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PROPULSION CONFIGURATION EFFECT ON PERFORMANCE OF AN INVERTED JOINED WING AIRPLANE

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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 the front of the lower one is an example of such a concept. Therefore, a project consisting of an 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 was undertaken by consortium led by the Institute of Aviation, including also Warsaw University of Technology, Air Force Institute of Technology and small company MSP. Results of this project led to the conclusion that inverted joined wing configuration allows to build an airplane with the best performance in the world, but its advantage against conventional airplanes is marginal. One reason for this is large trimming drag of the configuration with relatively high position of the thrust vector. Therefore, other configurations of the propulsion were also considered to see if airplane performance could be further improved. This effort is described in the present paper.

Keywords: *inverted joined wing, propulsion, performance, CFD*

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 the lifting surfaces is attached in the front of the 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 [31]. Concept was further developed by Wolkovitch [39] and many others. Researchers in Poland got interested in this concept in early eighties [4, 5]. 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 [7, 27].

Joined wing configuration is difficult to design due to the strong aerodynamic coupling [18] and static indeterminacy. Therefore dedicated research programme was undertaken to explore its properties [9, 10], utilizing previous experiences in optimisation [15, 21, 28, 33, 35, 36] and UAV flight-testing [8, 17, 19, 20]. Institute of Aviation was chosen as a leader of this effort because of its specialization [37] and previous experiences in general aviation [38].

In the course of this project, flying unmanned demonstrator was built to explore flight properties of the configuration [12]. Its flight characteristics were thoroughly investigated [25, 26] with application of data from both CFD analysis and wind tunnel measurements [6, 13]. Simultaneously further multicriterial aerodynamic optimisation was conducted to explore boarders of the configuration performance potential [34]. Finally, software for multidisciplinary optimisation was developed and applied to include also structural analysis into consideration [22, 29]. As a result it appeared that inverted joined wing configuration allows to build an airplane with the best performance in the world, but its advantage against conventional airplanes is marginal [11]. One reason for this is large trimming drag of the configuration applied. Four sources of the trimming drag were identified in the flying demonstrator [14, 30]:

– negative value of the pitching moment obtained for most high performance airfoils developed so far,
– the need for stability which implies application of CG position in front of point of neutral stability,
– large lift coefficient close to the wingtips of the front wing due to the application of front-aft wing tip plates,
– high position of the thrust vector.

First of them is difficult to avoid since airfoils with positive pitching moment usually have either poor performance or other disadvantageous flow characteristics. Second is unavoidable in airplanes without fly-by wire system and artificial stability augmentation. Third seems to be a natural consequence of application of joined wing configuration. Connection between front and aft wings decreases induced drag but shifts maximum of lift coefficient to the wing tip. With certain CG position, it will always result with additional negative pitching moment unless radical configuration modifications are applied [23]. Therefore, position of the thrust vector seems to be the only design parameter that can easily improve the pitching moment and decrease the trim drag. Therefore, two configurations of the propulsion system with lower thrust vector were considered to see if airplane performance could be further improved.

2. Propulsion systems applied and considered

Joined wing flying Demonstrator was to resemble manned large-scale airplane for 2-4 persons. Therefore, problem of visibility from "pilot seat" had to be addressed. The 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. Airplane rotating during take-off and landing operations can easily damage the propeller with large diameter. On the other hand, small multiblade propellers usually have much lower efficiency. That is why propeller was installed on flying demonstrator for first flights but ducted fan concept was also considered to decrease the diameter of the system [1, 2, 3, 16, 32]. Unfortunately, results of this effort proved that fan diameter could not be significantly smaller than propeller. As a result, both propeller and fan have to be installed relatively high above CG. Oblique thrust axis was considered since it would go close or even through the CG despite high position of the propeller/fan. However, this would also result with reduction of horizontal projection of thrust vector and lift reduction due to existence of vertical projection of the thrust vector. Therefore, another concept of the propulsion had to be also considered for the future. Jet engine installed at the same level with aft wing or distributed hybrid/electric propulsion installed in front of the aft wing could generate positive pitching moment.

3. Effect of thrust vector position on joined wing airplane performance

Brief experiment was undertaken to check the effect of application of lower thrust vector position on performance of existing demonstrator. CFD calculations for wings configuration were made with application of XFLR5 software first. During the analysis, the longitudinal balance of the aircraft was ensured for two specified flight conditions, corresponding to maximum glide ratio and maximum endurance factor values respectively. In both cases, needed thrust was estimated basing on experimental data for wind tunnel tested demonstrator. To achieve longitudinal balance of the aircraft the elevator placed on the aft wing were deflected properly. The result of direct shift of the thrust vector is presented in Fig. 2. As can be seen from this drawing effect on L/D ratio appeared insignificant, however power factor was increased by 2.5%.

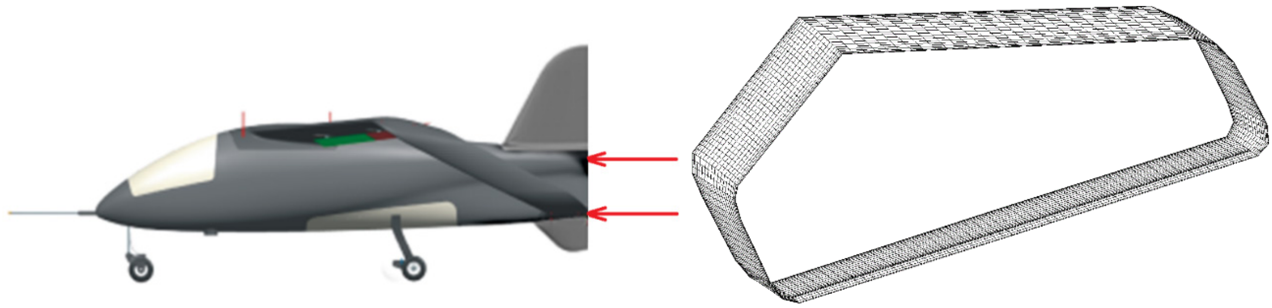

Fig. 1. Thrust vector position modification considered and wing configuration applied for initial analysis

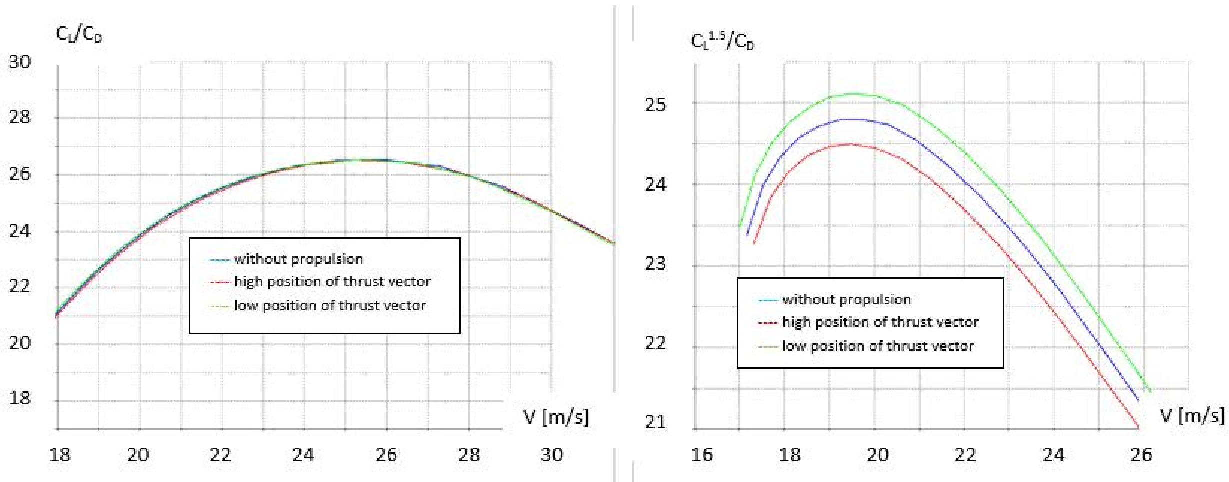

Fig. 2. Effect of thrust vector position on the demonstrator L/D ratio and power factor (curves: blue – glider configuration, red – high thrust vector position, green – low thrust vector position)

Notwithstanding, direct shift of the thrust vector is not the only modification that could be made if jet or distributed propulsion were applied.

Certain position of the CG in existing demonstrator was not resulting from static longitudinal stability but from directional stability, which was considered as low basing on the flight tests results. Unfortunately, with propeller driven propulsion, it was not possible to increase the chord of the vertical stabilizer and only small extension of the stabilizer could be made.

Therefore, CG position had to be moved forward resulting with large longitudinal stability margin and large trim drag. With jet or distributed propulsion, chord of the vertical stabilizer could be extended increasing directional stability without CG shift. Therefore, stability margin could be reduced to 5%.

The CG translation needed to achieve this goal was so large that the inclination angle of the aft wing had to be increased to avoid excessive elevator deflections, and therefore provide higher lift force on the aft wing in the most efficient way. Effect of this attempt can be seen in Fig. 3.

As can be seen from Fig. 3 further improvement of power factor by 8.4% can be observed, however difference between configurations with different thrust vector position is smaller in this case and equal to 1%. Moreover, improvement of L/D ratio by 3.8% was also observed as a result of stability margin decrease and more balanced lifting force distribution between the front and the aft wing (Fig. 4).

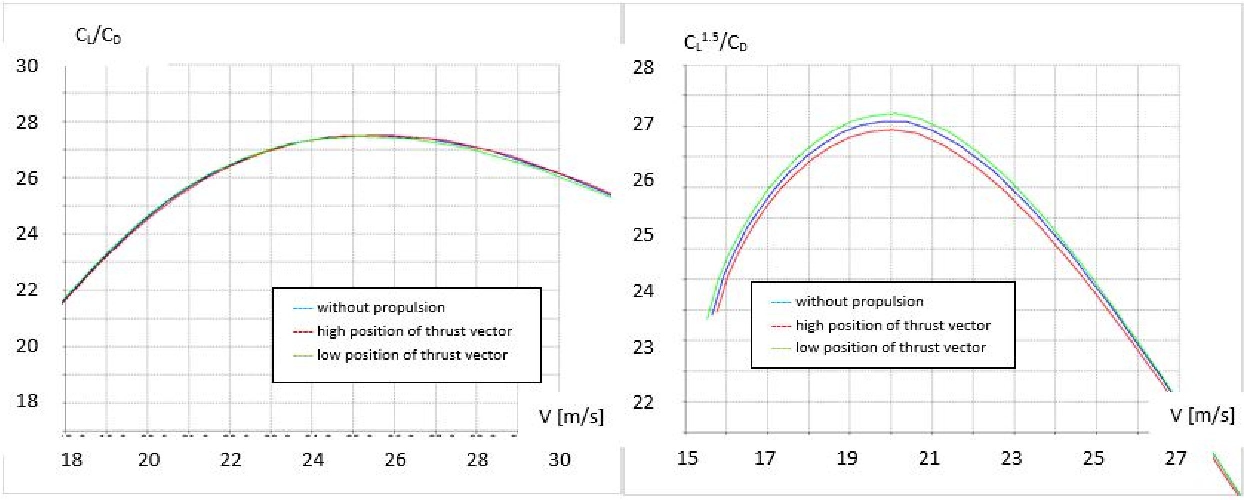

Fig. 3. Combined effect of thrust vector position and reduced stability margin on the demonstrator L/D ratio and power factor (curves: blue - glider configuration, red - high thrust vector position, green - low thrust vector position)

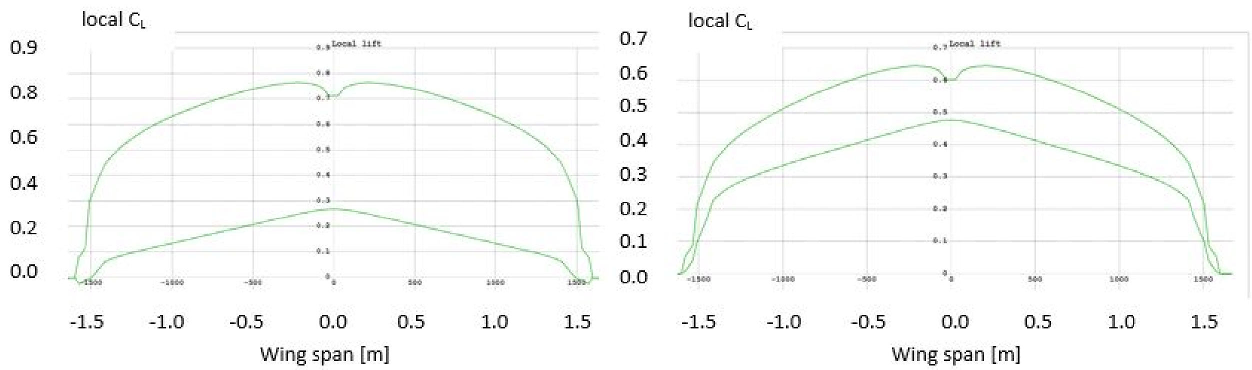

Fig. 4. Lifting force distribution with large stability margin (left) and reduced to 5% (right)

Application of ducted fan propulsion should also improve directional stability. Moreover, it should also allow for further shift of the CG position backwards. Therefore, it was investigated if such indirect improvement of the airplane performance is possible. A duct was added to the CFD model (Fig. 5) and calculations were performed again with assumption that stability margin is the same like in the previous case. Variant with lower thrust vector position was not considered because lower installation of the duct was not possible. Results of this part of experiment are presented in Fig. 6. As can be seen from this plot advantage of the ducted fan application may result only from greater propulsive efficiency since drag of the duct decreases both L/D ratio and power factor. These loses have to be balanced by greater propulsive efficiency of the duct – fan system.

Finally, complete configuration with fuselage (but without duct) was also examined with stability margin of 10%. A part of multidisciplinary software was used in this case. It was utilizing PanAir software for inviscid analysis, supplemented by analytical calculation of turbulent flow friction drag [24]. Quite small improvements were observed. Maximal value of L/D was increased by 0.1% and power factor by 0.5%. Smaller improvements can be explained by presence of the fuselage (which contributes significant part of the drag) and greater stability margin than in previous cases.

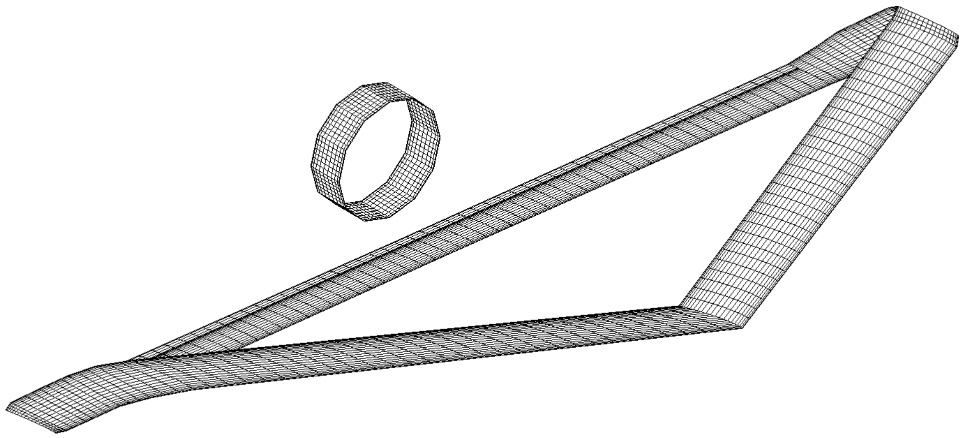

Fig. 5. The model of joined wing configuration with propulsion duct

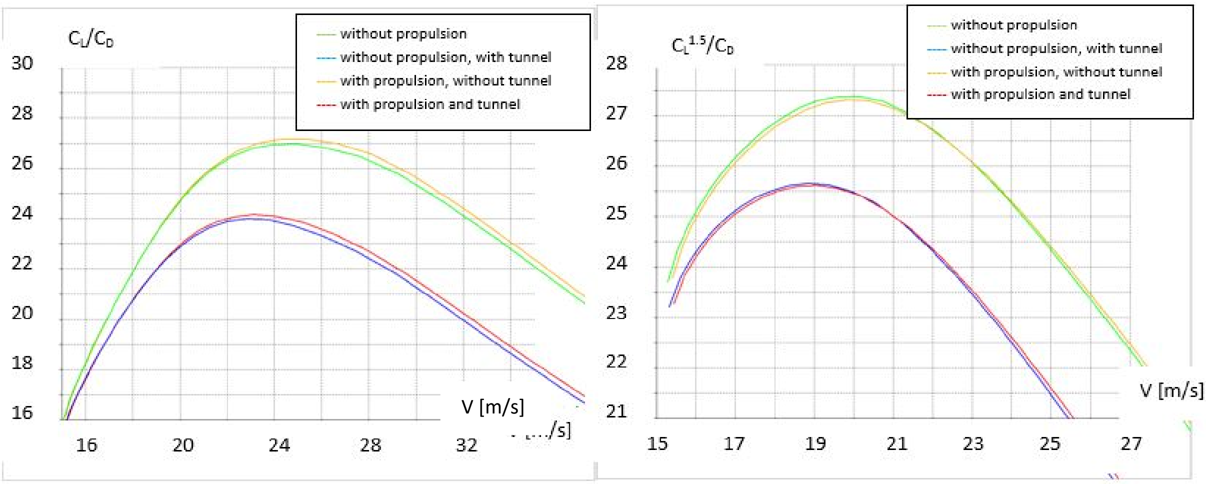

Fig. 6. L/D ratio and power factor for joined wing configuration with propulsion duct influencing longitudinal stability analysis (curves: blue/green – glider configuration with/without influence of duct drag , red/yellow – high thrust vector position with/without influence of duct drag)

4. Conclusions

Application of the propulsion configuration with low position of the thrust vector can improve performance of an inverted joined wing airplane. However, the improvement connected directly with the shift of the thrust vector is not impressive. However, the low position of propulsion system allowed for another design change, which previously would not be possible. With the assumption of fulfilling all lateral stability requirements, the CG could be shifted backward to achieve longitudinal stability margin of 5%. It caused significant change in the loads proportion between the front and the aft wing, giving the highest improvement of the airplane performance. The high position of the thrust vector, even with added propulsion duct and further shifted CG backwards, seems not guarantee better results. Analysis more sophisticated would be necessary to confirm this fact (including propulsive efficiency estimation).

Acknowledgments

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