Progress in Inverted Joined Wing Scaled Demonstrator Programme

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ABSTRACT

Efficiency is crucial for an airplane to reduce both costs of operations and emissions of air pollutants. There are several airplane concepts that potentially allow to increase the efficiency, which were not investigated thoroughly enough. Inverted join wing configuration, where upper wing is located in front of the lower one is an example of such a concept. Therefore, the project described in this paper is dedicated to fill this gap. CFD analyses, wind tunnel tests and flight tests of scaled demonstrator have been undertaken to perform this task. This paper presents a summary of results achieved so far with particular attention put on CFD and flight test results.

1 INTRODUCTION

Joined wing configuration is considered as a candidate for future airplanes. 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 (box wing). For the first time it was proposed by Prandtl in [1]. This concept has many possible advantages like induced drag reduction and weight reduction due to the closed wing concept. Unfortunately it is much more complicated to design than conventional airplane due to the strong aerodynamic coupling [2] and static indeterminacy. Therefore it was not possible to build successful, safe and efficient airplane in this configuration before computer aided design systems became available [3, 4] and even its early versions were not powerful enough. Large meshes are necessary to describe it accurately enough for precise CFD analysis, so very capable computers were required and unfortunately unavailable. On the other hand potential weight reduction comes from the static indeterminacy of the joined wing configuration. Once again powerful computers were necessary to analyze it with FEM method with satisfactory accuracy. Moreover, static indeterminacy causes significant manufacturing problems due to tight tolerances required to assembly the joined wing with no random internal stresses. All these difficulties can be resolved with application of modern CFD and FEM software, increased computing capabilities and prototyping capabilities based on computer controlled machining. All of them are currently available, so attempts to design a joined wing airplane are more frequent. However in most cases researchers concentrate on configuration where front wing is attached at the bottom of fuselage and aft wing is installed either at the top of the fuselage or at the top of the vertical stabilizer [5-21]. Our previous experience [22] led to the conclusion that joined wing airplane could fly much better in upside down configuration. The most probable reason of this fact comes from the interaction between wings. Front wing wake is very close to the aft wing if gap between wings is

too small. It becomes even smaller at high angles of attack if front wing is located below aft wing. As a result, aerodynamic advantages are diminished. They may be recovered if aft wing is installed high at the top of the vertical stabilizer, however this requires strong stabilizer which decreases potential weight reduction. Configuration with front wing above aft wing should work in the opposite way, thus delivering expected advantages, assuming that fuselage is reasonably high.

CFD analyses run a few years ago confirmed, that joined wing airplane L/D grows together with increasing gap between wings [23]. Moreover, assuming the same gap, configuration with front wing above aft wing provides not only greater maximum L/D, but also greater L/D in wider range of angles of attack. In particular, L/D at high angles of attack is greater in this configuration, which suggests advantageous flight endurance. Configuration with front wing below aft wing is advantageous only at low angles of attack assuming that aft wing is installed at the top of the vertical stabilizer. However, as mentioned before, weight advantage will be reduced in this case due to increased loads of vertical stabilizer. As can be seen from this result, final conclusion is not clear yet, which was the motivation to undertake our current project.

2 PROJECT ORGANIZATION

In the quest for the following project after I-31T [24], the Institute of Aviation [25, 26] undertook the project of an inverted joined-wing UAV [27-29]. It is leading the consortium consisting of Warsaw University of Technology, Air Force Institute of Technology and small company MSP. Multidisciplinary optimization, performance, stability and control analyses of the joined wing unmanned aerial vehicle (UAV) are the main goals of this project. Theoretical analyses are being verified by wind tunnel and flight tests. It is believed that it will allow for collecting an extensive database of knowledge concerning joined wing airplane configuration. Most of the analyses and optimization in this project have been conducted for UAV since this allowed for building inexpensive real flying test-beds [30-33]. Three UAVs are to be tested in this project, one with wing span of 1,2m (model) and two with wing span of 3m (demonstrators). Two of them are currently flight tested.

Multidisciplinary optimization is a key to successful development of the joined wing airplane. Unfortunately, at the beginning of the project, software necessary for multidisciplinary optimization of the joined wing airplane was not available. It was also known that the development of such a software is very time-consuming. Therefore, it was decided that the software development will be a separate part of the project [29, 34]. It will be used at the end of the project to show how much better airplane can be built in a comparison to the one flight tested in current project.

Large demonstrators used in current project were optimized with the software for multicriterial aerodynamic optimization [35-37]. Quite strict constraints were imposed on the process to make sure that large demonstrators will fly safely. Therefore, top and front view of the airplane was based on the geometry of the small model described in [28]. This ensured correct stability and handling stability but did not allow achieving high performances. Therefore, additional session of aerodynamic optimization was performed with relaxed constraints [38] to check the limits of pure aerodynamic optimization.

After each session of optimization, CFD analysis was performed [39]. After first session it was necessary to calculate loads of the large demonstrator during wind tunnel and flight test. Results of this session were also used for comparison with wind tunnel test results. Data generated with experimental and CFD methods were used to simulate demonstrator performance [40] and dynamic characteristics [41]. CFD results obtained after second session of aerodynamic optimization have been compared with data generated for a few existing airplanes.

The demonstrator used for wind tunnel tests is also used for flight tests, however, it is equipped with electrical propulsion, which constrains flight endurance. Therefore, second large UAV was built and equipped with internal combustion piston engine.

Selected results of the CFD analysis performed after second session of aerodynamic optimization, observations after first flight of electric UAV and performances calculated for UAV driven by the piston engine are presented below.

3 CFD ANALYSIS

CFD analysis, based on the Finite Volume Method (FVM), is a very useful tool in aircraft design and prototyping. It combines high reliability and accuracy of results with relatively low cost. In the following work one of the most widely recognized as an industrial standard RANS solvers - ANSYS Fluent - was used. At the beginning of the most recent part of Inverted Joined Wing Scaled Demonstrator Programme, the CFD simulations have been undertaken to verify results of the multicriterial aerodynamic optimization. The optimization used a Vortex Lattice Method (VLM), expanded by Prandtl equations for viscosity effects (boundary layer region), to evaluate objective functions and find optimal solutions. Comparing to FVM, it is simplified method for deriving aerodynamic forces acting on an airplane and therefore, due to strong aerodynamic coupling between front and rear wing, its verification was needed. As a result of the optimization, a set of Pareto optimal solutions was received. The CFD analyses gave necessary information to choose only one optimal configuration from the calculated Pareto frontier for further study. The above-mentioned optimization was conducted for isolated lifting surfaces only. The simulations performed in ANSYS Fluent software allowed to include into calculations also other parts of the airframe, such as fuselage or landing gear, and assess their influence on final aerodynamic characteristics of complete airplane.

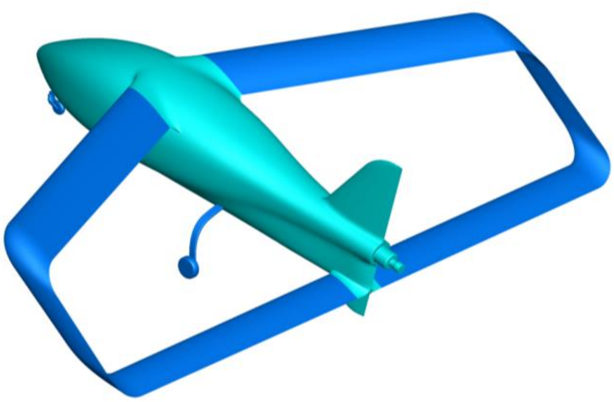

Figure 1: Baseline plane model (after 1st session of optimisation)

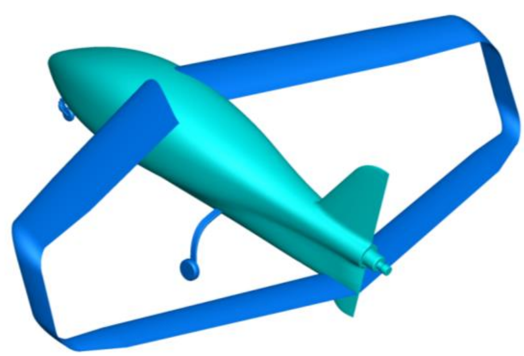

Figure 2: Pareto-34 plane model (after 2nd session of optimisation)

Subsequently, two classical configuration airplanes of similar application were modeled in order to make a comparison with the inverted joined wing airplane concept. The simplified models of these widely known high performance airplanes (Model 1 - low wing, retractable landing gear, Model 2 - high wing, fixed landing gear) were created in a scale corresponding to the 3 meter wingspan demonstrator, based on information available for public with application of some inverse engineering methods. In order to fairly compare two different types of airplane configuration - the classical one and the inverted joined wing - total lifting surface area, including rear wing or horizontal tail, had to be taken into account as reference area when calculating selected aerodynamic coefficients. Finally, the results of CFD analysis gave detailed information about static

stability issues and stall performance of all calculated cases. Some FLUENT calculations could also be compared with experimental data from wind tunnel tests of the Baseline airplane configuration (configuration of currently flying demonstrator) and allowed to evaluate the reliability of the work.
Most cases were analyzed with the same solver settings and mesh parameters. Double precision pressure based solver with incompressible flow and k-ω SST Transitional (4 equations) turbulence model was used. This implied the necessity of high resolution meshes generation with y+ values around 1 and below. Tetrahedral meshes with prism layers to simulate flow in boundary layer region were created in ANSYS ICEM software. So configured and prepared models had the capability of capturing not only turbulent flow in domain but also laminar regions which potentially could have great influence on aerodynamic performance (laminar separation bubbles, etc.) in corresponding Reynolds numbers range (about 500 000). Surface roughness was not modeled which corresponds to assumption of perfectly smooth wetted surfaces of all calculation models. However, some cases were also calculated with standard k-ω SST (2 equations) turbulence model assuming fully turbulent flow anywhere in the computational domain. This way the impact of laminar flow regions on final aerodynamic characteristics could be easily evaluated by comparing results from both turbulence models used. With this knowledge, importance of the airframe surface finish (roughness) could be easily judged. The range of angles of attack for simulations was set mostly to AoA=<-10°; 20°> (with 2 degree step) and simulation airspeed was 24.5 m/s (value received from optimization).

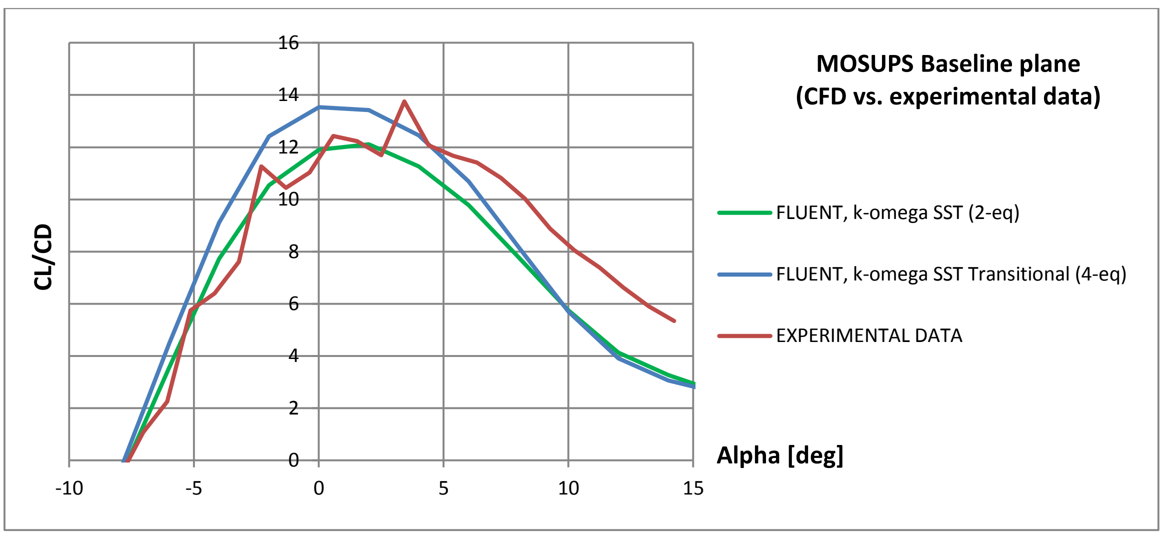

Figure 3: Results from both turbulence models compared with experimental data

The CFD analysis of complete Baseline airplane configuration revealed that in general, experimental data appear between results received from calculations with the transitional turbulence model and the fully turbulent one. Although the first model assumes perfectly smooth wetted surfaces (idealization), it could be seen that for selected angles of attack the experimental data are getting close to it. Assumption of fully turbulent flow led to higher aerodynamic drag coefficients, but also made it possible to achieve higher CL due to stall delay. For isolated wing of the Baseline configuration there is an improvement of about 15 % in terms of CL/CD ratio and almost 30 % in case of CL^3/CD^2 when the transitional turbulence model is used

(compared to fully turbulent). In this conditions, selected optimized wing configuration (named Pareto-34) has about 7 % higher maximum CL/CD ratio and 18 % higher CL^3/CD^2 than the Baseline wing configuration. Therefore, the CFD analysis confirmed successful optimization results. Also higher maximum CL was achieved, but at the expense of mild stall characteristics of the Baseline configuration. There the stall occurs simultaneously on the entire span of the front wing, not firstly in the middle of the wing, as it was previously.

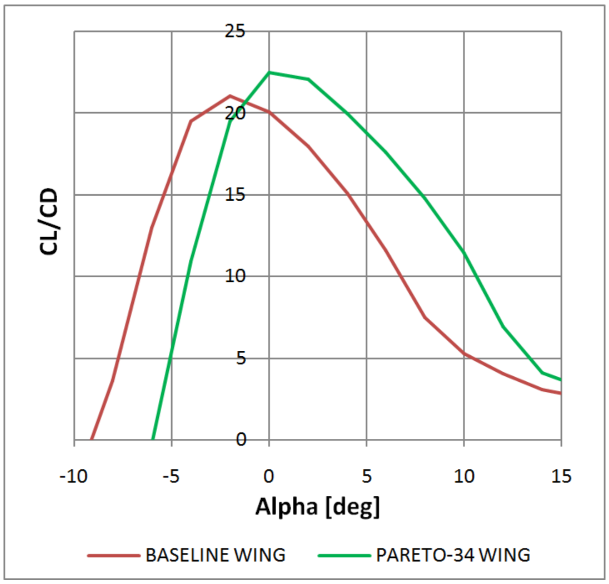

Figure 4: Aerodynamic optimization results verification (CL/CD - 7% increase).

K-omega SST Transitional turbulence model

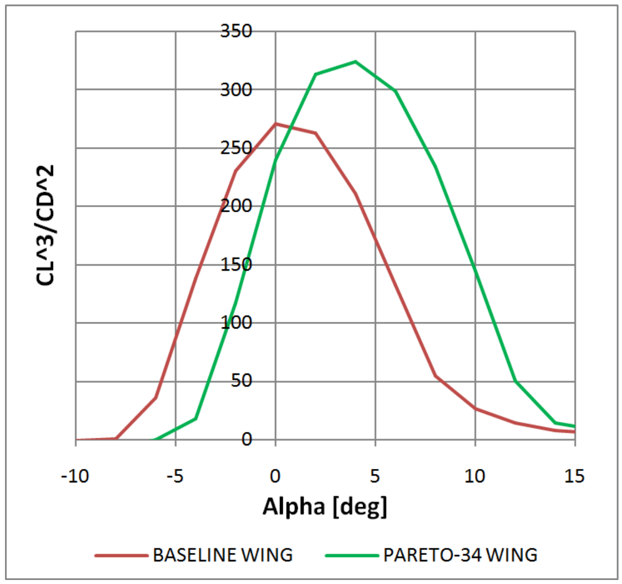

Figure 5: Aerodynamic optimization results verification (CL^3/CD^2 - 18% increase)

K-omega SST Transitional turbulence model

When comparing to two other airplanes analyzed, it turned out that both have some advantage over the inverted joined wing demonstrator. As expected, first model of much heavier and faster Model 1 has better CL/CD ratio in the low CL range and lower zero-lift CD, mainly due to retractable landing gear and smoother fuselage. Whereas, the second model - based on ultralight Model 2 turned out to be better in both CL/CD ratio and CL^3/CD^2 in the whole range of CL. It was contrary to expectations, especially in terms of flight endurance factor, but it should be also remembered that these comparisons were made for untrimmed flight conditions. In the future, more precise calculations should be done, including longitudinal stability analysis. It is expected that inverted joined wing will suffer less aerodynamic characteristics deterioration than classical configuration airplane with horizontal tail when longitudinal balance will be ensured. In addition, more work is also needed to optimize the shape of fuselage or add some wheel fairings. That is because for current inverted joined wing demonstrator, contribution of these parts of the airframe in aerodynamic drag formation is greater than for similar airplanes.

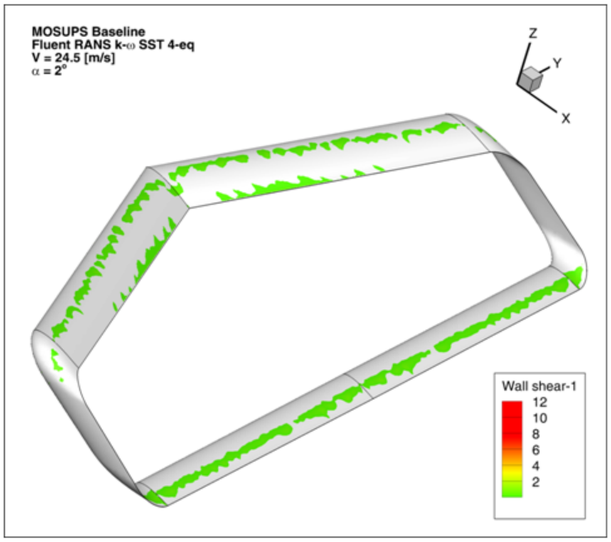

Figure 6: Reverse flow regions visualisation for Baseline wing configuration

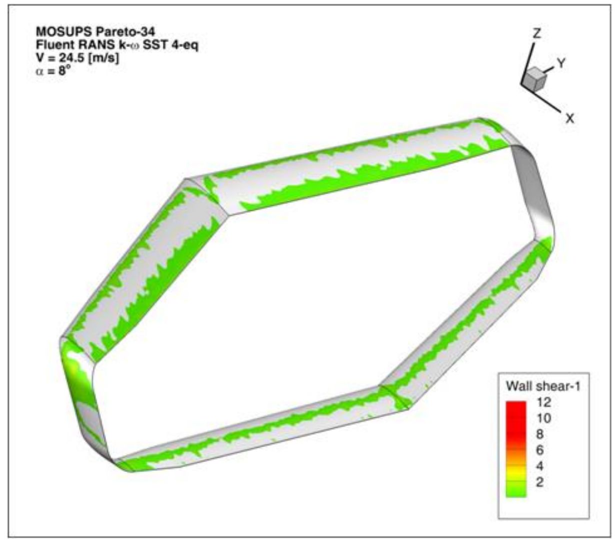

Figure 7: Reverse flow regions visualisation for Pareto-34 wing configuration

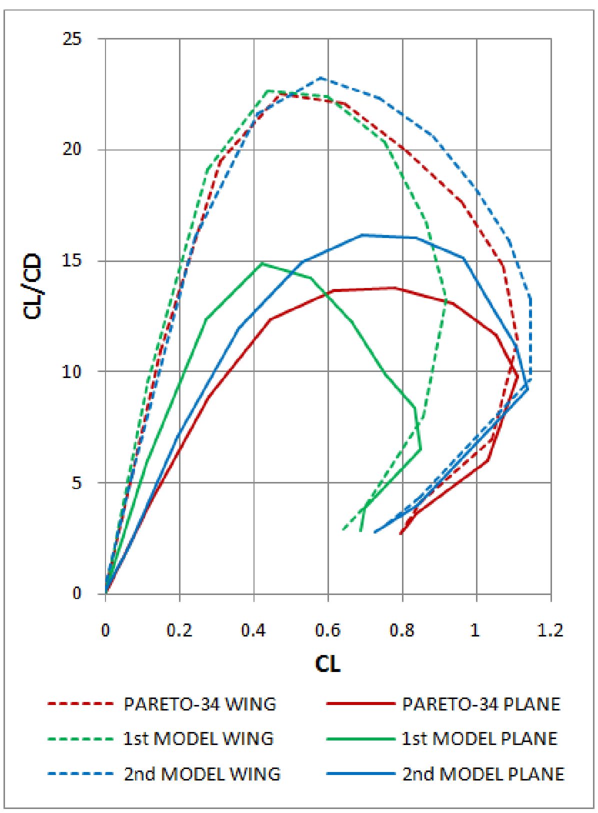

Figure 8: CL/CD ratio vs. CL for isolated wings and complete airplanes. K-omega SST Transitional turbulence model

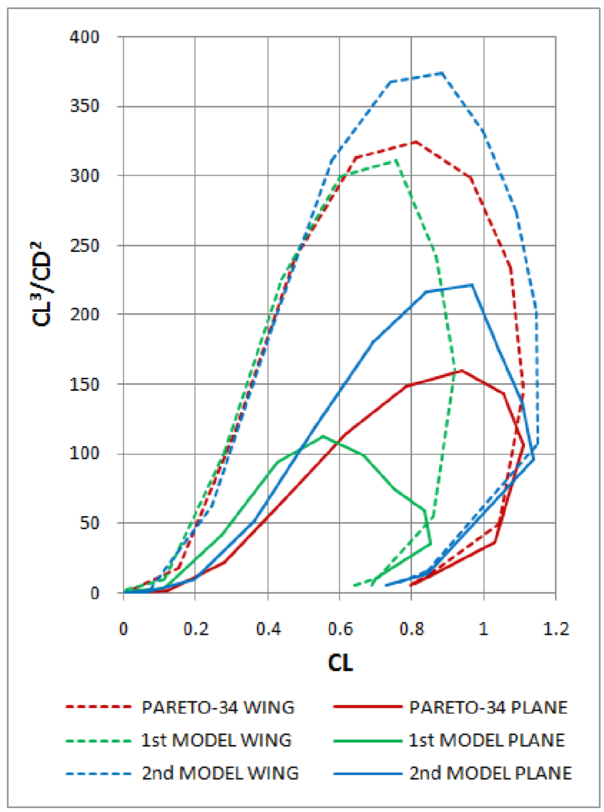

Figure 9: CL^3/CD^2 ratio vs. CL for isolated wings and complete airplanes. K-omega SST Transitional turbulence model

4 FLIGHT TESTS

First flight of large, electrically driven demonstrator took place on 28th August 2014 at the Grądy airfield [42]. Two flights were performed to verify basic airworthiness of the airplane.

4.1 Conditions and configuration

Wind speed: 4 – 8 m/s
Temperature: about 17^0 C
Wind direction: S-W (45^0 to the runway axis)
TO weight during first flight: 23.78 kg (aft CG)
TO weight during second flight: 24.28 kg (CG moved slightly forward)


Figure 10: First demonstrator with wing span of 3m in flight

4.2 Observations

4.2.1 Longitudinal motion

Uncommanded takeoff after airspeed of 70km/h was achieved. Main wheels were raised first, therefore last phase of the takeoff run on the front wheel was unstable. Front wheel took off after rotation commanded by the elevator. It should be mentioned here that the airplane was designed to takeoff from all three wheels without rotation to protect a propeller against hitting a runway. First flight revealed that in current configuration elevator should be deflected upwards or flaps should be deflected downwards during takeoff run.
Thrust eccentricity was clearly observable, in particular when flying with low airspeed. This feature complicates approach to landing since rapid thrust changes have to be avoided, not to excite large amplitude oscillations.

4.2.2 Lateral motion

Controllability with ailerons seemed to be relatively poor. Direction of flight was maintained despite noticeable bank angle was achieved, therefore rudder deflection into the turning direction was necessary. Perhaps ailerons differential was not large enough.
On the other hand airplane was giving an impression of low directional stability. Recovery trend was clearly observable after excitation by the rudder, but damping of oscillations was smaller than in the case of

conventional airplane with large dihedral. This behavior may be caused by larger moment of inertia about vertical axis in comparison to the conventional airplane.
It is possible to control the direction of flight (and bank angle to some extent) with rudder only (without ailerons application). On the other hand maintaining the straight flight is not easy, in particular in gusty weather.

4.2.3. Performance

Climb rate and the difference between maximum and minimum airspeed seem to be satisfactory and sufficient for safe flying. Climb rate is close to 5 m/s at the beginning and to 4 m/s after batteries are discharged to about 50%.
Flight endurance was equal to about 10 min with energy reserve for additional approach. Li-Fe 12S4P batteries are currently applied with 39V, 10Ah, and energy density of about 85Wh/kg. In the case of rational flight planning measurement flights with safe endurance of about 14 – 15 min should be possible. Airspeed between optimal and economical should be maintained to achieve this as well as climbing no higher than 200m and full energy utilization. Flight endurance may be extended by application of Li-poly batteries with energy density of about 145Wh/kg.

5 SECOND PROTOTYPE

Electrical propulsion was applied into the first demonstrator [43] to facilitate wind tunnel tests and enable flight testing [27-29] using the same airframe. However, relatively short flight endurance constrains number of experiments possible to perform in single flight. As a result number of flights necessary to conclude the project would be relatively large. This drawback, together with long time of batteries recharging would extend the project significantly. Therefore, second demonstrator was built with piston engine DLE-40. It has similar output power to the motor Turnigy RotoMax 1.60 applied into the first demonstrator. As a result, airplane performance was not significantly changed, except range and flight endurance. Both of them were extended thanks to the higher density of energy accumulated in gasoline (approximately 10 times greater than for Li-poly and 20 greater than for Li-Fe batteries).

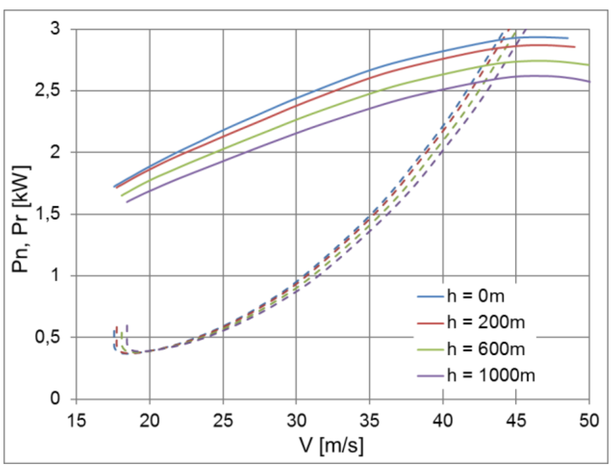

Figure 11: Power available (solid) and required (dashed) to fly

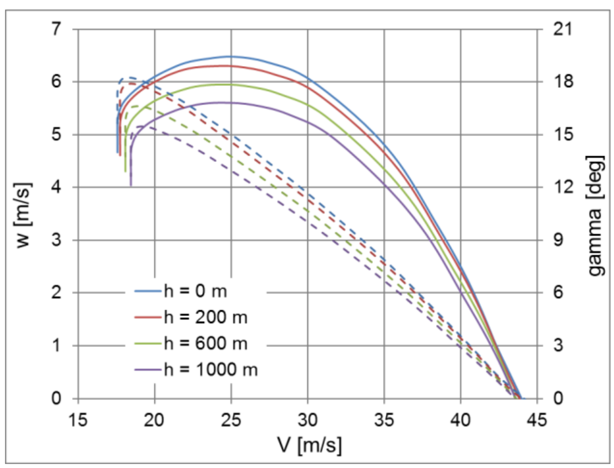

Figure 12: Calculated climb rate (solid) and climb angle (dashed)

Different performance variation within one flight provides additional advantage of internal combustion propulsion. Airplane equipped with piston engine consumes the fuel during the flight which makes it lighter before landing. Therefore in the case of emergency, airplane may achieve greater climb rate at the end of flight than at the beginning, which is advantageous in the case of go-around maneuver. In the contrary, electrically driven airplanes maintain constant weight during the flight. In the same time voltage of batteries falls down together with discharging. As a result much smaller climb rate is possible at the end of each flight.
Figures 11 - 13 show predicted performances, calculated with the same method as presented in [40].

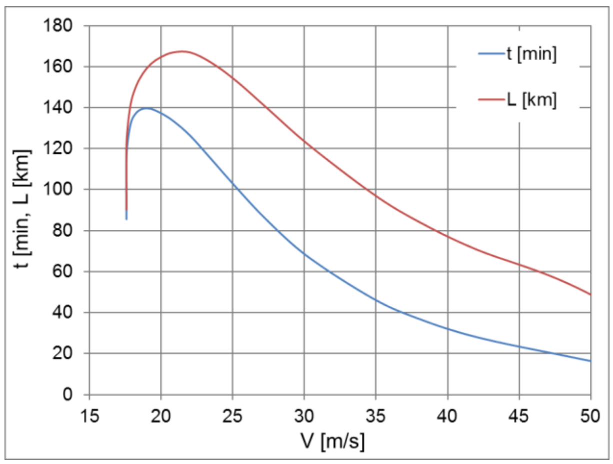

Figure 13: Calculated range and endurance of the second demonstrator

6 CONCLUSION

Two unmanned demonstrators of the joined wing airplane were built. First of them is powered by electrical motor, second by piston engine. First flight of electrical demonstrator revealed significant effect of thrust eccentricity and safe but small directional stability with aft CG. More flights are needed to investigate demonstrator's dynamic properties.
Significantly constrained multicriterial aerodynamic optimization was applied to design geometry of existing demonstrators for the programme safety. Second session of multicriterial aerodynamic optimization was run with significantly relaxed constraints allowing for performance improvement. Achieved configuration seems to have performance comparable to the most advanced conventional designs, but not better. Therefore more work is necessary to prove advantages of the joined wing airplane. It may be achieved with application of the new software for multidisciplinary optimization, which is currently developed.

7 ACKNOLEDGEMENTS

This work was supported by The National Centre for Research and Development under grant No. PBS1/A6/14/2012. Special thanks to the all personnel of MSP company, which manufactured the model and to the all personnel of the AFIT, which performed the flight experiment.

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