASELINE and optimised configurations together with CG position shifted much forward. As a result optimised configuration resembles conventional airplane.

It is slightly surprising, since CG position located between wings should require positive lift from aft wing, thus increasing total lift of the whole configuration. However, the size of the propeller/fan in the pusher configuration imposed thrust vector position relatively high above CG, thus increasing value of the pitching moment. As a result lift from aft wing was significantly reduced, changing its function to the function of stabilizer. In such case smaller wing sweep of the front wing became more advantageous.

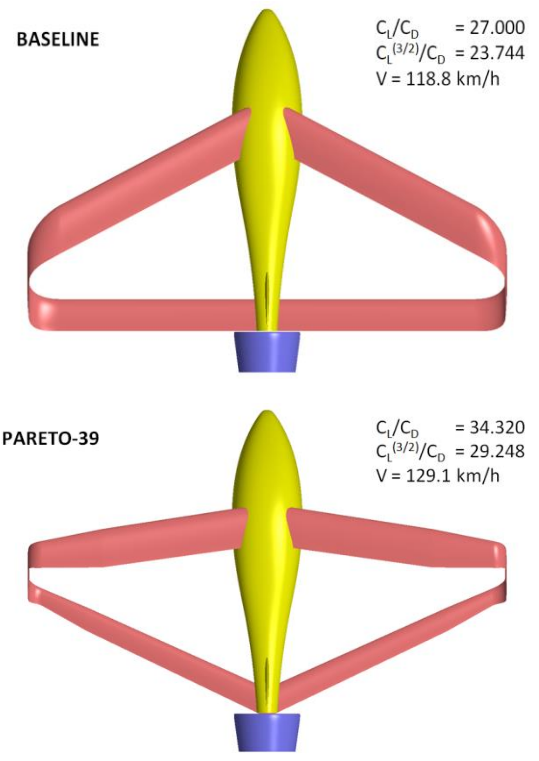

Fig.6. Possible VLA airplane based on MOSUPS project results: a) baseline, b) aerodynamically optimised geometry.

One of Pareto optimal solutions was then chosen and analysed with application of ANSYS FLUENT. Result of this analysis was compared with similar results obtained from analyses of two very well designed existing airplanes in conventional configuration [33]. Performance achievable for optimised joined wing airplane appeared slightly better. However difference is not very large. Moreover, careful aerodynamic optimisation is necessary for secondary airplane components like fuselage or landing gear to achieve this advantage.

Moderate result in this area was achieved because of the problem of compromise between performance, stability and balance of the airplane. The need for stability implies application of positive stability margin, which also requires reduced or even negative lift force on the aft wing which is contradictory with assumptions stated in [1], thus decreasing possible advantages of the configuration. Lift on the aft wing is reduced further by high installation of the propeller/fan because thrust generates negative pitching moment. It is not advantageous to decrease propeller/fan diameter and install it lower because this decreases efficiency of the propulsion. Therefore another concept of the propulsion should be applied to unveil advantages of the joined wing airplane. It should be designed in such way that thrust vector is pointing below CG. In such case the need to balance positive pitching moment from the propulsion would increase the lift on the aft wing, which would move the concept closer to the original assumptions taken in [1]. Jet engine installed at the same level with aft wing or distributed hybrid/electric propulsion installed in front of the aft wing could have this effect on the airplane balance.

4 Dynamic stability issue

Demonstrator appeared safe to fly, however not very easy. Small deficit of directional stability has been discovered during first flights. This adverse behaviour was observed especially in rapid reaction of the airplane to rudder control and tendency of the airplane to oscillate in yaw after even small disturbance. For this reason, three possible modifications of vertical stabilizer were investigated to find the way for directional stability improvement. Except for the CG position change, there were dorsal fin, ventral fin and extension surface on the vertical stabilizer tip tested as shown in Fig. 7. During several flights performed with different configurations of the tail, the last one was chosen. In test pilot’s opinion only additional surface on the vertical stabilizer tip gave

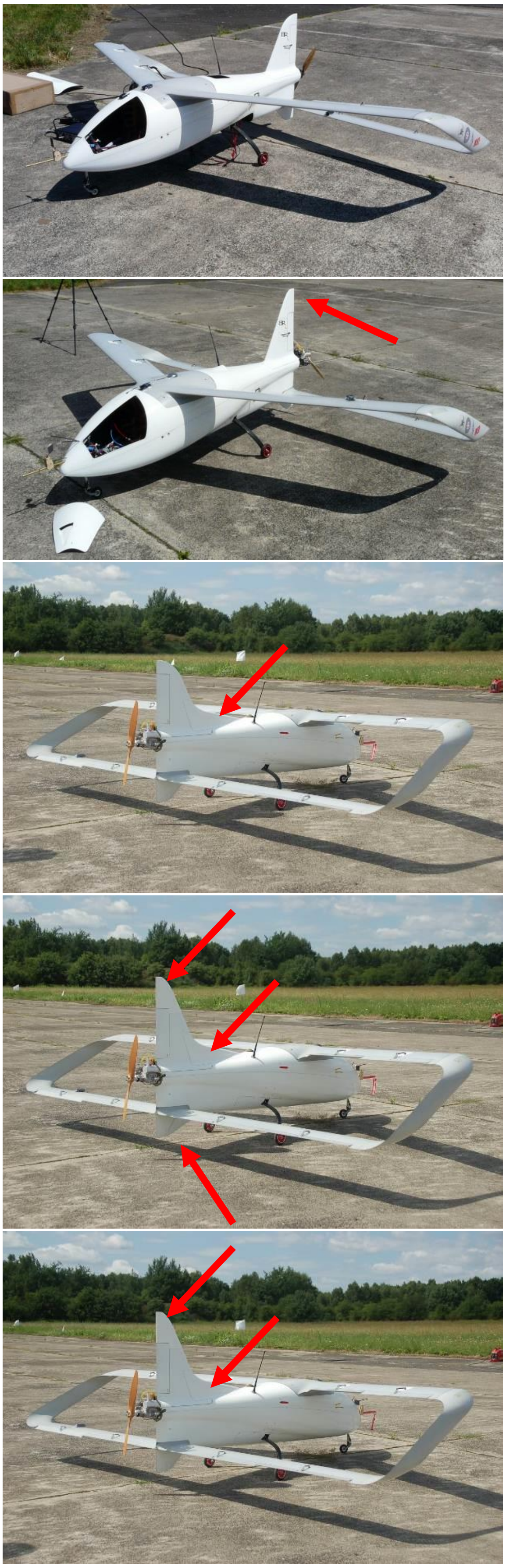

Fig.7. Various modifications of MOSUPS tail applied to improve its directional stability.

significant improvement in stability, so that it was permanently implemented into next flights.

Not only one, but one of most crucial factors driving an airplane directional stability is yawing moment coefficient with respect to the sideslip angle. Therefore, Fig. 8-9 show characteristics of $C_n(\alpha, \beta)$ obtained from wind tunnel tests before and after vertical stabilizer modification, respectively.

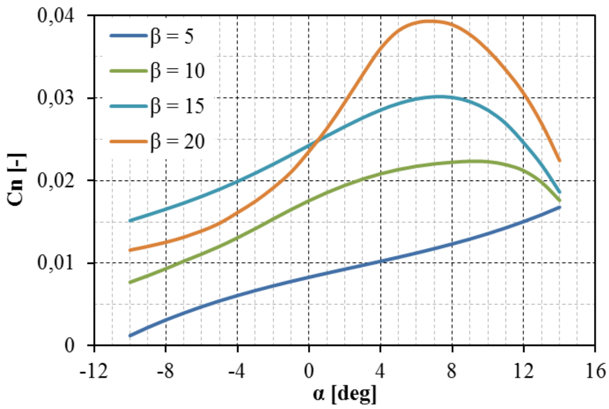

Fig.8. Yawing moment characteristics for various sideslip-angle values and baseline vertical stabilizer geometry.

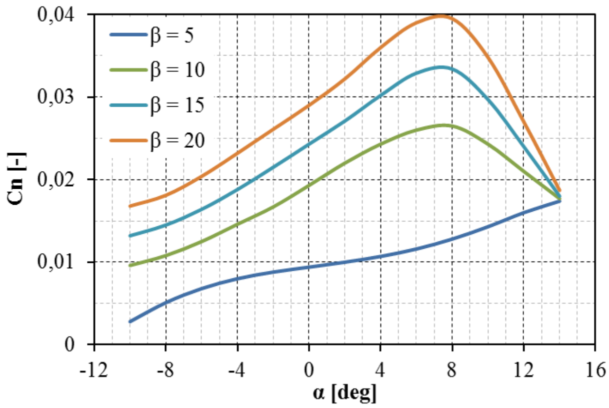

Fig.9. Yawing moment characteristics for various sideslip angle values and modified vertical stabilizer

It can be seen from Fig. 9 that magnitude of restoring moment during sideslip was increased, that explains better flying characteristics. The reason for stability improvement was better stabilizer effectiveness driven directly by is size and higher aspect ratio. Insignificant influence of dorsal fin can be explained by the fact that it usually becomes effective on higher sideslip angles and low angles of attack. Additionally, it is the fact that fuselage geometry drives its effectiveness as well. On the other hand, small ventral fin was supposedly affected by turbulent airflow behind the landing gear and fuselage, which probably made it ineffective.

Directional stability can be further improved by application of the ducted fan type of propulsion due to the increase of vertical surface behind the CG. This type of propulsion has been designed and tested as described in [34-38]. However, there were no flights performed with ducted fan propulsion so far, so that it is not confirmed yet.

With the use of aerodynamic data obtained from wind tunnel tests, a number of flight simulations have been performed including dynamic stability analysis. Software package SDSA was used to perform these simulations [39]. Results presented in [29, 32] were based on aerodynamic data retrieved for baseline vertical stabilizer configuration. After modifications that aimed at stability improvement, further simulations have been carried out. The results confirmed subjective pilot's opinion that stability properties have improved. This fact can be easily illustrated by comparison of Dutch roll properties for both cases: before and after modification. As shown in Fig. 10, demonstrator's oscillation period has decreased in the whole airspeed range, what means that from analytical point of view, the airplane aerodynamic "stiffness" to inertia ratio has increased. Since there was significant change in inertial properties, it proved that restoring moment from vertical stabilizer effect was higher than before.

Fig. 11 presents comparison of time to half the amplitude for baseline and modified stabilizer geometry. This parameter describes ability of an airplane to return to the equilibrium state and is directly connected with airplane aerodynamic damping effects, which are mainly driven by vertical stabilizer "paddle" effects. As can be seen, it was considerably reduced for airspeed range above 20 m/s, which confirms directional stability improvement, especially for airspeeds 24 m/s and higher. Data presented above have been prepared on the basis of demonstrator's simulations executed for flight altitude of 200 m and airspeeds in range of 18 – 35 m/s. In every case Dutch roll oscillations have been initiated by pulsed rudder deflections of +/-5 deg in the total period of 2 s. Exemplary plot of sideslip angle versus time as a response for this disturbance performed for initial airspeed of 25 m/s is presented in Fig. 12.

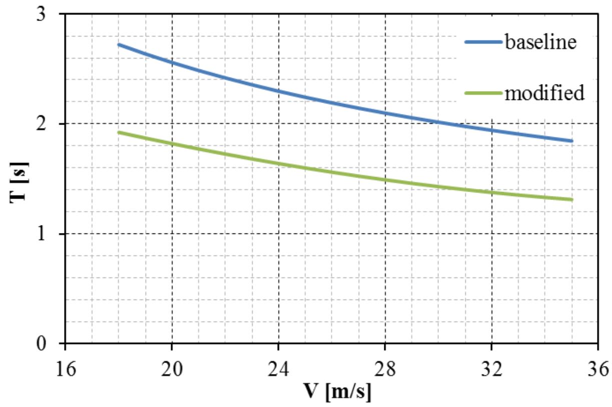

Fig.10. Dutch roll oscillation period for baseline and modified vertical stabilizer geometry

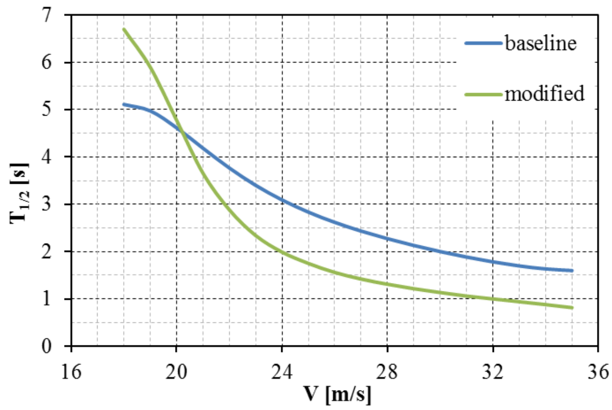

Fig.11. Time to half the amplitude of Dutch roll oscillation for baseline and modified vertical stabilizer geometry

Comparison of sideslip angle plots for baseline and modified stabilizer geometry with rudder deflection plot in time gives brief insight into differences of airplane properties. First of all, in the first case the amplitude and period of oscillations are higher, that means the aerodynamic damping is weaker. Secondly, the airplane responds slowly for rudder deflection change and still rises for some time even then rudder input diminishes, that confirms higher inertia. On the other hands, airplane with modified geometry manifests response that is robust and correlated to the control input. Simultaneously, oscillation period and damping is higher, that confirms better handling and stability properties in general.

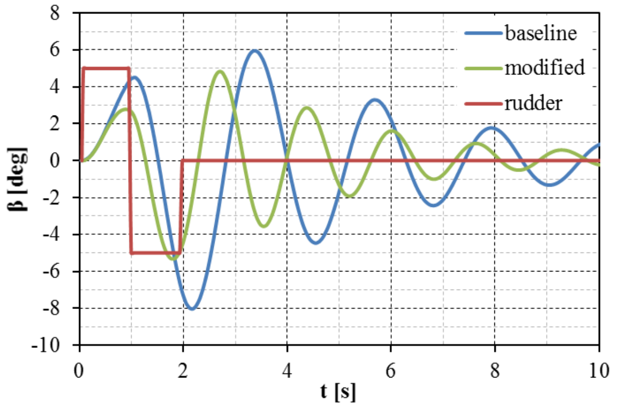

Fig.12. Sideslip angle variation after rudder double step deflection for baseline and modified vertical stabilizer geometry

Another test that was simulated to evaluate directional stability of the airplane was the case with pre-defined initial sideslip angle, which in result initiated spiral motion connected with oscillations in yaw. Comparison of results received for both configurations are presented in Fig. 13-14. As shown in Fig. 13, for the current configuration oscillation period decreased while damping in yaw increased, which confirms conclusions drawn previously about Dutch roll mode. Despite the motion amplitude is not much highly damped than before modification, the improvement is evident.

While studying Fig. 14, that shows roll angle in time after sideslip disturbance, strong coupling of directional and lateral motion is visible. That is because oscillatory motion in yaw induces oscillations in roll motion.

Furthermore, because roll angle after disturbance does not oscillate around neutral value, it is evident that spiral motion has been generated. It is typical situation when directional effect outbalances lateral restoring forces. However, it is not critical, since spiral mode is stable and is not dangerous in this case.

All the results presented above confirm that tail modification proposed by the pilot and later implemented into further flights resulted in stability improvement. Despite insufficient directional stability was not revealed based on the numerical results before initial flights were performed, it can be stated now that the airplane possess correct handling and stability properties.

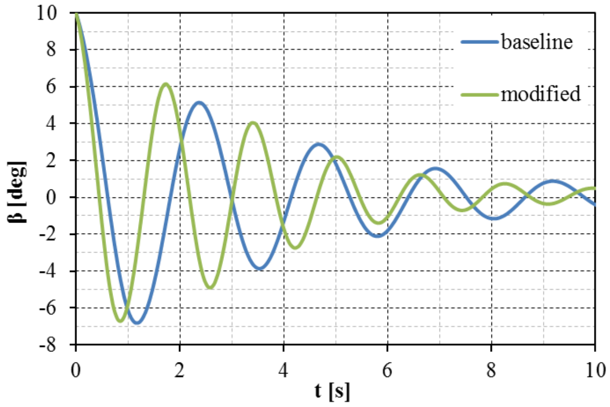

Fig.13. Sideslip angle variation in time after initial 10 deg sideslip disturbance

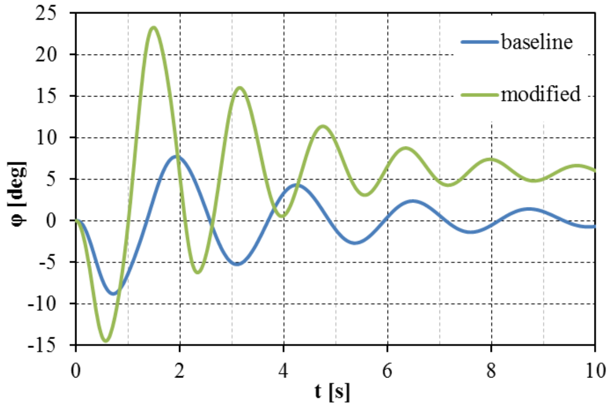

Fig.14. Roll angle variation in time after initial 10 deg sideslip disturbance

5 Conclusions

1. Safely flying unmanned airplane in the inverted joined wing configuration have been built and tested.
2. Low trimming drag is a key to the success of the joined wing airplane.
3. Propeller propulsion thrust vector, located above CG, generates disadvantageous pitching moment, since it has to be balanced by “elevator”, thus decreasing joined-wing airplane efficiency.
4. Application of the jet engine or distributed hybrid-electric propulsion installed at aft wing would be very advantageous for an inverted joined wing airplane.

Acknowledgments

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