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ASSUMPTIONS OF THE JOINED WING FLYING MODEL PROGRAMME

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Abstract

Joined wing configuration is considered as a candidate for future airplanes. Potentially it should allow reducing both empty weight and drag of the airplane. Both effects can reduce the fuel consumption thus decreasing operational costs and greenhouse gasses emission. However this configuration is very difficult to apply due to the aerodynamic coupling and static indeterminacy. This paper presents the research project taken to expand the knowledge concerning this configuration. Its novel version with front wing at the top of the fuselage will be investigated in details. The paper describes assumptions of the project, the following steps and expected results.

Keywords: Joined wing, CFD, simulation, wind tunnel tests, flight tests, dynamically scaledmodel, demonstrator.

INTRODUCTION

Multicriterial optimisation, performance, stability and control analyses of the joined wing unmanned aerial vehicle (UAV) are a main goal of the joined wing flying model programme. Joined wing 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). Application of this concept was proposed for the first time by Prandtl in 1924 [1]. It 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. As a result attempts to build practical airplane with application of conventional analytical and experimental methods could not be successful [2, 3]. Appearance of numerical tools in 60-70-ties gave a possibility to return to this concept [4-10]. Unfortunately software available those days was quite simple and did not allow for efficient multicriterial optimisation.

Recently advanced aircraft configurations became interesting for researchers again, that results with growing number of published papers [11-29]. It is possible thanks to the development of integrated software which provides an opportunity to run quite complicated multidisciplinary optimisation also in smaller research teams. This allows for experiments with variations of the joined wing concept that have never been tested. That is also the case of this project. Authors previous experience [10, 18, 31] suggests that joined wing configuration should have positive stagger instead of negative, which is usually explored. In the course of students final year projects it was analysed at the Mechanical Faculty of Power and Aeronautical Engineering [30-32] in terms of aerodynamic drag reduction possibilities. Results obtained in these studies suggest that configuration with positive stagger (upper wing in the front) is advantageous. The most probable explanation is that the gap between wings grows with increasing angle of attack, which improves the flow conditions at aft wing. Investigation in this project will be focused on this novel approach. Positive result should allow for increasing the gliding ratio, thus decreasing the fuel consumption. As a result more economically efficient and environment friendly airplane configuration could be created.

PURPOSE OF THE PROJECT

Joined wing configuration is considered as a candidate for future airplanes. Potentially it should allow reducing both empty weight and drag. Both effects can reduce the fuel consumption thus decreasing operational costs and greenhouse gases emission.

Analysis and optimisation in this project will be run for UAV, since this will allow for building inexpensive real flying test-bed. UAV flight test results can be verified on the full scale airplane in the following project provided that outcome of this one is positive. This approach was already taken several times in Poland [33-36]. On the other hand commercial UAV could also be developed directly from current flying test-bed. Application of the joined wing configuration in the commercial UAV should provide not only better performance but also more compact and tougher structure, which is important in the case of takeoff performed from launching machines and landings on the parachute. Combination of good performance with tough structure is quite rare on the current UAV market.

Proposed configuration can be also applied in other: general, utility and local transport airplanes. All these categories were traditionally interesting for Polish aerospace industry.

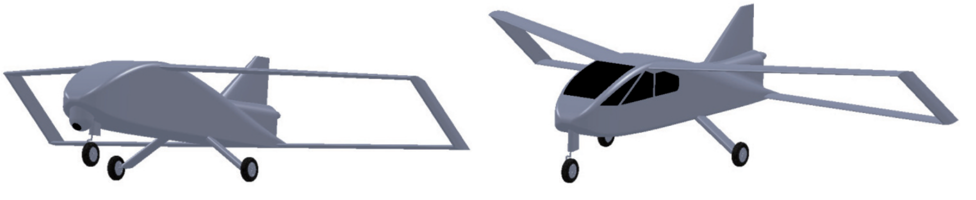

Fig. 1. UAV and manned joined wing airplanes that could be developed as a result of this project [C. Galiński, 2012]

Fig. 1 presents concepts of such airplanes. Manned one can be built as a small tourist airplane designed for two persons according to CS-VLA requirements. It could be manufactured by a small company employing a few dozens of workers. This concept can be also applied in airplane for 2-4 persons designed according to CS-23 requirements. Further development envisages small local transport airplane in the size of An-2, M-28 Skytruck or DH Twin Otter.

STATE OF THE ART

As already mentioned application of the joined wing airplane configuration was proposed for the first time by Prandtl in 1924 [1]. According to his paper joined wing configuration is optimal in terms of induced drag generation, thus promising smaller fuel consumption.

Unfortunately, economy was not a priority in twenties and thirties because forthcoming war required focusing efforts on maximum airspeed increase. Moreover fuel prices were relatively low. Flying with maximum airspeed requires large lift over drag ratio (L/D) for low lift coefficients, where induced drag is very small anyway. Moreover in the case of small lift coefficients, joined wing drag coefficient is slightly greater than for conventional airplane, because of additional drag of wingtip plates and interference drag.

Similar trend was present during first decades after World War II leading to the supersonic passenger airplanes. As a result only a few attempts [2, 3] were taken to build more economic airplane due to the induced drag reduction. Joined wing is much more complicated configuration than conventional and amount of information concerning it was also very limited. All these reasons were discouraging for anybody who would like to design a joined wing. Finally oil crisis of seventies, success of Boeing-747 and market failure of Concorde turned designers attention towards more economical airplanes. In the same time computers became widely available together with CFD and FEM software. These conditions encouraged some scientists to recall Prandtl idea. Initial research [4-10] gave promising results, but revealed also difficulties arising from the concept complexity. These difficulties are caused by aerodynamic, structural and manufacturing reasons. Joined wing is aerodynamically closely coupled which means strong interaction between wings [37]. As a result detailed aerodynamic analysis was not possible without CFD software and even its early versions were not powerful enough to design a joined wing. Large meshes are necessary to describe it accurately enough, 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 analyse 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. Tight tolerances are achievable only now with application of modern CAM systems. 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 an advanced airplane configurations are more frequent [11-29]. However in most cases researchers concentrate on joined wing 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. According to our previous experience this configuration cannot provide expected advantages.

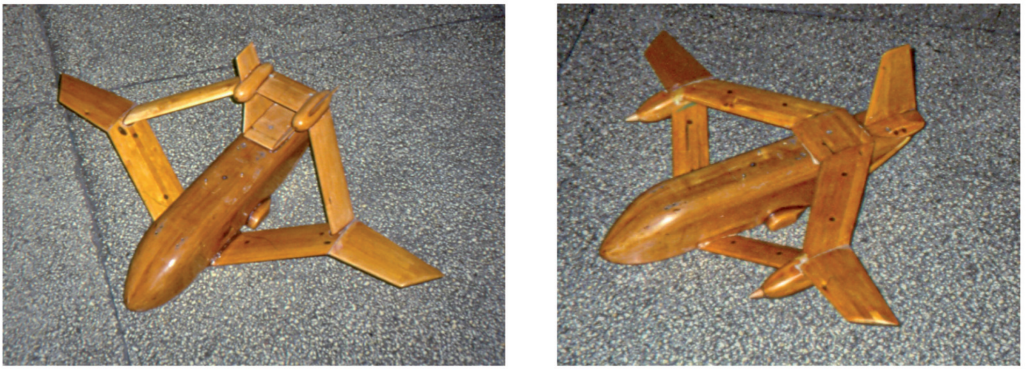

Fig. 2. Wind tunnel joined wing models applied by Warsaw University of Technology in early nineties [C. Galiński, 1990]

First attempts to design a joined wing at Warsaw University of Technology were undertaken in late eighties [8-9]. One of these projects was run by the team leader of the current project (Fig. 2). Results were presented during Aerospace Atlantic Conference in Dayton Ohio in 1992 [10]. Two flying models were also built, exhibiting excellent handling qualities (Fig. 3). All these efforts were focused on the most popular joined wing configuration with front wing at the bottom of the fuselage. However results of investigation lead to the conclusion that joined wing airplane could fly much better in upside down position. 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, providing that fuselage is reasonably high. Unfortunately lack of time and resources did not allow exploring this concept those days.

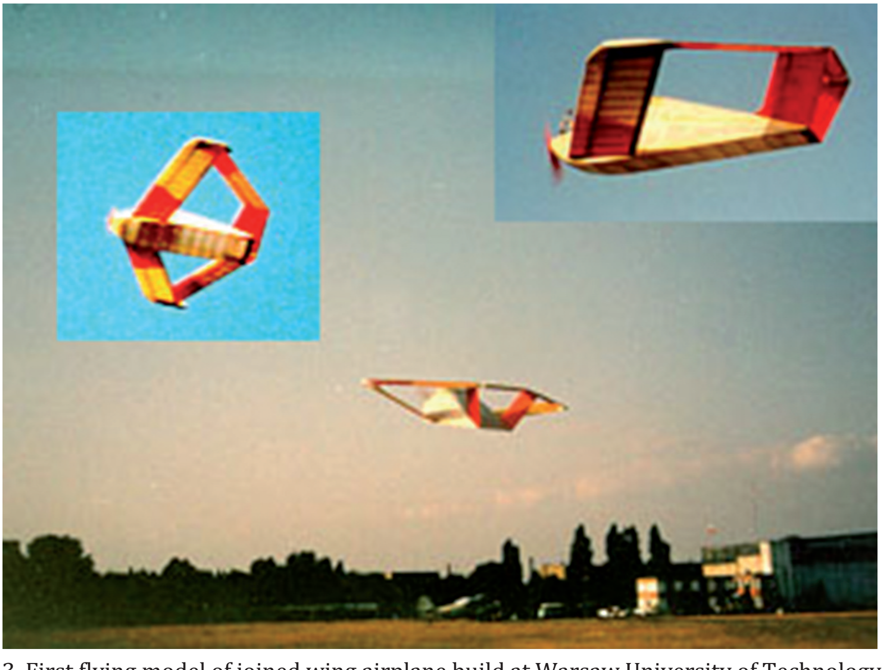

Fig. 3. First flying model of joined wing airplane build at Warsaw University of Technology [C. Galiński, 1991]

Topic was recently refreshed. Series of simple CFD analyses was carried out to check if previous conclusions were correct [18]. Summing up, current results confirm, that joined wing airplane L/D grows together with increasing gap between wings. 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 should be reduced in this case due to the increased loads of vertical stabilizer. As can be seen from this result, final answer depends not only on aerodynamic consideration but on multicriterial optimisation. It should take into account at least aerodynamic performance, strength and weight analyses as well as stability and control analyses since any airplane has to be controllable and stable (aerodynamically or artificially). All these analyses should be conducted together so that result is acceptable from all points of view.

THE CONCEPT OF THE PROJECT AND THE VEHICLES

The Institute of Aviation [19, 20] is leading the consortium, consisting of Warsaw University of Technology, Air Force Institute of Technology and small company MSP, conducting the project dedicated to investigate the above observations.

This project will create foundation for the future manned airplane project. It is supposed to deliver two types of results: database of experiences necessary to run the following project safely and software allowing for multicriterial optimisation. Therefore this project consists of two separate parts: software development and UAV investigation.

As a result of the first part optimisation package will be created. Optimisation performed with this software will combine aerodynamic performance, stability and control together with weight and strength optimisation. At the end aeroelasticity of resulting system will be also verified. The task is very ambitious, so it is supposed to last from the beginning to the end of the project. As a result final version of the software cannot be used in the second part of the project.

Second part of the project assumes extensive analyses and experiments on the UAV designed in joined wing configuration. UAV configuration will be only aerodynamically optimised since multidisciplinary optimisation software will be available only at the end of the project. Therefore it is supposed only to be safe enough to conduct significant number of flight tests to gather valuable data. First attempt to external geometry of the airplane was done in preliminary works, which allowed creating 3D computer model for aerodynamic analysis that began immediately after the start of the project. Moreover, simplified flying model was built to support these analyses, in particular in the area of control surfaces effectiveness. The model is built in 0.12 scale in respect to the manned aeroplane for four persons. This model has 11 different control surfaces. Various combinations of their deflections were tested in flight to find the most advantageous one. This combination will be then used in CFD analyses to save time of computations. The size of wing tip plates was also tested. This allowed creating first estimate of vertical surfaces areas and arrangements, which again saved a lot of computing time. First flights of this model confirmed correct and easy handling qualities and stability of the airplane. However, due to the very low Reynolds numbers achieved in flight, results cannot be perceived as final.

Close co-operation between flight test and computation teams gave first save geometry of the airplane within first four months of the project. This geometry is only aerodynamically optimised with software described in [38, 39], but it is good enough to start the design of the final UAV. Again close cooperation between CFD team and design/manufacturing team will be necessary to introduce minor changes in the airplane geometry later on in the project. It is assumed that CFD analyses will be carried out over about two years with descending intensity.

The UAV will be built in scale 0.3 in respect to the manned aeroplane for four persons. It was selected because the same set of tooling will be used to build wind tunnel model and UAV. Therefore it should fit to the wind tunnel, which has measurement area with diameter of 5 m.

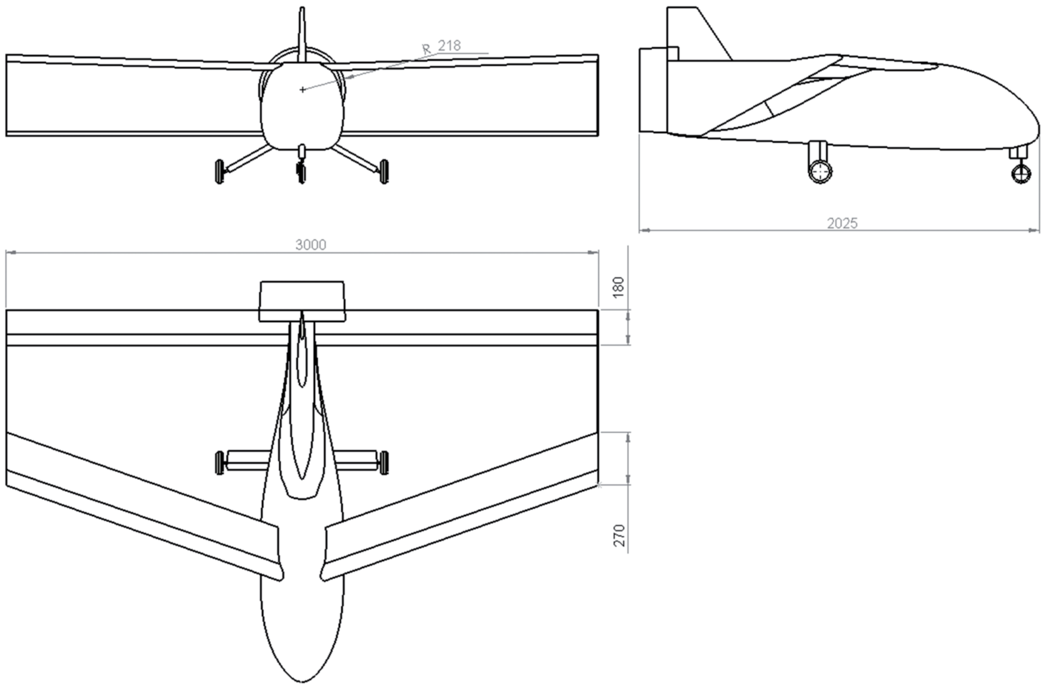

Fig. 4. Initial geometry of the UAV in scale 0.3
[C. Galiński, 2012]

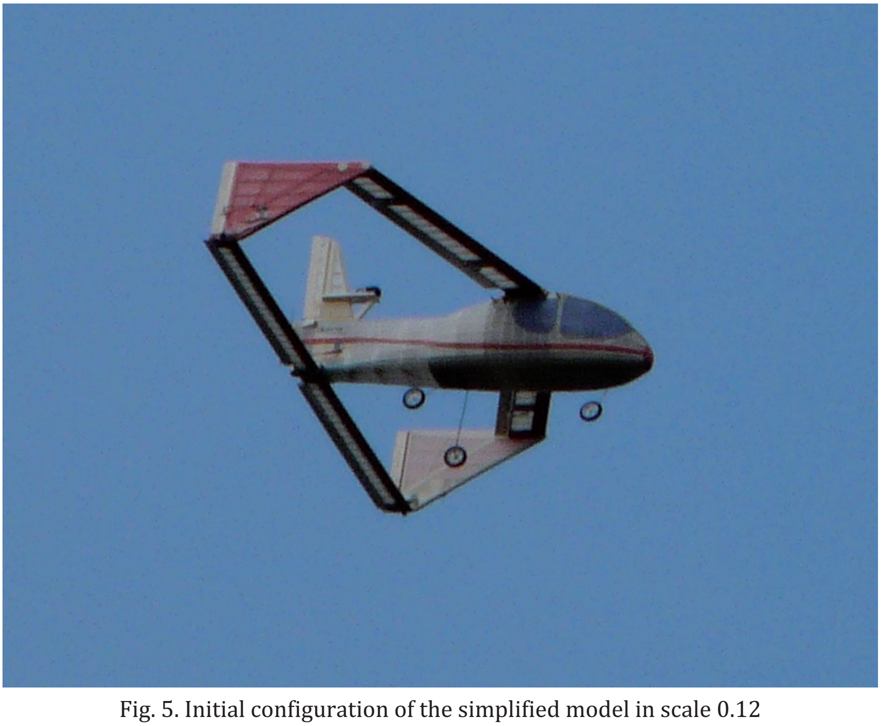

Fig. 5. Initial configuration of the simplified model in scale 0.12
[C. Galiński, 2013]

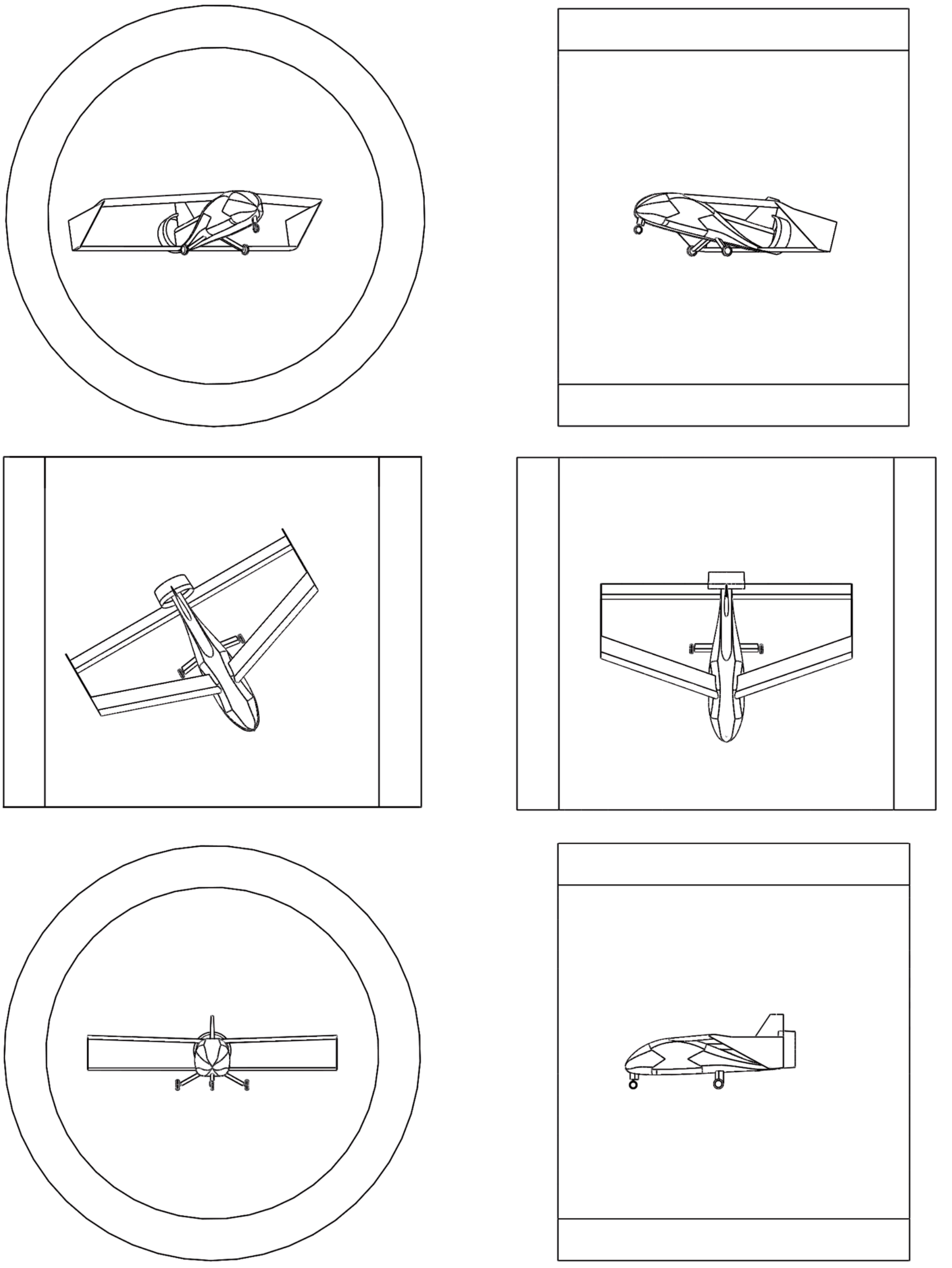

Fig. 6. Comparison of the model in scale 0.3 with the wind tunnel measurement area [C. Galiński, 2012]

Assuming that full-scale airplane is comparable to Cessna 152, the model in scale 0.3 should have the weight of 20.5 kg, which is quite significant for a flying model. Electrical propulsion would be desirable because the same propulsion system could be used both for wind tunnel tests and flight tests, however neither piston nor turbine motors are excluded for UAV. According to previous experiences climb rate of 3 m/s is necessary to perform save flight of the research model. In the case of internal combustion engines this is an initial climb rate immediately after takeoff, because climb rate rises over the flight time due to the fuel consumption and resulting weight reduction. Therefore the final climb rate is usually greater then initial allowing for safe abort landings. Electrical airplane has a constant weight over the whole flight, but batteries voltage is falling (more then 10%), therefore the power available for flight is also falling (more then 20%). As a result climb rate of 3 m/s should be available just before touch down (with almost fully discharged main battery) in the case if abort landing is necessary. It is assumed that initial climb rate of 6 m/s will allow both for reasonable fight duration and final climb rate of 3 m/s. However, this means that electrical propulsion has to be more powerful thus would be heavier than internal combusting system. Another reason for greater weight of electrical systems is lower density of energy stored in batteries than in liquid fuel. Altogether electrical propulsion system usually is twice heavier than internal combusting system. On the other hand it is much easier to control, generates less vibration and allows for convenient weight distribution. Moreover it is cleaner, that is particularly important in the wind tunnel. Therefore final decision will be taken when the precise weight of the model structure is known.

Propulsion system is pushing to provide both airplane balance and correct visibility from future pilot's seat. It is also equipped with a ducted propeller to avoid collisions between the propeller and runaway during takeoffs and landings. It should be also safer in the case of emergency egress than conventional propeller and should allow for noise reduction. However ducted propellers are known to suck debris from the runway easily. Therefore model applied in this project has duct located behind and above the rear wing, which should protect the propeller. As a result aerodynamics of the propulsion system will be extremely complicated. First iteration of the duct and propeller was created at the very beginning of the project to allow for global aerodynamic analysis, however detailed design will be carried out much longer, therefore propulsion system will be designed as exchangeable both in wind tunnel and in flying model. This will also create an opportunity to conduct several experiments with ducted propellers.

PRELIMINARY FLIGHT TEST FESULTS

Flight test campaign of the model in scale 0.12 was undertaken to check basic airworthiness of the aerodynamic configuration. The model appeared stable and controllable which allowed for the following experiments. First of them concerned lateral-directional dynamic stability. Large wing tip plates visible in Fig. 5 were gradually reduced to the shape of parallelogram with chord equal to the chord of main wing. Neither stability nor controllability were affected significantly in the course of this experiment. This leads to the conclusion that wing tip plates and rudders installed on them were not very effective as stabilizers and control surfaces. Second experiment concerned the effect of a propeller duct on the stability and balance of the model. Therefore simplified duct was installed around the propeller. It appeared very effective as a stabilizer so center of gravity was moved backwards. Moreover the area of the central vertical stabilizer was reduced. Stability appeared correct after these modifications but directional controllability was lost. Therefore the shape of the vertical stabilizer was modified allowing to install tubular rudder which appeared very effective. Effect of the duct on propulsion efficiency was not investigated since the duct was not optimized. The last experiment concerned application of elevator. In all previous experiments control surfaces on aft wing were used to perform this function. Now application of all control surfaces on the front wing were used as the elevators or elevons. Longitudinal control appeared better than previously, but lateral control by front-external elevons was not always correct. In deep turns model exhibited tendency for spiral instability. Therefore final configuration dedicated internal control surfaces on the front wing for elevator and external control surfaces on the front wing for ailerons. As a result control surfaces on aft wing were not used at all. They may be used as flaps or trimmers in the UAV in scale 0.3.

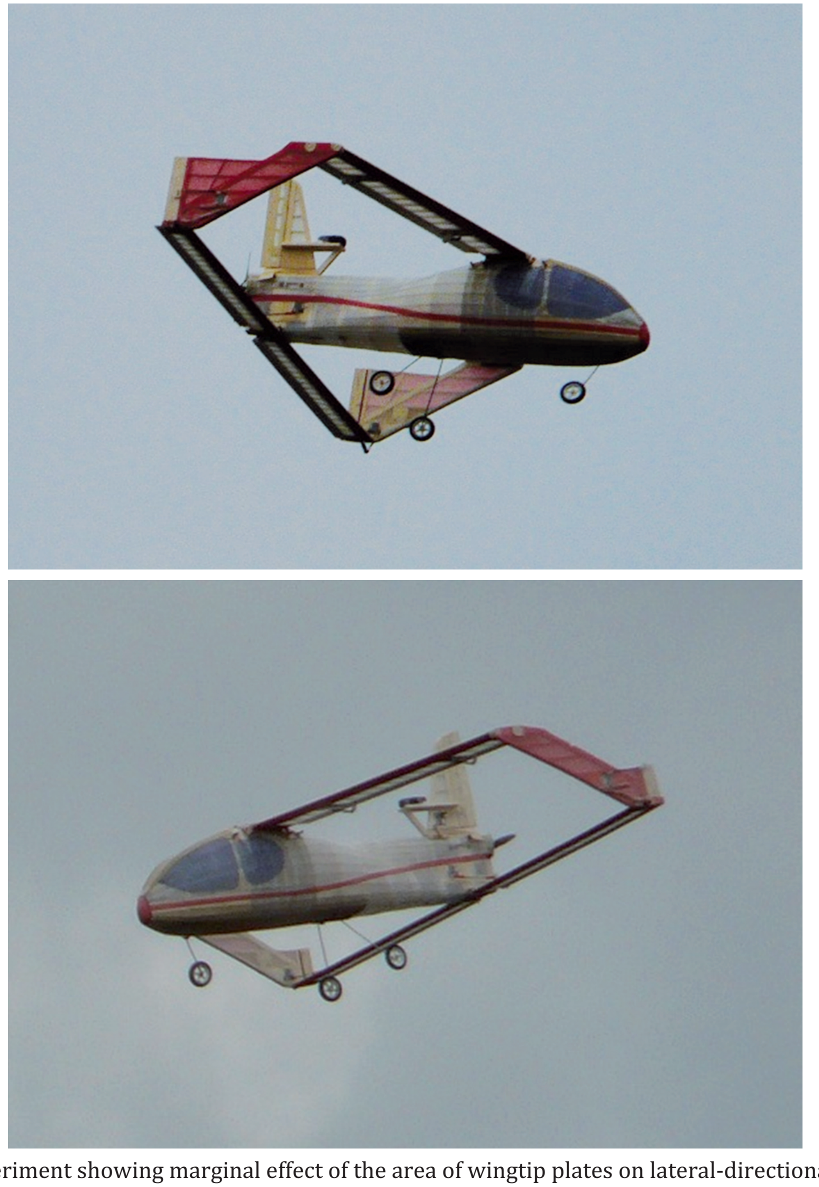

Fig. 7. Experiment showing marginal effect of the area of wingtip plates on lateral-directional stability [C. Galiński, 2013]

Fig. 8. Experiment showing the effect of the propeller duct on the model stability
[C. Galiński, 2013]

Fig. 9. Final configuration of the model in scale 0.12, equipped with tubular rudder
[C. Galiński, 2013]

UAV FLIGHT TEST CONCEPT AND EQUIPMENT

Flight test campaign of the model in scale 0.3 should allow estimating both handling qualities and performance of the future manned join wing airplane [40-46]. Therefore flight test programme will be quite extensive. It consists of the following types of experiments:

- Airplane stability validation,
- Airplane controllability validation,
- Definition of the trimmed flight range along all three axes (longitudinal, lateral and directional) for the whole airspeed range,
- Measurement of gliding velocity polar,
- Measurement of performance in powered flight,
- Assessment of the effect of propulsion on stability and controllability,
- Comparison with airplane in conventional configuration.

Trimmed flight experiments will include exploration of the concept of lift control with multiple control surfaces. Assumed configuration of the model allows for installing 4 control surfaces in front wing and 4 control surfaces in rear wing. This should allow for efficient performance optimization in wide range of airspeeds, weights and weight distributions.

It is assumed that each flight will last at least 15 minutes, so the whole campaign will consist of approximately 40 flights. Further assuming that 3-5 flights can be done in the course of one flight test session, 8-12 sessions are needed to perform all necessary flights. Flights will be performed at altitudes between 0-1000 m, in the circle with radius of 1500 m from the takeoff point. The following parameters will be measured:

- Static pressure,
- Total pressure,
- Control surfaces deflections,
- Propeller RPMs,
- Current,
- Batteries voltage,

- Batteries temperatures,
- Motor temperature,
- GPS time,
- GPS geographic position,
- GPS precision coefficients,
- Number of satellites,
- GPS velocity,
- GPS altitude,
- Climb rate,
- Heading,
- Angular velocities P, Q and R,
- Linear accelerations Ax, Ay and Az,
- Orientation angles.

All these parameters will be measured, stored and transmitted with application of the following instruments:

- AHRS Crossbow AHRS500GA221,
- Magnetometer Crossbow CRM500GA-200,
- GPS receiver Garmin 18x 5Hz,
- Radio modem Satel 3AS,
- Flight computer (autopilot with data recorder) ITWL AP-1,
- Aerometric sensor system HARCO Mini ADC,
- TV transmission system.

FINAL CONSIDERATIONS

Data collected in the course of numerical analyses, wind tunnel tests and flight tests will be taken together and analyzed to create join wing database. Optimization software developed within first part of the whole programme will be then used to assess how much airplane performance can be improved. This will lead to the conclusion if application of the joined wing concept is advantageous. Finally decision will be taken if the following project of manned airplane should be conducted.

CONCLUSION

The research project was undertaken to develop the knowledge concerning joined wing airplane configuration. Novel concept of this configuration with front wing at the top of the fuselage is explored. The project consists of the numerical analyses, wind tunnel tests and flight tests of the flying models. Also multidisciplinary optimization software will be developed. Multidisciplinary optimization is envisaged to consider aerodynamic performance, stability, loads, strength and aero-elastic issues. However due to the complexity it will be available only at the end of the project. Therefore flying models are to be only aerodynamically optimized. As a result continuation of this project is envisaged to fully utilize its results.

Flight testing is performed in two stages. Small flying model was tested first to decrease the risk of the project and to explore basic flight characteristics. Greater UAV will be used for wind tunnel testing and detailed flight measurements. This will allow for direct comparability of CFD, wind tunnel and flight test results. The size of the UAV was defined by the size of available wind tunnel. Electrical propulsion system is preferred also because of wind tunnel investigation. On the other hand internal combustion system can be applied later on to reduce UAV weight and to provide safe climb rate in the case of abort landings. All flights will be performed with direct UAV visibility. At least 40 measurement flights are predicted. Each should last at least 15 minutes.

It is believed that collected data will allow designing and building manned experimental airplane in this configuration leading to the commercial product.

ACKNOWLEDGMENTS

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ZAŁOŻENIA DO PROJEKTU MODELU LATAJĄCEGO W UKŁADZIE POŁĄCZONYCH SKRZYDEŁ

Streszczenie

Joined wing to perspektywiczna konfiguracja samolotu. Jej zastosowanie powinno pozwolić na redukcję zarówno masy własnej samolotu, jak i jego oporu. Dzięki temu oczekuje się zmniejszenia zużycia paliwa, a co za tym idzie obniżenia kosztów eksploatacji i zmniejszenia emisji gazów cieplarnianych. Jednakże stosowanie tej konfiguracji jest utrudnione ze względu na sprzężenia aerodynamiczne i statyczną niewyznaczalność konstrukcji. Ten artykuł przedstawia projekt podjęty w celu poszerzenia wiedzy na temat tej konfiguracji samolotu. W szczególności badana będzie jego nowa wersja, z przednim skrzydłem w układzie górnopłata. Artykuł opisuje założenia projektu, kolejne kroki jego realizacji oraz spodziewane efekty.

Słowa kluczowe: skrzydło zespolone, CFD, symulacja, testy w tunelu aerodynamicznym, próby w locie, model dynamicznie podobny, demonstrator.