MINI UAV DESIGN AND OPTIMIZATION FOR LONG ENDURANCE MISSION

Zdobyslaw Goraj*, Jerzy Cisowski, Andrzej Frydrychewicz**, Wojciech Grendysa**, Marek Jonas****
***WUT-IAAM, **WUT-"Centre of Excellence of Aircraft Design"**

Keywords: *UAS, aircraft design, stability, composite technology*

Abstract

This paper is focused on design and optimisation of a mini UAV. Project in its current version - known as SAMONIT - is a national Polish project in an early design stage and financially supported by Ministry of Science and Higher Education. The main goal of the activity within this project is to design an UAV system for long endurance border surveillance and monitoring having high level requirements in term of reliability and safety and being affordable for potential users in terms of cost. The design process is treated as an interdisciplinary approach, and includes a selection of thick laminar wing, aerodynamic optimisation of swept wing, stability analysis, weight balance, structural and flutter analysis, many on-board redundant systems, reliability and maintainability analysis, safety improvement, cost and performance optimisation. This paper focuses mainly on platform design, selection of its external layout and control devices. A baseline configuration (straight wing with V-tailplane placed behind the main wing) will be used as a reference for more advanced layouts, especially swept tailless configuration, considered as the target configuration. Comparisons between both configurations will be used to show expected advantages and possible drawbacks. Full scale free flight airplane testing will be preceded by a scaled (1:2) dynamic and geometry similar model airplane (now in the flight test experiments).

1 Introduction

The main goal of the activity within this project is to design an UAV system for long endurance border surveillance and monitoring [1], having high level requirements in term of reliability and safety (expected by other users of national airspace and people on ground) and being affordable for potential users in terms of cost. One such system (2 airplanes + sensors + Ground Control Station) should not cost more than 200 000 euros [2]. The design process is treated with an interdisciplinary approach, and includes a selection of a thick laminar wing [3], aerodynamic optimisation of swept wing, stability analysis, weight balance, structural and flutter analysis, many on-board integrated redundant systems, reliability and maintainability analysis, safety improvement, cost and performance optimisation. Assumed endurance is 24 hours, the main aircraft parts and systems weight is as follows: composite structure - 15 kg, power unit - 6 kg, communication + navigation + flight control systems – 6 kg, emergency parachute – 2 kg, payload –14 kg, fuel for 24 hours flight – 24 kg. The target airplane will have either single-element wing section (for example Wortmann's wing section FX66-17AII-182/20) or two-element airfoil (for example SA-21, [3]). Wing area is equal to 1.4 m^2, wing aspect ratio is 11.4. Stall speed at SLF is 24 m/s, typical landing speed is 20 m/s. Typical lift coefficient during patrol is equal to 0.46, aerodynamic efficiency is 15, power coefficient (required power over the available power) during typical patrol is equal to 0.44. The airplane is powered by two KOMATSU gasoline engines, model G800BPU, 8 bhp each, air cooled two stroke cycle opposed cylinder type. Full scale free flight airplane testing will be preceded by a scaled (1:2) dynamic and geometry similar model airplane (now in the flight test experiments). This scaled model will be powered by electrical engines. A research of a mutual in-flight interference is also planned, and will correspond to the case when a smaller (scaled) airplane enters into the wake shed behind the full scale airplane. This paper is focused mainly on the design aspects, a selection and refinement of its external layout – choice between straight wing with V_tail configuration and tailless, swept wing configuration and is based on the author's experience gained during former, UAS related design activity, [5-12]. Design details, technology of manufacturing processes encompassing both negative moulds and positive aircraft components, and progress in production of prototype is shown and discussed.

2 Design layout

Tailless, swept wing configuration for a long endurance surveillance mission was adopted, mainly due to its aerodynamic characteristics and utility properties [13-15]. Such a layout has improved aerodynamic efficiency due to a lower wetted area, also possessing less parts that could be exposed to damage, especially during a difficult landing. Self-stable, 15% wing section was intentionally designed [16] to increase negative pitching moment by inclination of trailing edge up.

Chord of the wing is constant along the span. Wing tip is twisted down with respect to the wing central part on -3^{o} to move the stall from elevon area into the wing central part. The so-called end plates are mounted at the wing tips and they play the role of vertical stabilizers. These plates have rudders, deflected outside of the wing only (the reason that rudders are not deflected inside the wing is to avoid the interference between rudders and elevons).

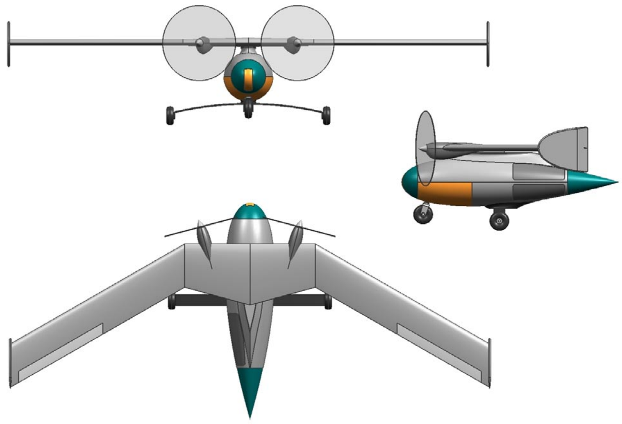

Fig.1 Swept wing tailless configuration – version with wing tip plates [13-15]

Fuselage plays the role of container, and holds different on-board systems – navigation, communication, surveillance and fuel. It was assumed that initially FLIR system will be used. In second stage of aircraft development also a SAR system can be hosted into the fuselage, so the fuselage (container) dimensions are dictated by one of such systems available on the marked (SANDIA mini SAR,[17]).

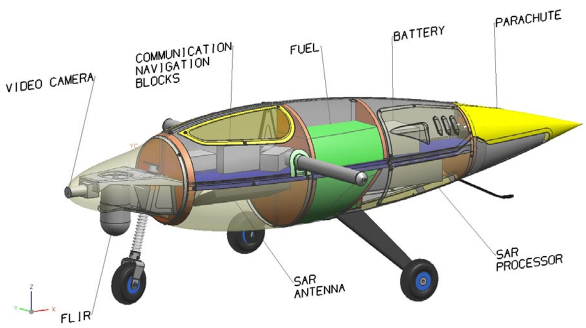

Fig.2 Fuselage - container for sensors, electronics and fuel tank

On-board SAR system [17] is optional – either can be selected and mounted, or not, and therefore its centre of gravity (CG) is located in order not to influence the whole aircraft's CG location. A SAR antenna is relatively large and it is the reason why the fuselage cross-section is also large. Fuselage overall shape was designed and optimised to minimise its drag coefficient. It was found that a streamline (droplet) shape will fulfil this requirement well. The large fuselage cross-section, in a natural way, offers a possibility to design a high capacity fuel tank, which can be located ideally at the aircraft centre of gravity (CG). The rear part of the fuselage is used as a container for a recovery parachute. Such a recovery system offers the possibility to land in a difficult environment (where vertical falling is unavoidable), and also increases the safety factor in standard operation, when in an emergency. This two-stage parachute system consists of smaller breaking parachute (a piloting chute) and bigger recovery parachute (to be opened after a deceleration phase). This COTS system is routinely used in para-gliding and produced in Poland by AirPol-Legionowo ltd.

Tailless configuration offers many advantages over the orthodox configuration, however it is still aerodynamically difficult and can reveal some unexpected phenomena (trim issues, stability etc.). It is the reason why it has been decided to develop a second configuration with a straight wing and V-tail control surface placed behind of the main wing, called further baseline configuration. It was assumed that both configurations (tailless and baseline) are unified as much as possibly (they have the same wing aspect ratio, wing loading, power-to-weight ratio, on-board systems, fuselage etc.). The wing section of the baseline configuration, the Wortmann profile (FX66-17A-II-182/20), was selected because in this case, the pitching moment can be controlled by elevator's deflection and there is no need to modify the pitching moment through the change of profile camber in the TE region. The baseline configuration will be used as a reference for different comparisons between both configurations and for evaluation of expected advantages and possible drawbacks. Attachment of the wing on a pylon above the fuselage will facilitate an easily change of this wing (from swept to straight and vice versa) using the same fuselage, landing gear system etc.

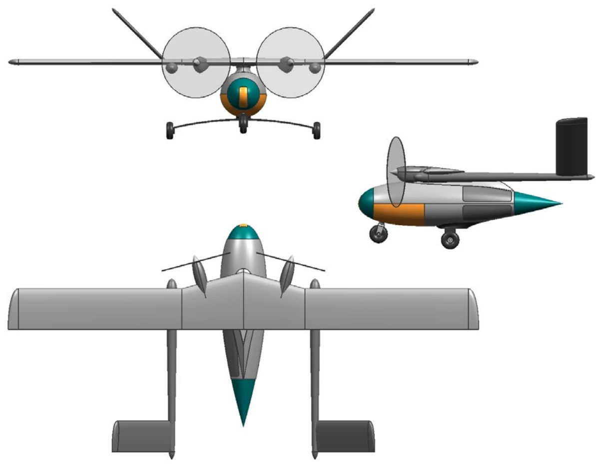

Fig.3 Baseline configuration – starting point, [2,13-15]

Additionally, to reduce the unavoidable risk connected with first flights of unconventional configuration (tailless one), it was decided to design, manufacture and test in flight a scaled (1:2) tailless configuration model. These flight tests have shown that the configuration initially proposed for the tailless layout must be changed. It appeared that during the take-off run a normal reaction force acting on the front landing gear was too high, mainly due to nose-down pitching moment generated by highly located engines. Elevons were not able to produce the counterbalancing, nose-up pitching moment and the accelerating model turned over on the runway. After the necessary redesign process the new layout of tailless configuration are shown at Fig.4-6 and baseline configuration at Fig.7.

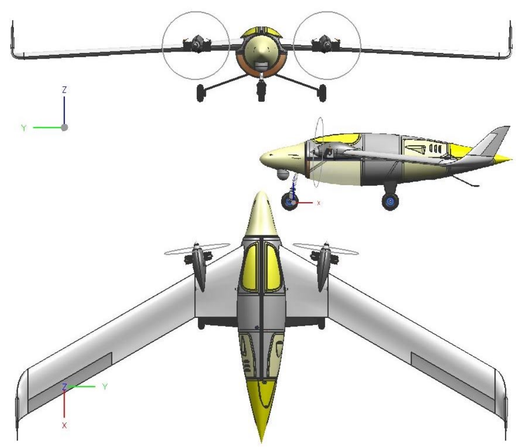

Fig. 4 Swept wing tailless configuration – current version with the wing moved down and wing tips optimised for lateral dynamic stability

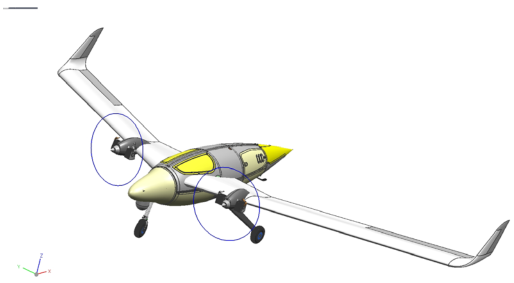

Fig. 5 Swept wing tailless configuration – top-left view

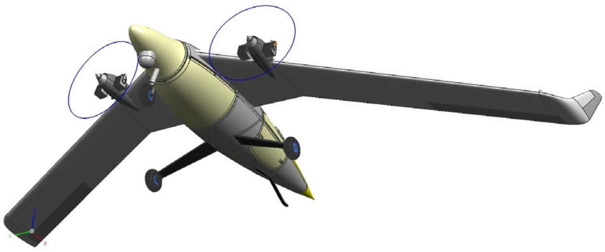

Fig. 6 Swept wing tailless configuration – down-left view

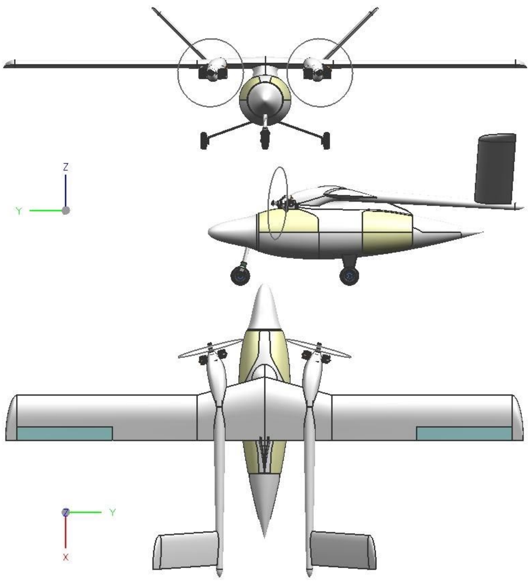

Fig.7 Baseline configuration – redesign to be unified with last, modified version of the swept wing configuration

3 Selection of power unit

The two-engined configuration was selected to increase the safety level (according to statistics gathered in IAI, one of the most frequent critical failures of UAVs was engine dysfunction [4] and redundancy can increase the so-called MTBL (Mean Time Between Losses). Engines are placed along the wing's centreplane, close to the aircraft's vertical plane of symmetry. Moreover, they are skewed at 6^{o} outward with respect to vertical plane of symmetry to decrease yawing engine torque when one engine is not working. In order to decrease the level of vibration (important for stable usage of sensors) the two cylinder engines (KOMATSU) were selected. Another desired feature of these engines, especially required for long endurance mission, is their high mean life. The design philosophy and production technology of the main components of this type of engines, are based on experience gained from the family of engines produced for pumps widely applied in civil engineering. Therefore they are likely to able to work for several dozens of hours with no failure. With respect to earlier requirements of power access, the available power was increased to 8 hbp and therefore it will make it possible to increase MTOW in the future, if necessary. A further reduction of vibration transferred from engine into the aircraft structure is possible through the flexible friction dampers of an engine suspension system. The special dumpers developed by KOMATSU were also used for noise reduction. The engine spark device (originally supplied with the engine by KOMATSU) together with an additionally designed and manufactured coil was used as a current generator.

4 Components of aircraft structure

The structure is designed from carbon fibre. The main parts of fuselage consists of horizontal and vertical plates, attached to a set of frames and with a few easily disassembled covers. Plates are designed for a sandwich construction. The wing spar in the fuselage area is made from a steel, with a circular cross-section (ϕ 50 * 48), being hardened for high strength. The integral fuel tank, in the fuselage central part, has 49 litres capacity.

Wing (and tailplane) are built from the same materials as the fuselage. Straight wing consists of a central part and two outer wings. Two tailbeams are attached to the wing central part and ended with V-tails. Central part of the wing is attached to the fuselage through a pylon and therefore aerodynamic interference is reduced. Wing has a single spar only, Fig.9-11.

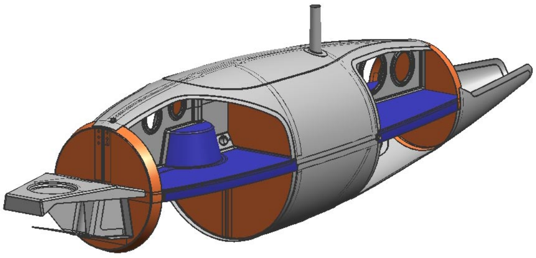

Fig.8 Design structure of sensor container - lower and upper covers disassembled for inspection

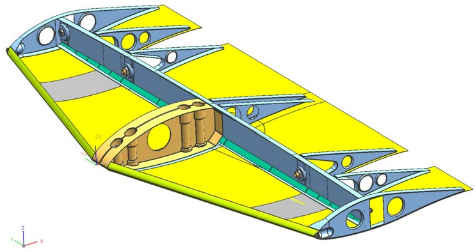

Fig.9 Design details of the straight wing central part

Swept wing is divided into left and right parts, Fig.10. Both parts are slid over the pipe spar standing out from the fuselage. Fast joining can be performed screwing down two screws, one per each wing, Fig.10-11.

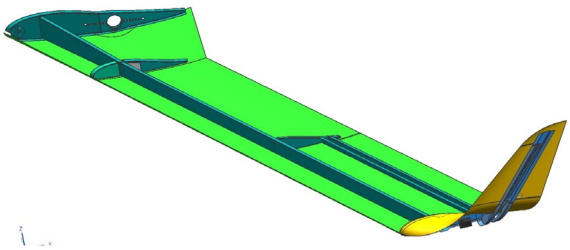

Fig.10 Design details of the swept wing

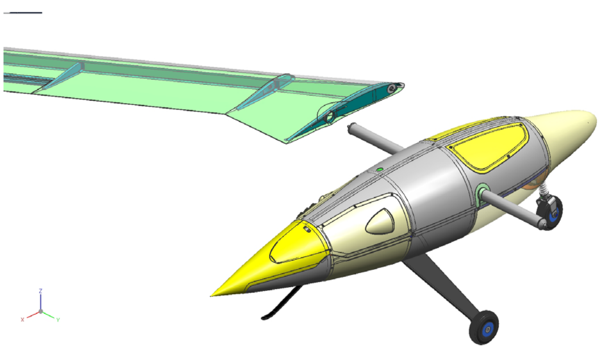

Fig.11 Method of join between swept wing and fuselage

The aircraft with straight wing has the V-tails, mounted on tailbeams. The method of attachment between tailbeams and the wing central parts, and between tailbeams and the engine's mount, is shown at Fig.12.

Main landing gear was designed as a composite spring beam, Fig.13, and the front landing gear is of telescopic type, external spiral spring and internal pneumatic damper.

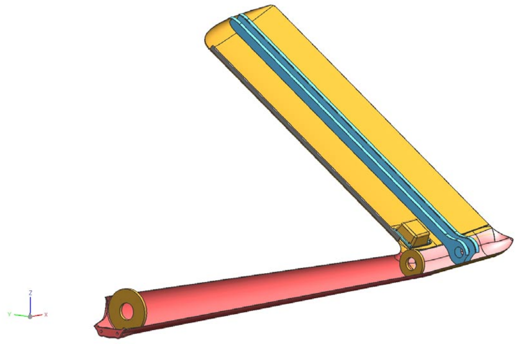

Fig.12 Baseline configuration - design details of right V-tail

Fig.13 Main landing gear

5 Parachute recovery system

This system is important to decrease the probability of a ground collision – the case in which either innocent people could be injured or/and infrastructure could be damaged. The system is based on the well-known parachute produced by AirPol ltd (KSKY-36,7), widely used by para-gliding pilots (standard load equal to 70 kg), fully ertified. To avoid damage to the aircraft's structure due to a rapid deceleration, the opening of main parachute is preceded by opening of a breaking, much smaller parachute (area of 1 m^2), which is shown at Fig. 14.

Fig.14 Successive phases of parachute deployment

6 Trim and stability analysis

Stability analysis was preceded by finding the trim conditions, computed by use of STB software, solving nonlinear equations of equilibrium. Nonlinearity usually comes from nonlinear aerodynamic characteristics, nonlinear coupling between forces acting on main wing and flaps, rudders (for example alpha influences on normal force via CL and also on drag force via CL^2), thrust inclination factor and many other reasons. Available maximum power and power required for steady level flight (in bhp) are presented in Fig.15. Selected results of computation in trim are shown in Fig.16 (as a flight speed function) and in Fig.22 (as a function of centre of gravity position, X_{CG}).

Initial results of stability analysis showed that spiral mode is rapidly convergent and unacceptable if compared to requirements of flying qualities. A kind of optimisation was performed to elongate the time to double T_2 of spiral mode. It was done mainly by optimisation of the area of vertical stabilizers. Also, phugoid mode is partly unstable at low speeds, however its time to double is long enough to be acceptable. Some modes are also very sensitive to the travel of the centre gravity, especially the short period (Fig.23), phugoid (Fig.25) and spiral (Fig.26). Fig.17-26 present details of stability analysis and show that after necessary modification the wing swept configuration fully fulfils stability requirements and that the stability correction to be done by Automatic Flight Control System (AFCS) in terms of dynamic stability will be marginal.

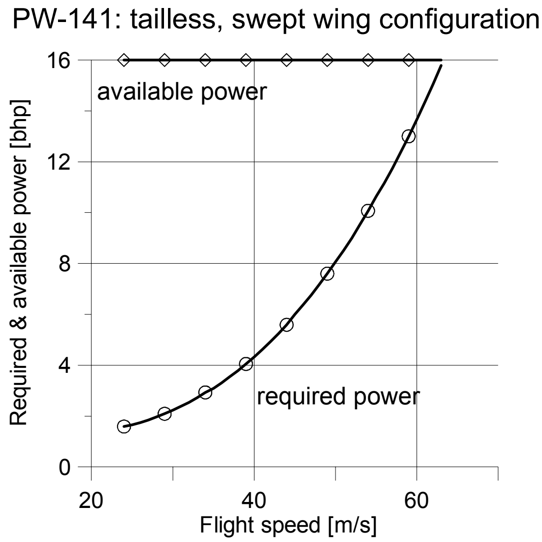

Fig.15 Required and available power versus flight speed

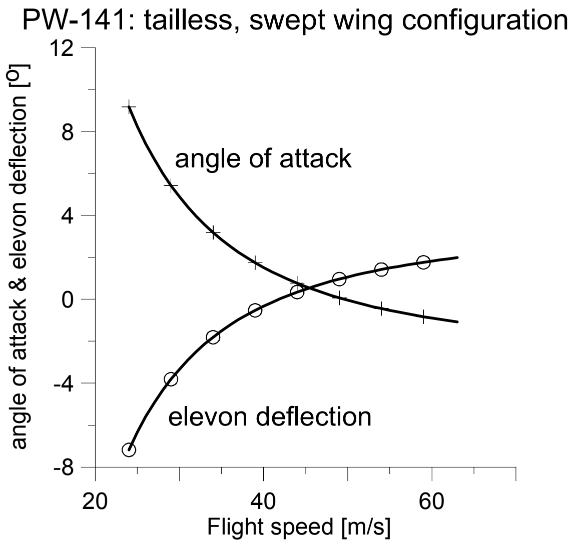

Fig. 16 Angle of attack and elevon deflection as a function of flight speed in trim. X_{CG}=15%

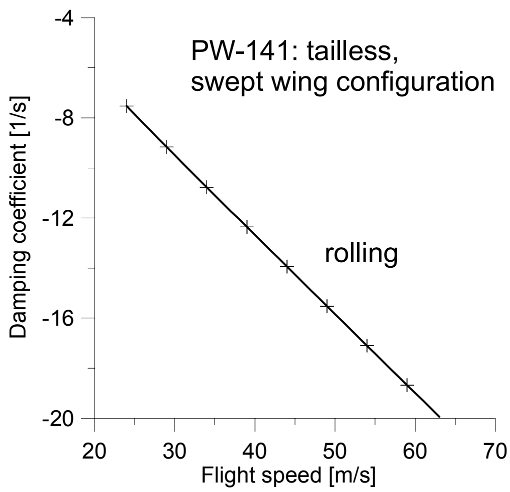

Fig. 17 Damping coefficient of rolling mode as a function of flight speed in trim. X_{CG}=15%

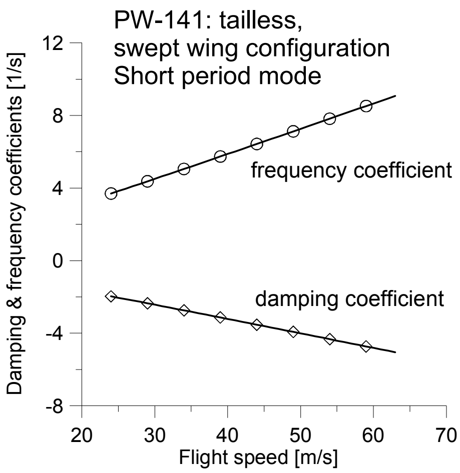

Fig. 18 Damping and frequency coefficients of short period mode as a function of flight speed in trim. X_{CG}=15%

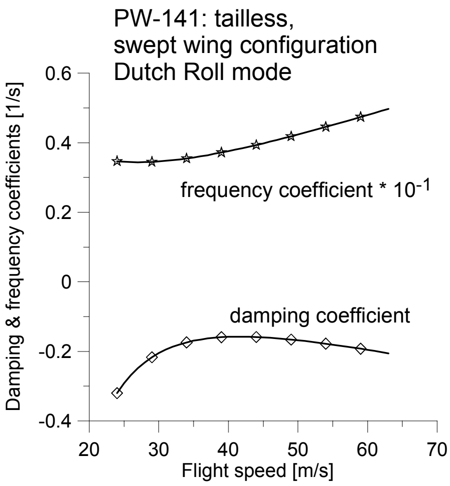

Fig. 19 Damping and frequency coefficients of Dutch Roll mode as a function of flight speed in trim. X_{CG}=15%

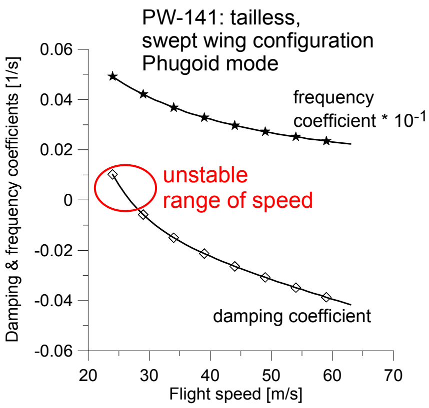

Fig. 20 Damping and frequency coefficients of Phugoid mode as a function of flight speed in trim. X_{CG}=15%

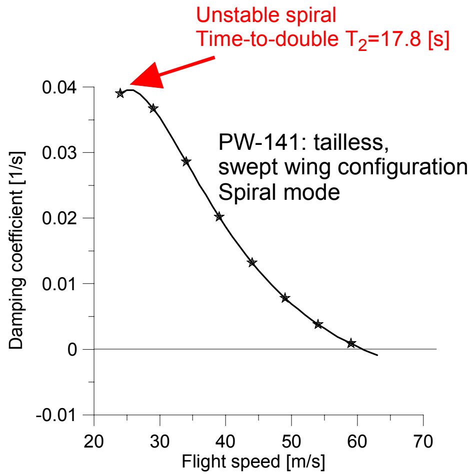

Fig. 21 Damping coefficient of Spiral mode as a function of flight speed in trim. X_{CG}=15%

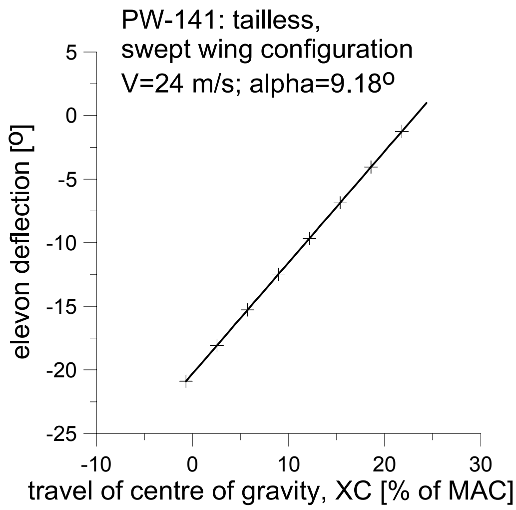

Fig. 22 Elevon deflection as a function of centre of gravity position, X_{CG}

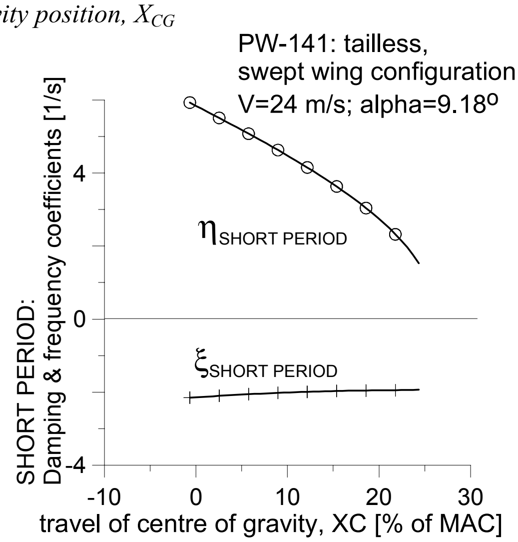

Fig. 23 Damping and frequency coefficients of short period mode as a function of centre of gravity position, X_{CG}

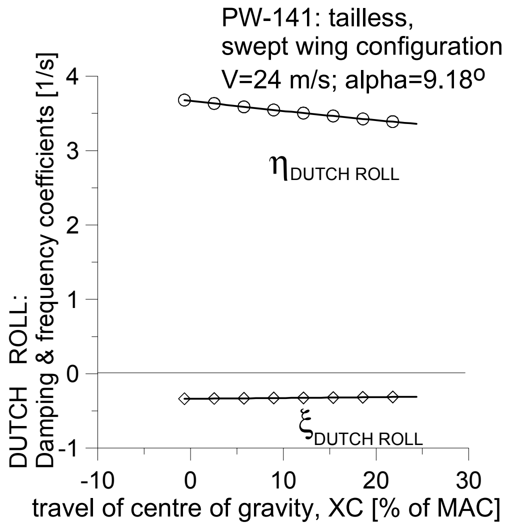

Fig. 24 Damping and frequency coefficients of Dutch Roll mode as a function of centre of gravity position, X_{CG}

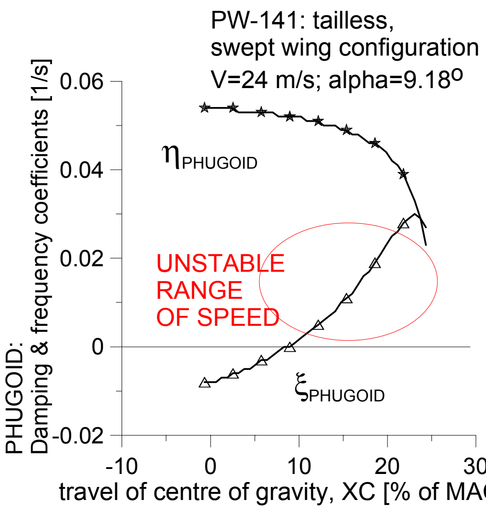

Fig. 25 Damping and frequency coefficients of Phugoid mode as a function of centre of gravity position, X_{CG}

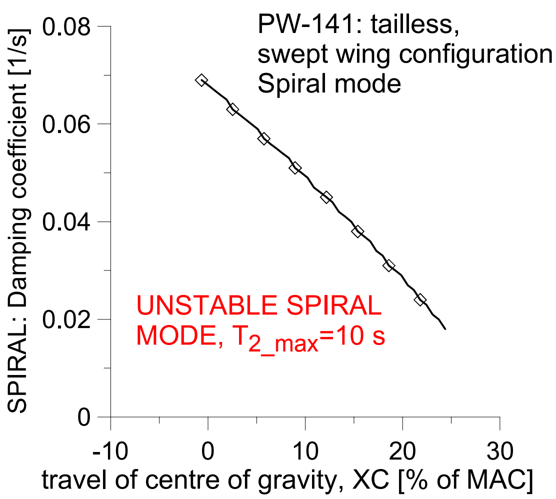

Fig. 26 Damping coefficients of Spiral mode as a function of centre of gravity position, X_{CG}

7 Summary of design features

- Tailless layout is the target configuration. Baseline layout is used for comparison and evaluation only;
- Aircraft design is easy for transportation on the trolley behind a passenger car and easy for quick assembling / disassembling;
- Tailless configuration with selfstable wing section and geometry offering wide range of angles of attack is resistant to stall;
- Two engines of high reliability offer increased MTBF level with high power access;
- Parachute recovery system increases safety level for people and property on the ground;
- Main landing gear made from carbon fibre, endowed with efficient breaking system, ensures short, well dampened landing. Front landing gear consisting of telescopic type external spiral spring and internal pneumatic damper, ensures good damping characteristics and protects against potential turnover on the runway;
- Wing tip plates used on tailless configuration increase wing aspect ratio, provide lateral stability and good controllability in sideslip;
- Centre of gravity (CG) does not travel with respect to aircraft during flight mission.
- The swept wing configuration was modified to fulfil stability requirements. Corrections to be done by the Automatic Flight Control System (AFCS) in terms of dynamic stability will be marginal.

8 Technology

Moulds: Aircraft structure is done of carbon-epoxy composite using the wet lay up technique, and the LPC process (Low Pressure Curing). External shells of wing, tail-beams and most of ribs were laminated in negative moulds, being prepared using CNC (Computer Numerical Control) machine. Moulds were done of PROLAB-65, Fig.27. Smaller moulds were milled at one PROLAB-65 plate, Fig.28. Moulds of the container were prepared in two phases: in the first phase a number of PROLAB-65 plates were CNC-machined and then joined to obtain a positive model of the container, next in the second phase a negative mould for container was manufactured using the wet lay up technique. The material chosen for the moulds, i.e. PROLAB-65 is a non-porous material of very good dimensional stability, easy for milling and has a very good surface quality (smoothness) after finishing the milled surfaces. Its density is equal to 0,65 g/cm^3, hardness equal to 63 Shore D (according ISO-868-85).

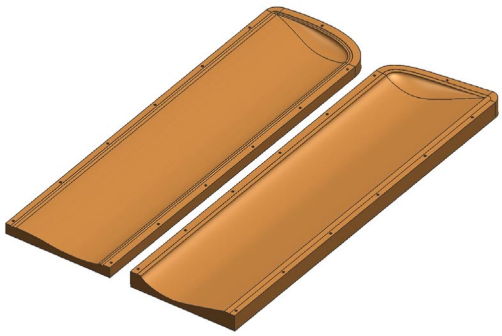

Fig. 27 Negative moulds of the straight wing shell

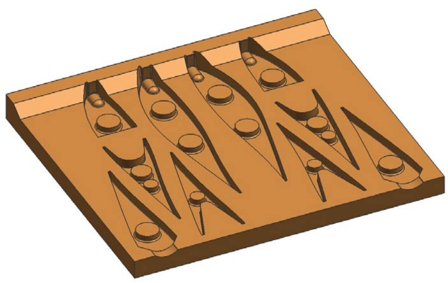

Fig. 28 Negative moulds of internal parts of the wing (ribs)

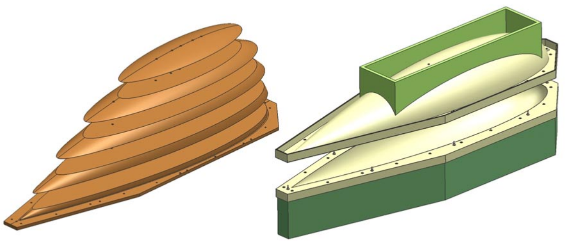

Fig. 29 "Positive" model (left) and negative mould of fuselage (right)

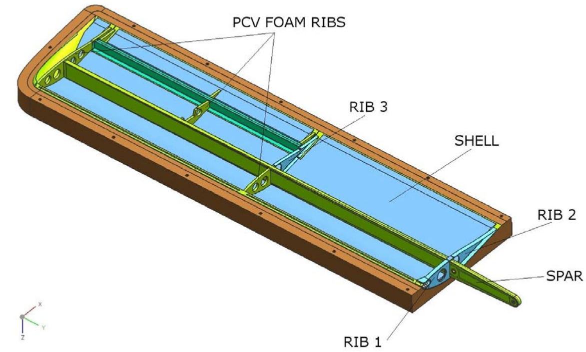

Fig. 30 Internal components of the straight wing

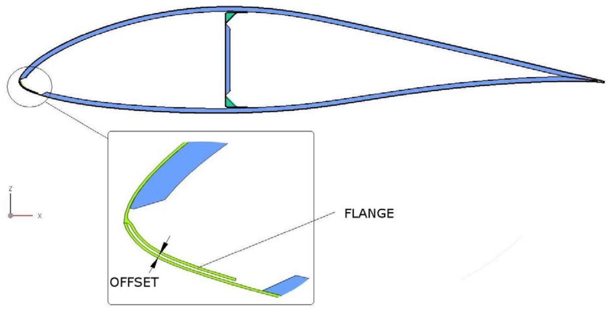

Fig. 31 Lower and upper coverage are joined via the flange with offset

8.1 Wing assembling

Assembly of the wing's internal components will be performed in the negative mould of upper wing-shell, Fig.30. Glue-bonding can join upper and lower wing-shells using the overlap (flange) on the leading edge. This method gives acceptable results, however a special mould is needed to form the overlap extending the upper wing-shell. The lower wing-shell is attached (glued) to this overlap, Fig.30. Wing shell was made of two layer of carbon fibre 93 g/m^2 with the foam-core PCV of 3 mm thickness and density of 60 kg/m^3. Spar strips are made of carbon roving TENAX HTS-5631, spar walls are made of two layers of carbon fibre 93 g/m^2 with foam-core PCV of 3 mm thickness and density of 60 kg/m^3. Ribs no 1,2,3 are made of two layers of carbon fibre 160 g/m^2. Resin L335 and hardener Ha 335/340 were used as the impregnating agent

8.2 Other examples of assembling

Forces coming from landing gears are introduced into fuselage structure through a double beam, Fig.35. Left and right halves of this beam, Fig.32, are attached one to the other, immediately after they are laminated and before composite is hardened. The metal fittings are put inside, and bonded during beam halves attachment operation, see Fig.33-34. Fig.36 shows how V-tail was manufactured using left and right halves (in fact four different negative moulds were manufactured, because left and right V-tails are not the same). All the time a general rule was used - decreasing the number of positioning elements was done anytime if possible. An example is shown just at Fig.36 – putting a smaller mould directly on a bigger one it was possible to attach the V-tail spar into the shell. Selected moulds and aircraft parts manufactured at Warsaw University of Technology and ready for assembling are shown in photos presented at Fig.37-39.

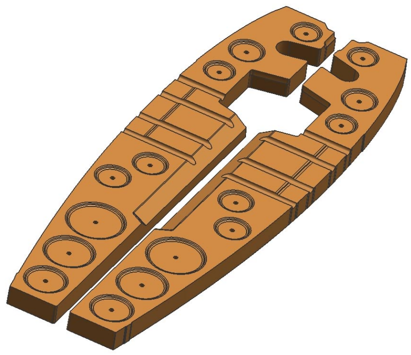

Fig. 32 Moulds of the left and right parts of the fuselage beam

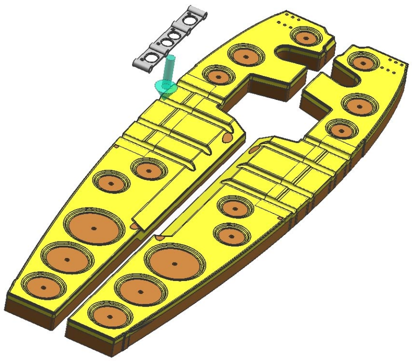

Fig. 33 Moulds of the left and right parts of this fuselage beam with metal fittings put inside

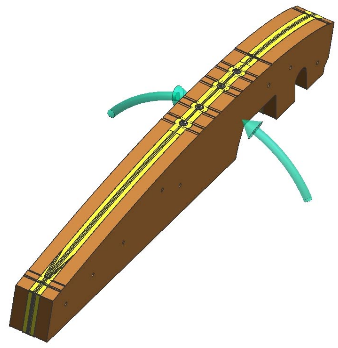

Fig. 34 Both parts of the fuselage beam moulds being attached and pressed for hardening

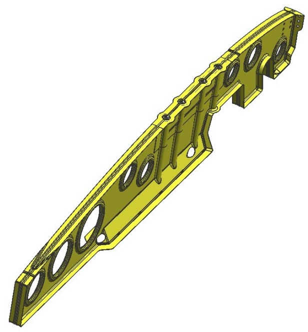

Fig. 35 Double beam hardened and ready for the fuselage assembling

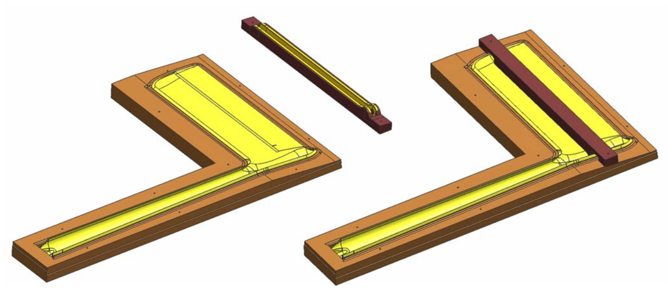

Fig. 36 Before the V-tail is assembled a stabilizing wall (spar) is attached to one of V-tail negative mould

Fig.37 Mould of the upper-left straight wing

Fig. 38 Negative moulds and positive frames ready for the fuselage assembling

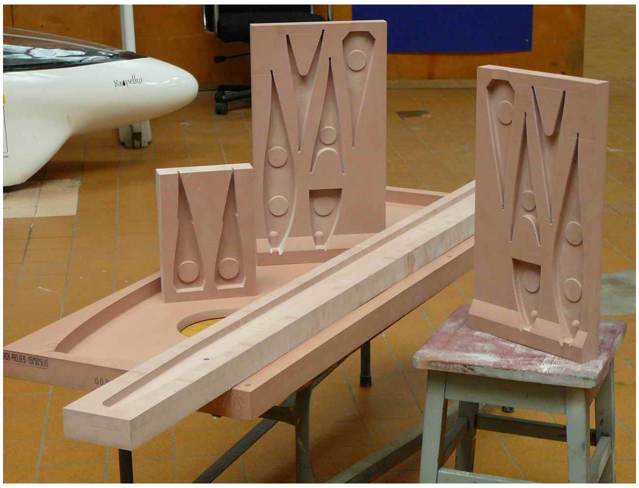

Fig. 39 Negative moulds of wing ribs and spar

9 Conclusion

SAMONIT project, focused on the design, optimisation, manufacturing and testing of a surveillance long endurance mission aircraft, named as PW-141, is well advanced. Both versions (baseline with straight wing and empennage placed after the main wing, and swept, tailless wing configuration) will be fitted with fully autonomous flight control system. Before the free flight experiments both aircraft will be aerodynamically tested in ϕ5 WT. The main goal of the whole programme is to optimise the platform and its systems to obtain the economically competitive aircraft, safe, affordable and efficient in its main long endurance, surveillance mission.

References

[1] European Civil Unmanned Air Vehicle Roadmap, www.uavnet.com.

[2] CAPECON Project No GRD1-2001-40162 ("Civil UAV Applications & Economic Effectivity of Potential CONfiguration Solutions"), Technical documents 2002-2004. V FR of European Union.

[3] M. Steinbuch, B. Marcus, M. Shepshelovich, Development of UAV Wings – Subsonic Designs. AIAA 2003, 41th Aerospace Sciences Meeting & Exhibit. Jan., 2003, Reno, NV.

[4] M.Allouche, Civil UAV Safety Issues – Airworthiness and Operational Certification aspects. UAVNET, Stockholm, Oct.2001, www.uavnet.com

[5] Goraj Z., "Civilian Unmanned Aerial Vehicles – Overview of European Effort and Challenges for the Future". Aviation Journal, Vilnius 2003, Aviation, Vol.VII, No 2, pp.1-18, 2003.

[6] Goraj Z., Frydrychewicz A., „Development Approach of the PW_103 - An Increased Reliability MALE UAV - Under the CAPECON Project Within the V FR of EU", Proc. Of 24th ICAS Congress, Yokohama 2004, Paper 443.

[7] J.Gadomski, B.Hernik, Z.Goraj, Analysis And Opimisation of a Male UAV Loaded Structure. Aircraft Engineering and Aerospace Technology, Vol.78, No. 2, 2006, pp.120-131.

[8] Goraj Z., Frydrychewicz A., de'Tallec C., Hermetz J., "HALE UAV platform optimised for a specialized 20-km altitude patrol mission", Proc. Of 24th ICAS Congress, Yokohama 2004, Paper 285.

[9] Goraj Z., Frydrychewicz A., Świtkiewicz R., Hernik B., Gadomski J., Goetzendorf T., Figat M., Suchodolski S., Chajec W., "High Altitude Long Endurance Unmanned Aerial Vehicle of a New Generation – a Design Challenge for a Low Cost, Reliable And High Performance Aircraft", Bulletin of Polish Academy of Sciences, Vol.52, No.3/2004, pp.173-194.

[10] Z.Goraj, PW-125 MALE UAV design project developed in Warsaw University of Technology. AIAA 3rd conference "Unmanned Unlimitted", Chicago, Sept. 2004, AIAA paper 6326.

[11] Z.Goraj, Design Challenges associated with development of a new generation UAV. Aircraft Engineering and Aerospace Technology, Vol.77, No. 7, 2005, pp.361-368.

[12] M.Figat, T.Goetzendorf-Grabowski, Z.Goraj, Aerodynamic Calculation of Unmanned Aircraft. Aircraft Engineering and Aerospace Technology, Vol.77, No. 6, 2005, pp.467-474.

[13] Z.Goraj, An Integrated System for Border Surveillance and Monitoring Based on Very Light

MALE UAV. Proc. Of 25th ICAS Congress, Hamburg, Sept 2006, Paper 417.
[14] Z.Goraj, UAV platforms designed in WUT for border surveillance. AIAA Infotech @ Aerospace 2007 Conference and Exhibit. San Francisco - Rohnert Park, 7-10 May, 2007.
[15] Z.Goraj, Mini UAV Designed for Surveillance Long Endurance Mission. The 4th Internat. Symposium on Innovative Aerial / Space Flyer System. Tokyo, 14 Jan. 2008, Plenary, Invited Lecture. Proceedings of the 4th Int. Symposium, pp.11-20.
[16] C.Galinski, Wing section designed for PW-141. SAMONIT internal report (unpublished). Warsaw, May 2007.
[17] www.sandia.gov/radar.sar.html

Copyright Statement

This paper contains results of SAMONIT project supported by Polish Ministry of Science and Higher Education, grant no R10/ 010/ 02 under the agreement of 0597/R/2/T02/07/02. Design Team was established under the umbrella of the “Centre of Excellence of Aircraft Design” created at Warsaw University of Technology under the auspices and financial support received from the “Association of Polish Pilots” established in Great Britain, with special acknowledgement addressed to Andrzej Jeziorski - Colonel Pilot and Head of the association.