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# Three surface aircraft (TSA) configuration – flying qualities evaluation

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**Abstract**

**Purpose** – Unconventional configuration aircrafts are not often designed because of many problems, mainly with stability and trim. However, they could be very promising. The problems can be compensated by extraordinary performance and some flying characteristics. The three-surface aircraft, presented in the paper, is such a configuration – problems and profits are both present, but advantages seem to be more prevalent. This paper aims to present main assumptions for a new, three-surfaces aircraft design, its evaluation according to flying quality requirements and the discussion on selected performance characteristics. The paper completes with the first experimental results of flight tests of a 40 per cent scaled model.

**Design/methodology/approach** – Aerodynamic computations were made using panel method code (KK-AERO, PANUKL). Stability analysis was done using SDSA package, developed within the SimSAC project.

**Findings** – Initial design assumptions and numerical analysis results were proven during flight tests.

**Practical implications** – The paper contains results of numerical analysis, which were crucial in designing the layout of the new, three-surface aircraft.

**Originality/value** – This paper presents an original approach to design a new, unconventional aircraft. The approach and results could be useful in other projects.

**Keywords** Aircraft design, Stability, Canard, Three-surfaces configuration

**Paper type** Research paper

## Introduction

Designing a new aircraft is always a challenge, especially when unconventional configuration is considered. Unconventional configuration is usually the reason of many problems; however, it could be very promising due to extraordinary characteristics – small drag, high performance, etc. The flying qualities are fundamental from the pilot's and potential customer's points of views and have to be tested during the conceptual stage of the project (Rizzi, 2011; Goetzendorf-Grabowski *et al.*, 2011). The paper presents the stability and trim analysis of a newly designed four-seat aircraft in a three-surface configuration (Figure 1).

The small aircraft in the presented unconventional configuration requires that trim and stability are taken care of, due to a very wide movement of gravity centre (CG). The position of CG in the presented aircraft changes from −22 to +10 per cent of MAC. The whole payload is located in front part of the fuselage (between main wing and canard). Canard plays an important role: to satisfy the longitudinal equilibrium. Therefore, it must be able to give a sufficient lift force, especially in the case of front CG position. From the stability point of view, good characteristics of canard (big lift curve slope) are not desired. Because of that, it was a real challenge to satisfy trim and stability in this range, in each case of payload.

This paper presents the design of this three-surface configuration, the stability analysis, its influence on the final layout of the aircraft and remarks about flying qualities. Selected parameters recorded during test flights of the scaled model were presented and compared with calculation results.

## Aircraft presentation

The fundamental feature of the current aircraft has to be its ability to sell. At least one parameter of a newly designed aircraft must be better in comparison to a competitive aircraft. It is a minimum requirement and it allows only for vegetation – see Mooney, Maule, Aviat, etc. The aircraft, which is willingly bought, must have some parameters surpassing competition. Usually, there are two basic performance parameters (i.e. STOL characteristics, payload) and some features which improve comfort or equipment (i.e.

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**Figure 1** AT6 – final concept

advanced avionics, satellite phone, etc.). A good example is Cirrus, which has high cruise airspeed, range and sufficient comfort even for tall people. Additionally, it has very good onboard equipment. However, the greatest achievement is to design an aircraft which has performance parameters surpassing competition, which are the opposite features, i.e. high maximum airspeed and low minimum airspeed or high stability and high manoeuvrability. If we add economics of use, high level of safety, some nice gadgets onboard and the reasonable price, the success is almost assured.

Usually opposite features cause, that price is growing (i.e. complicated superlift devices, expensive power unit, sophisticated and expensive materials, etc.). The classical configuration of an aircraft, with current engines, does not give a chance to improve performance characteristics significantly, although new technologies and new airworthiness regulation, generate some outstanding exceptions (i.e. Cirrus, Diamond, Pipistrel – Panthera). The big chance to obtain a significant increase of opposite parameters could be unconventional configuration.

The presented aircraft was designed as a four-seat, twin-engine light aircraft. It had to be comfortable, fast, safe and economical; thus, its name PSE – Performance Safety and Economy. Safety was satisfied by the use of two engines and a parachute recovery system. The economy was due to two Rotax engines, which are able to use the same fuel that is used by cars. Moreover, advanced aerodynamic project had to give good characteristics to improve economy and performance as well. Additionally, innovative flaps, which are deflected up in cruise condition and partially retracted to decrease wetted area, increase the aerodynamic effectiveness. Initially, the ergonomics of cabin was the starting point. It had to be free of other elements because of the convenience, but also because the cross-sectional area has a large impact on performance. Thus, the main spar and landing gear were moved out of the cabin space. The visibility from cabin had to be similar to visibility from helicopter cabin, not as in small Cessna case, so it should be a highly glazed cabin. Next – easy entering for each pilot and passenger, thus one large glazed door for pilots and two "gull wing" doors for each passenger. These requirements caused that the wheel base of the landing gear was increased and, what is most important, the main wing was shifted back, which caused that CG is located in front of the leading edge of main wing. Such an extreme CG position forces the additional lifting surface on the front of fuselage (canard) to satisfy trim and to decrease a very big, negative force on the horizontal tail. Thus, the concept of the three-surface aircraft was born and it was named AT-6.

The presented aircraft is designed using four-seats, twin-engine configuration. The main geometric, weight and performance (assumed) parameters are presented in Table I.

The aircraft has slotted flaps on the main wing and plain flap on the canard. Flaps on the main wing and canard are coupled. The classical elevator on the horizontal tail is used for pitch control. The primary configuration had dihedral 3.5° and relatively big vertical stabilizer (Figure 2). The engines were located on the upper surface of the wing to fulfil the requirement of the sufficient clearance between the propeller and the ground.

## Aerodynamic analysis

The aerodynamic analysis was done to obtain all characteristics necessary, next to stability analysis and parallel to optimizing all details (airfoil, flaps, engine nacelles, etc.). The aerodynamic design was made using XFOIL (Drela, 1989) and MSES for airfoil design, KK-AERO package (Kubryński, 1999), based on panel method with boundary layer, for 3D design (Kubryński, 2014). Analysis and optimization of the flow around AT-6 was done using ANSYS CFX software (Mazurkiewicz, 2014).

Aerodynamic characteristics, including stability derivatives, were computed using low-order panel code (PANUKL, 2012). Figures 3 and 4 present an example of mesh (primary

**Table I** The main geometric, weight and performance parameters

| | |
|---|---|
| **Wingspan** | 11.0 m |
| **Length** | 9.0 m |
| **Height** | 3.0 m |
| **Wing area** | 12.5 m$^2$ |
| **Maximum TO weight** | 1280 kg |
| **W/S** | 103 kg/m$^2$ |
| **Engines power** | 230 HP |
| **Minimum airspeed** | 90 km/h |
| **Cruise airspeed (at sea level)** | 280 km/h |
| **Cruise airspeed (at 14000 ft)** | 320 km/h |
| **Ceiling** | 1,8000 ft |

**Figure 2** AT6 – primary configuration

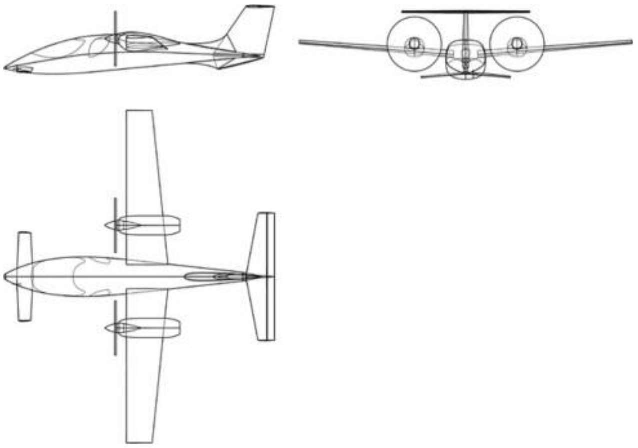
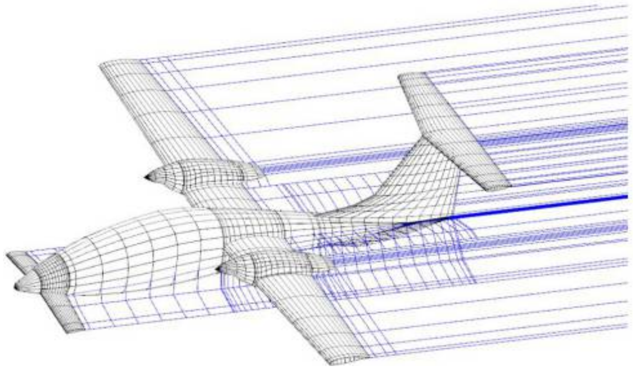


**Figure 3** PANUKL computation: Mesh AT6 – primary configuration – 3,609 panels



configuration) prepared in the PANUKL package and results of computation for angle of attack equal 7.5°. Basic characteristics (lift and pitching moment coefficients) obtained from PANUKL allow to determine static margin in fixed stick case (Goetzendorf-Grabowski, 2014). Free stick case also requires the hinge moment coefficients of elevator and downwash angle to be computed. Downwash was computed by using PANUKL and hinge moments using ESDU reports.

Most of stability derivatives were computed using the PANUKL package. Missing derivatives, especially derivatives with respect to vertical acceleration, were computed using handbook methods and formulae (Etkin, 1982; Roskam, 2003; Goraj, 2014).

The assumed methodology to obtain all necessary aerodynamic characteristics using the panel method was verified in other projects (Galiński *et al.*, 2014). Stability and control derivatives are compliant with classical methods presented in many handbooks and reports and usually are closer to data obtained from wind tunnel tests. Two groups of data have to be computed applying reports and handbook methods – hinge moments and the apparent masses (derivatives with respect to acceleration), due to different reasons. The results of hinge moments obtained using panel code were not verified, and the apparent masses usually cannot be computed by used panel code, although some commercial packages have such ability. Such an approach, i.e. mix of different data, was verified in some other projects and gave good results.

The static margin, which is a basic factor of longitudinal static stability, was computed for all configurations of the CG position versus the angle of attack and in consequence versus airspeed. The value of the static margin in fixed and free stick cases is shown in Figure 5. It shows, that, in case of the rear position of CG, which corresponds to a small payload (one light pilot), the aircraft can be longitudinally unstable in case of the free stick and for higher airspeed in case of fixed stick as well. Figure 5 also shows a big difference between rear and front CG position.

## Dynamic stability analysis

The dynamic analysis was done using the SDSA package, which is also able to analyze linear and nonlinear models (Goetzendorf-Grabowski *et al.*, 2011). All results of dynamic stability analysis, including figures of merit, presented in this paper, were obtained from SDSA. The assumed model does not take into account the engine effects on flight dynamics; however, the position of thrust vector was taken to determine the trim condition. It seems that the drag effect of propellers can improve directional stability a little because it increases the damping effect with respect to yaw rate and should not be a source of additional problems. Mass breakdown was estimated directly from the computer-aided design system used in the design process, concerning nine main configurations (combination of fuel, payload and position of landing gear). Three configurations were taken to the analysis: clean, take-off (main wing Fowler flaps deflected to 15° and

**Figure 4** PANUKL computation: pressure distribution for AoA 7.5° – primary configuration

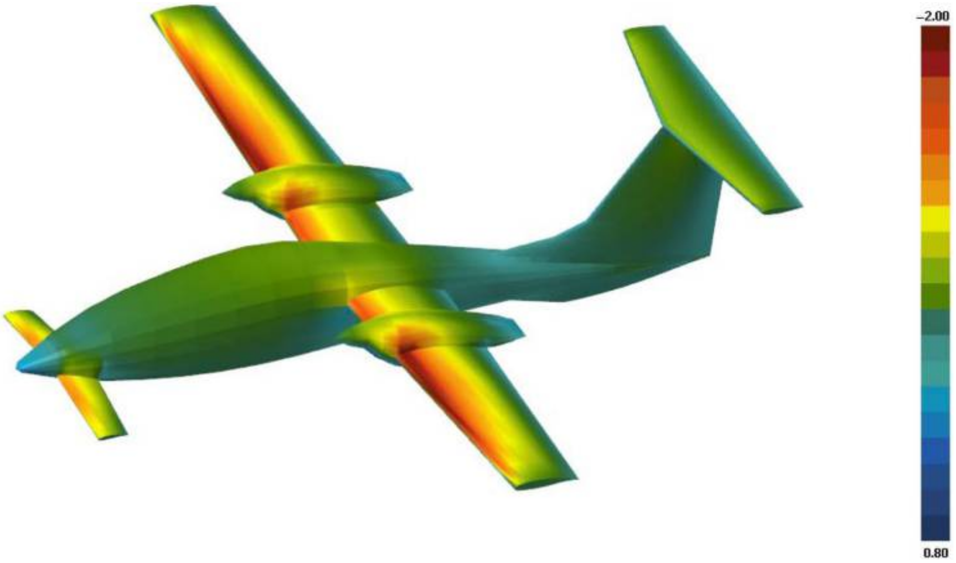
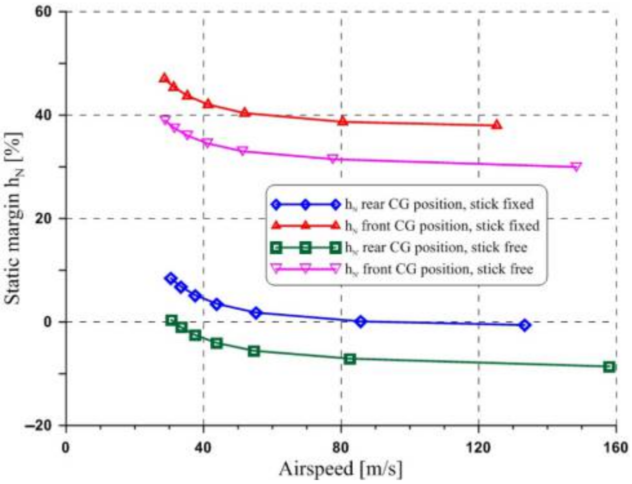


**Figure 5** Static margin versus airspeed



canard flap deflected to 15°) and landing (main wing Fowler flaps deflected to 35° and canard flap deflected to 30°).

The aircraft configuration, especially a major part of the fuselage in front of the main wing and a big dihedral angle of the main wing, is the reason why particular attention must be paid to the lateral stability.

The basic factor of directional static stability, i.e. derivative of yawing moment with respect to sideslip angle, is positive, which means that the aircraft is statically stable. However, the dynamic analysis shows that the characteristics of the most important, from flying qualities point of view, lateral mode of motion, i.e. Dutch roll, may not be satisfying, and it can even be unstable for a higher angle of attack. Figure 6 shows the Dutch roll characteristics against the background of criteria defined by CS-23. This criterion is not satisfied for low value of airspeed, which corresponds with higher angle of attack. Second, an essential lateral mode of motion is the spiral mode. This mode is stable in whole airspeed range, which is presented in Figure 7.

The results of stability analysis of the first version of presented aircraft were not satisfying. Both longitudinal and lateral characteristics had to be improved. Longitudinal stability was improved by changing the internal layout of the aircraft and by rearranging the weights' breakdown. The lateral stability required the change of the shape of the configuration. Usually, the dihedral angle reduces the Dutch roll and the vertical tail increases the directional stability, while the spiral mode can be worse, so the combination of change of the dihedral and vertical stabilizer was applied. The lateral stability was finally improved by decreasing the dihedral angle to zero and moving the main wing up, to perform the same position of engines (Figure 8). It improved the Dutch roll and allowed to decrease the vertical tail area. The spiral mode has still satisfying characteristics. Moreover, the results of aerodynamic analysis showed that such changes are advantageous from aerodynamics point of view (Mazurkiewicz, 2014). The flow around engine nacelles appeared more clean, which resulted in reducing the drag. The final configuration is presented in Figure 9.

New configuration was tested. Three aerodynamic configurations were considered: clean, take-off (flaps 15°) and landing (flaps 30°). The aerodynamic characteristics were obtained using panel methods (Figure 10). All modes of motion were checked, taking into account requirements from airworthiness regulation for handling qualities.

### Phugoid

The dominating state variable in the phugoid mode is the airspeed, and angle of attack is almost constant. The period is usually long and oscillations are well damped. The airworthiness requirements are not strong (CS-23, European

**Figure 6** Dutch roll characteristics versus calibrated airspeed (CS-23.181 criterion) – primary version

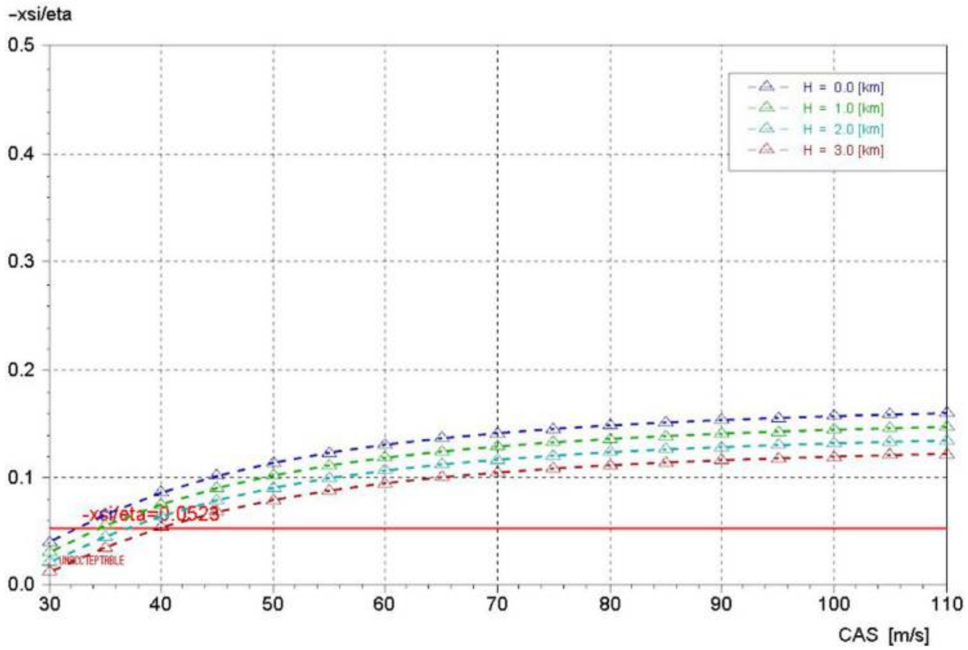


**Figure 7** Time to double for spiral mode against to background of MIL-F-8785C criterion – primary version

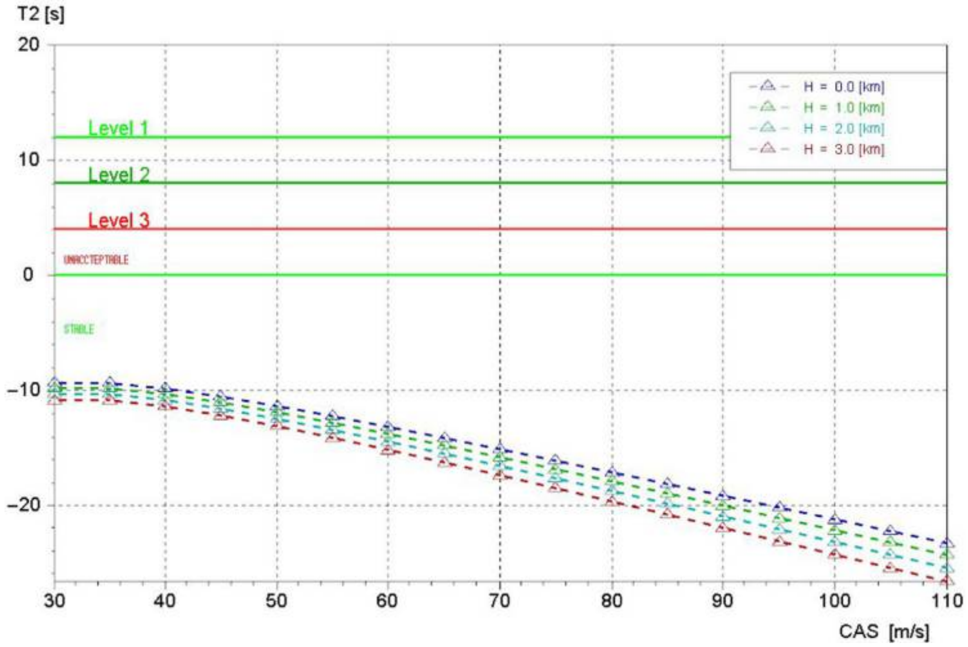


**Figure 8** Changes in the configuration as the result of stability analysis of the primary version

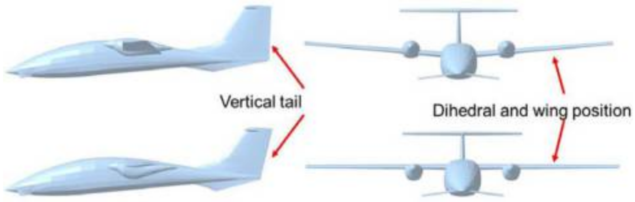
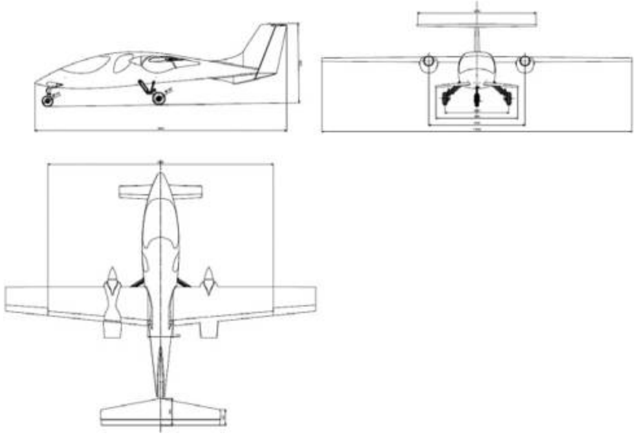


**Figure 9** AT-6 – final configuration



Aviation Safety Agency, 2012): "Any long-period oscillation of the flight path (phugoid) must not be so unstable as to cause an unacceptable increase in pilot workload or otherwise endanger the aeroplane" (CS-23.181).

The results obtained for AT-6 show (Figure 11) that phugoid is stable in the whole range of the CG position. Time needed to damp the amplitude to half is comparable with the period and varies between 40 and 60 s.

### Short period

The short-period oscillations connect rapid changes of angle of attack with the pitch rate. The period is usually very short. The requirements according to CS-23.181 say:

> Any short period oscillation not including combined lateral-directional oscillations occurring between the stalling speed and the maximum allowable speed appropriate to the configuration of the aeroplane must be heavily damped [. . .].

The results of computation show that short-period oscillations are well damped (Figure 12); however, for a clean configuration in case of the rear CG position, periodical character vanishes. Two non-periodical modes are stable.

### Dutch roll

The Dutch roll requirements according to CS-23.181 are well defined:

**Figure 10** PANUKL computation: pressure distribution for AoA $-5°$ – final configuration

**Figure 11** Phugoid – period and time to half damping versus calibrated airspeed

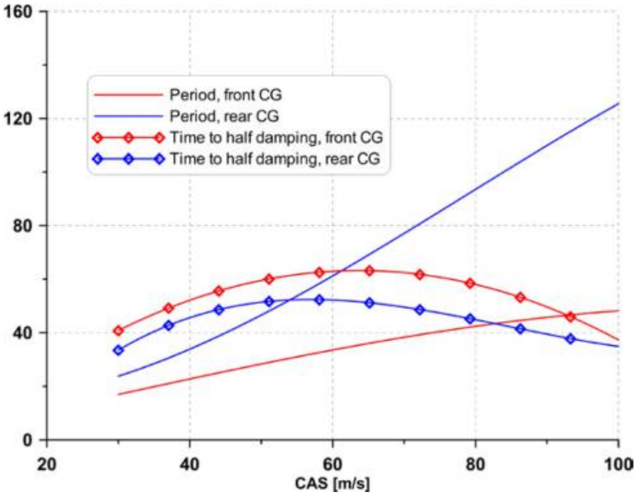
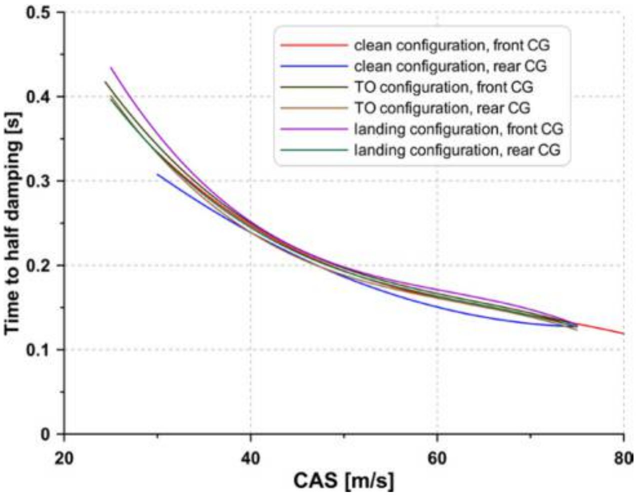


**Figure 12** Short period oscillations – time to half damping versus calibrated airspeed



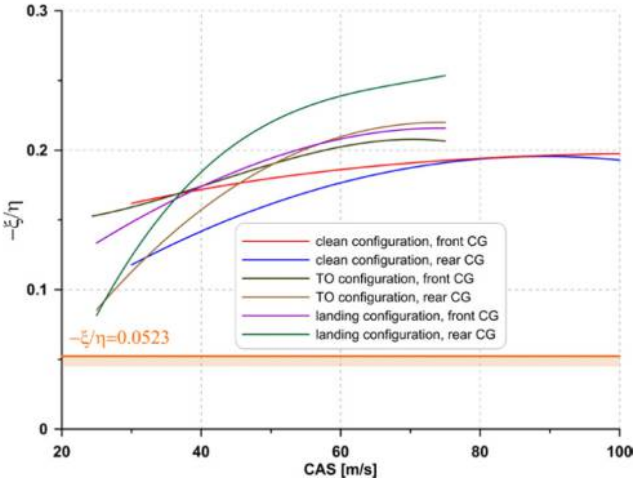
> Any combined lateral-directional oscillations ("Dutch roll") occurring between the stalling speed and the maximum allowable speed appropriate to the configuration of the aeroplane must be damped to 1/10 amplitude in 7 cycles [. . .].

The obtained results show (Figure 13) that all configurations satisfy airworthiness requirements.

### Spiral mode

After improvement of the previous version, spiral is the only mode that is worse. However, airworthiness requirements are not strong – CS-23-BOOK2: "[. . .] a slowacting mode called the spiral which may be stable, but is often neutrally stable or even mildly divergent in roll and yaw?". Similar requirements are seen in MIL-F-8785-C. Figure 14 shows the spiral mode time to double, which shows that spiral is unstable only for small values of airspeed and time to double is sufficiently big.

**Figure 13** Dutch roll characteristics versus calibrated airspeed (CS-23.181 criterion)



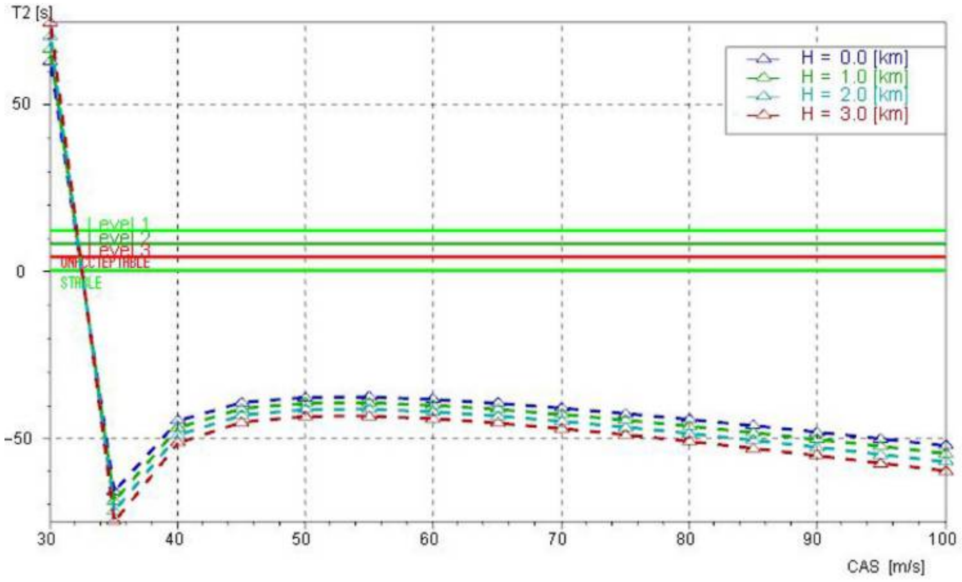
## Flight test

The unconventional configuration causes that there are many unknowns despite the fact that advanced methods of aerodynamic and stability analysis were applied. Thus, the 40 per cent scaled model was built and first flights were made in late Spring 2014 (Figure 15). Test flights proved the expected advantages of the configuration. Payload can be placed from −22 to 10 per cent of MAC (during tests even 13 per cent was checked) and the longitudinal stability with fixed stick is satisfied for each configuration (flaps, landing gear and airspeed) and for full range of CG position. The small area of canard has raised concerns due to its efficiency; however, despite this, canard flaps are sufficient for a short takeoff, even for the front CG position. The flight tests helped to determine the optimal location of canard flaps due to the short takeoff for the front CG position but also due to the reduction of the need for pushing the stick in the landing configuration at the rear CG position.

Releasing compartment cabin from the landing gear and wings caused small cross sections giving better performance which was a key parameter in the concept design. We also obtained significantly higher lift coefficient ($C_L$) for the whole plane through participation of canard. Also, the extreme angles of attack have been reached. For clean configuration, after conversion to a full-size aircraft, we expect $C_L$ about 1.65-1.7 and for Fowler flaps of 35° even $C_L = 2.4$.

Achieving high $C_L$ allowed to balance the surface of the wings, so as to ensure a good cruising speed but low minimum – only the combination of these two features will determine the success of a commercial aircraft. Behavior in stall, especially in configuration with flaps, and with the engine running is simply exemplary even at extreme rear CG position. This is because the vortex wake from the canard is directed under the horizontal tail, by downwash from flaps and engines. The clean configuration without an engine can dramatically roll the wing, but this is at extremely high angles of attack (18-20°), which is preceded by a strong vibration coming from the canard, whose role is to advance the stall, before stall on the main wing. The stall on the wing develops from the nacelle and propagates to the inside and outside of

**Figure 14** Time to double for spiral mode – clean configuration, front CG position



**Source:** MIL-F-8785C criterion (1980)

**Figure 15** Test flight of 40 per cent scaled model

the wings, however, holding the aileron area free from stall, up to angles of attack of 20°. Optimization of the position of the engine nacelles was done during aerodynamic analysis (Kubrynski, 2014; Mazurkiewicz, 2014).

Test flights proved that the Dutch roll is stable and strongly damped (Figure 16). Directional stability, which initially has raised concerns due to the short arm of the vertical tail, is also very good. Spiral is not unstable. Moreover, interesting features occurred (but occurring in the classical configurations as well) – accelerated stall during turn generates a decrease in the lift force on the "faster" wing and ultimately it returns the wings to level and prevents entering into a deep spiral or spin. The spin must be strongly initiated, and depending on the position of the CG, the first turn can also be a spiral. Regardless of the number of turns, recovery followed immediately after the rudder deflection.

The Dutch roll is a mode of motion, which caused that some serious changes had to be done. Thus, it was tested during the first flights. Figure 16 shows recorded flight parameters used for the Dutch roll rating and results of the stability analysis made by SDSA (Goetzendorf-Grabowski *et al.*, 2011). Two parameters were taken into consideration – roll rate and yaw rate. The Dutch roll was initiated by moving the rudder in a doublet that reached the left and right stops. Following this, the rudder was kept in the neutral. As it is seen in Figure 16, the Dutch roll is stable and well damped. The results are compliant with the results from numerical analysis. Airspeed for numerical analysis was scaled according to Froude number because calculations were made for full-scale aircraft and flight test was performed for 40 per cent scaled model.

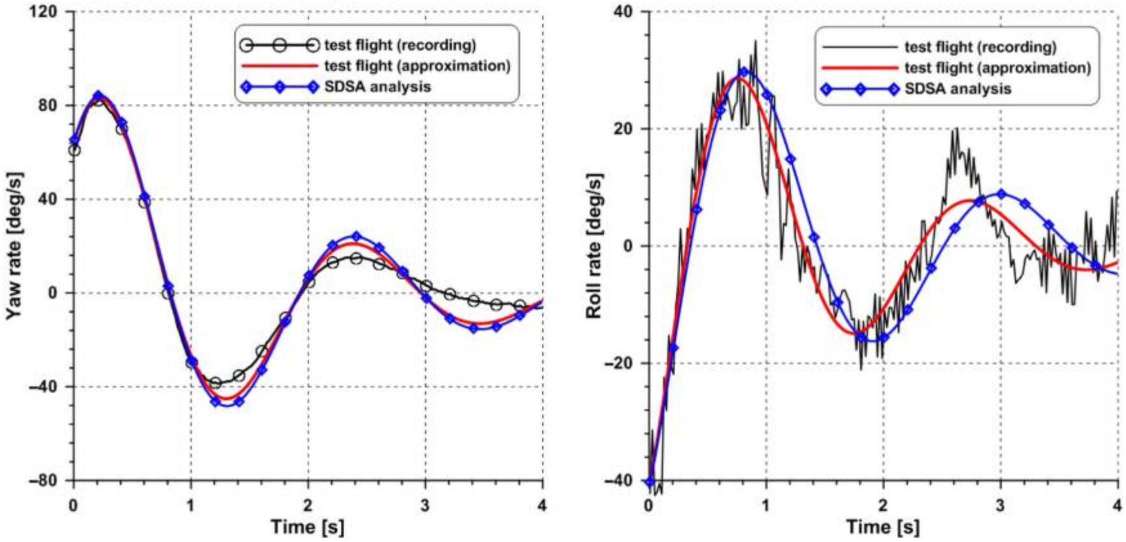
## Conclusion

According to the results of the flight tests of the scaled model, which is dynamically similar, we can be optimistic for the achievement of the objectives set for the full-size aircraft, namely:

- cruising speed should be greater than 150 knots;
- minimum airspeed, for configuration with flaps, corresponds to an aircraft with bigger area (with the same weight);
- "aerodynamic safety" is satisfied – stall, spin characteristics, static and dynamic stability;
- good visibility and comfort of cab; and
- other performance and low operating costs resulting from the aerodynamic (L/D over 15).

The presented analysis focused on the flying qualities and showed that all stability criteria defined in the airworthiness regulations are satisfied. It is very important from the certification point of view. The flight test results proved that numerical analysis is correct. The flight test must be repeated for a full-scaled aircraft; however, current results bode

**Figure 16** Comparison of test flight and calculation results



optimistic, especially, that criteria defined in MIL-F-8785C specification, which are usually stronger, are also satisfied.

## Further work

Full-scaled aircraft is under development. All results from numerical analysis and test flights of scaled model will be taken into account. The first flight is expected in one year.

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