AERODYNAMIC AND STABILITY ANALYSIS OF PPLANE VEHICLE TANDEM-WING CONFIGURATION

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Abstract. The paper presents aerodynamic and stability analysis of the tandem-wing configuration aircraft, that was designed in Warsaw University of Technology within the frame of PPlane project sponsored by European Union under 7 FP. The paper contains results of numerical computation of aerodynamics (Euler code) of the analyzed aircraft. Stability analysis was made using SDSA package.

Keywords. tandem wing, aerodynamics, stability

1 Introduction

The Personal Air Transport Systems (PATS) is going to be a new standard in the close future. Definition of the operational concept for the future PATS was one of the most important goal of the PPLANE project [1] (FP7 - Personal Plane: Assessment and Validation of Pioneering Concepts for Personal Air Transport Systems). The element of the whole system is a vehicle. Taking into account potential demands of customers [2] and the possible application of the aircraft, the tandem wing configuration with tilt rotors has been selected as promising one. This configuration is unconventional and requires an analysis of aerodynamics and flying qualities as well. For the calculation of aerodynamic characteristics the MGAERO software was used, which utilizes the Euler code. The stability analysis was performed by use of the SDSA package [3].

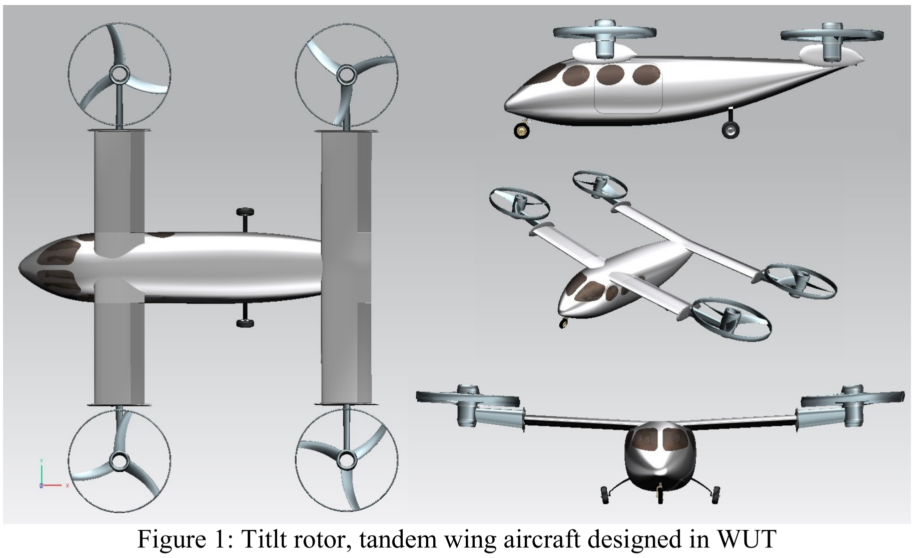

Figure 1: Titlt rotor, tandem wing aircraft designed in WUT

The considered aircraft is designed as four tilt rotor, tandem wing configuration (Figure 1). As tilt rotor it can fly as aircraft, when all rotors are give thrust forward, or as helicopter when all rotors give thrust upward. Stability analysis and flying qualities are usually defined for aircraft configuration, thus stability analysis concerns only “high speed” configuration. The linear and nonlinear flight dynamics analysis showed that the geometry improvements should be made, especially the addition of the vertical stabilizer was necessary.

2 Aerodynamic analysis

Aerodynamic analysis was performed to obtain the basic aerodynamic characteristics and aerodynamic derivatives as well. The configuration of presented aircraft is highly unconventional and highly coupled aerodynamically by the mutual influence of the two pairs of wings. Therefore, it was necessary to use advanced CFD methods.

As was mentioned before only the complete “high speed” configuration model was taken to the aerodynamic analysis. The model used for calculation consist of the fuselage body and two pairs of wings in tandem configuration. Engines with propeller rings are modeled by two coincident rings. The Figure 2 presents the model prepared for calculation.

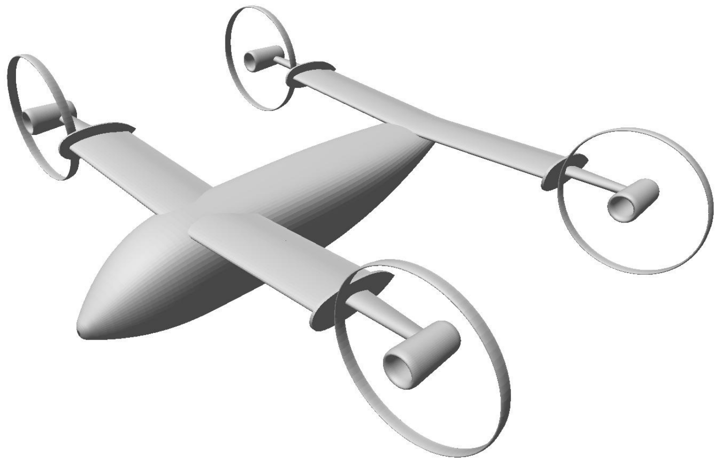

Figure 2: Model used to aerodynamic analysis

The other configuration like “low speed” [4] was also analyzed, however the results are not presented in the paper. The basic aerodynamic characteristics are similar to “high speed” case. Stability analysis of “low speed” configuration requires not only stability derivatives but also accurate rotors characteristics, which is not the topic of this paper.

2.1 Computational method

The aerodynamic analysis of presented tandem wing configuration was performed by MGAERO Software [5]. This software package includes a set of programs to calculate flow around an aircraft. It contains three elements: pre-processor – program to generate a mesh, the main program – to calculate flow around an aircraft and postprocessor – to show and analyze a solutions.

The numerical code of software bases on Euler model of flow [6]. A multigrid algorithm is usually used to reduce the computation time. In this case the multigrid scheme improves convergence of algorithm. The best way to solve this hyperbolic system of equations is V-cycle scheme of the multigrid method. The Figure 3 presents the six levels of mesh blocks prepared for model and Figure 4 presents the computational surface mesh.

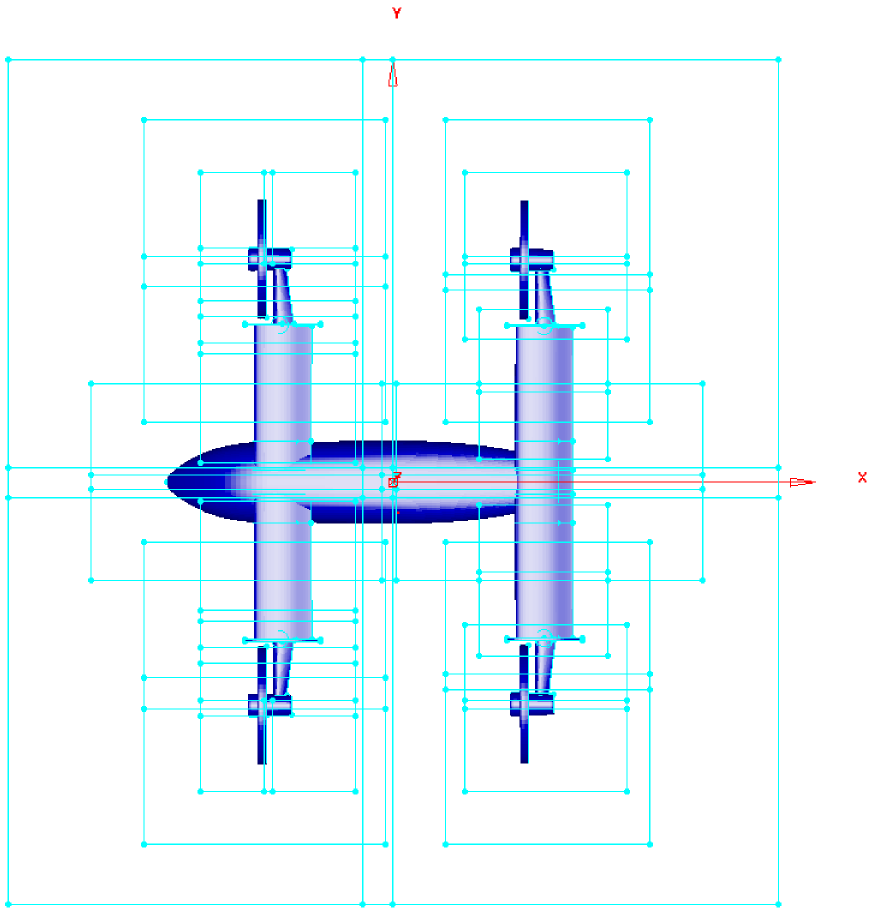

Figure 3: Multigrid Scheme for tilt rotor

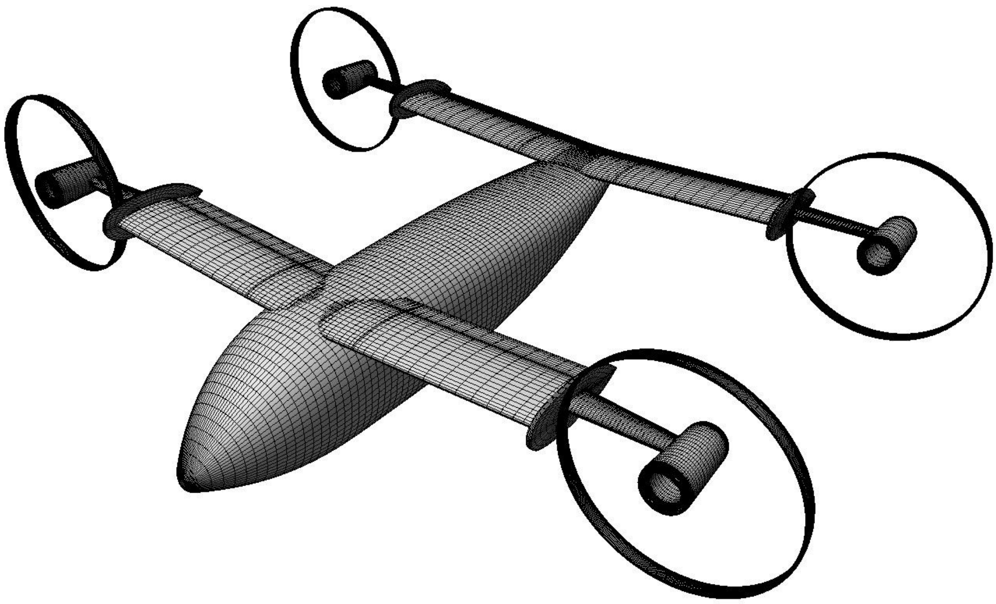

Figure 4: Mesh – High Speed Aircraft Configuration

2.2 Calculation

Aerodynamic calculation was made for single Mach number equal to 0,2. The reference dimensions for the model are presented in Table 1.

Table 1 Reference values

Reference	Value
Gross wing area [m^2]	10,76
Wing Span [m]	5,40
Mean Aerodynamic Chord [m]	2,00
$x_{25\%SCA}$ [m]	4,00
$x_{25\%SCA}$ [m]	0,05

One of the goals was to compute the stability and control derivatives. The analysis were performed but results of calculation revealed unsatisfied values of some stability derivatives, especially for lateral characteristics, e.g. C_{nv}. Therefore, some modification of basic model were made to satisfy stability requirements.

To improve static and dynamic lateral stability the vertical stabilizer was added. The area of vertical stabilizer is equal to $S_V = 2$ m^2. The Figure 5 presents the modified configuration.

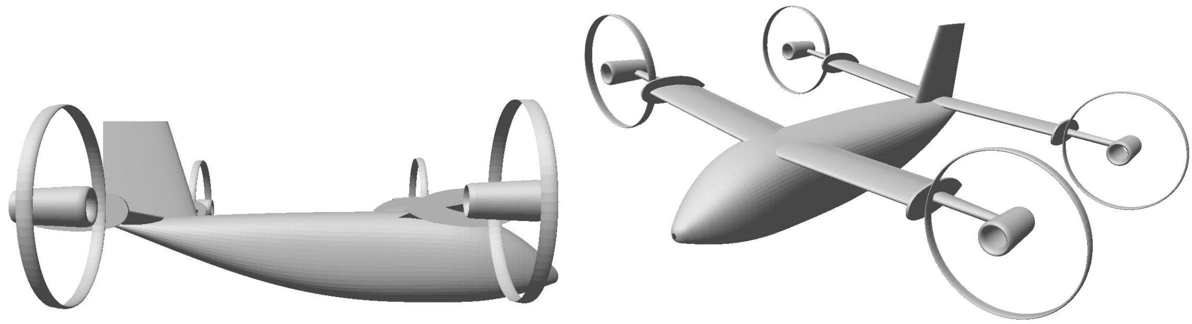

Figure 5: High Speed Configuration – Model with vertical stabiliser
(left – side view, right - izometric view)

The analysis of the second model (High Speed configuration with vertical stabilizer) was repeated for the same flow conditions and after that obtained stability derivatives were compared for both models.

2.3 Results

To determine aerodynamic characteristics needed for stability analysis, it was necessary to compute the flow of number of cases. The most interesting are unsymmetrical cases. As it was mentioned before two models were taken into account: without and with vertical stabilizer. The pressure distribution in case of the unsymmetrical velocity distribution, for both models present Figures 6-8.

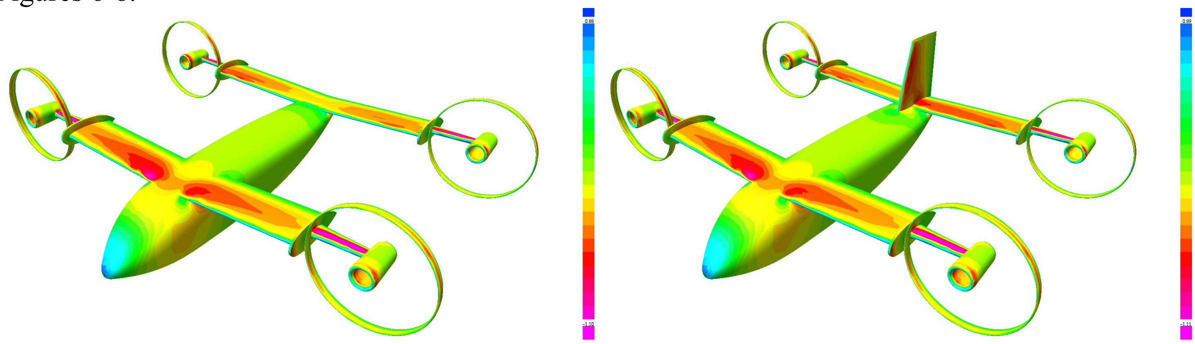

Figure 6: *Cp* distribution for sideslip angle β=3 [deg] aircraft without (left) and with vertical stabilizer (right).

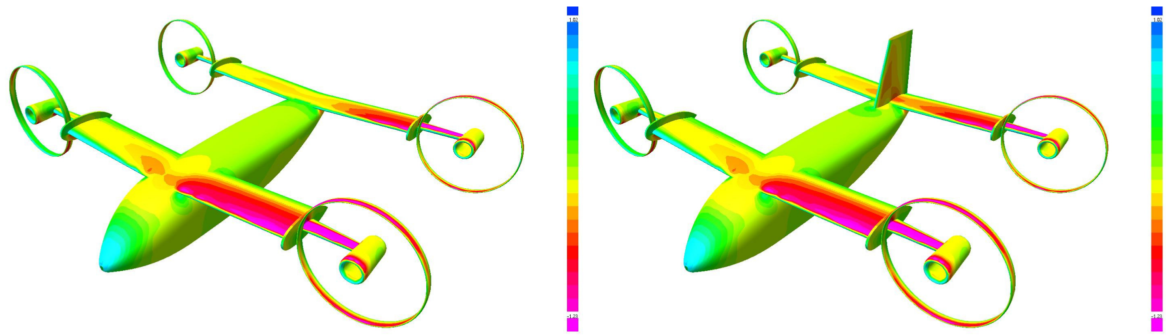

Figure 7 *Cp* distribution for roll rate p = 0,2 [rad/s] – aircraft without (left) and with vertical stabilizer (right)

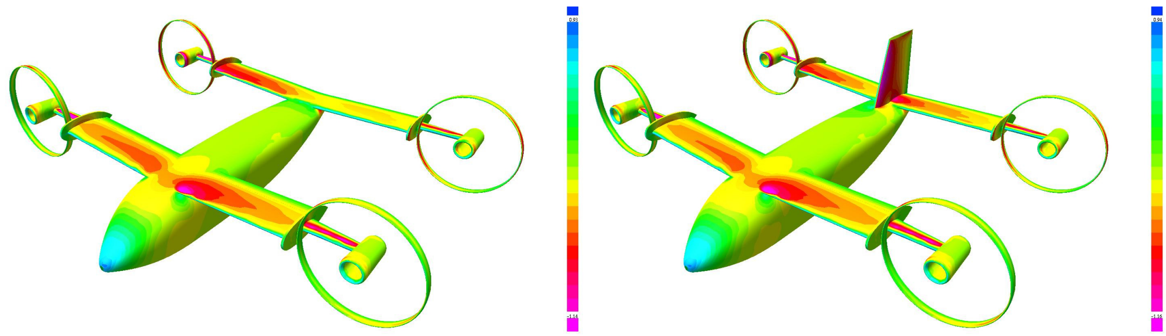

Figure 8 *Cp* distribution for yaw rate r =0,2 [rad/s] – aircraft without (left) and with vertical stabilizer (right)

2.3.1 Aerodynamic Characteristics

The computed basic aerodynamic characteristics - drag polar, lift coefficient and pitching moment coefficient versus angle of attack are presented on Figures 9-11. It should be noted that the pitching moment derivative with respect to angle of attack is a positive in a large extent of angle of attack, which can cause problems with longitudinal stability

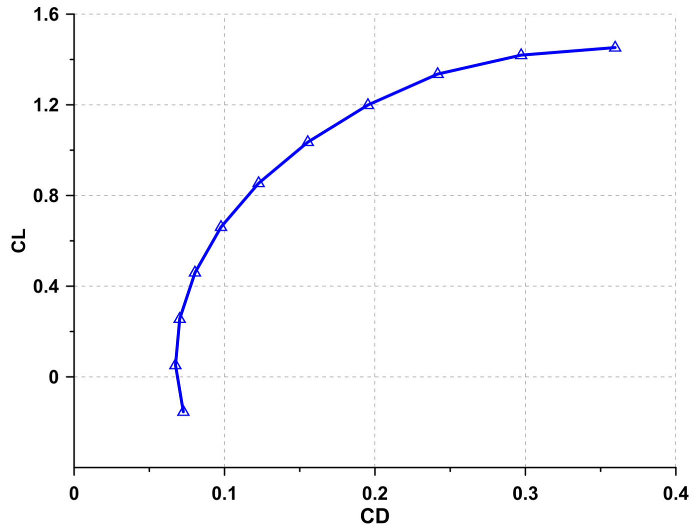

Figure 9: Drag Polar

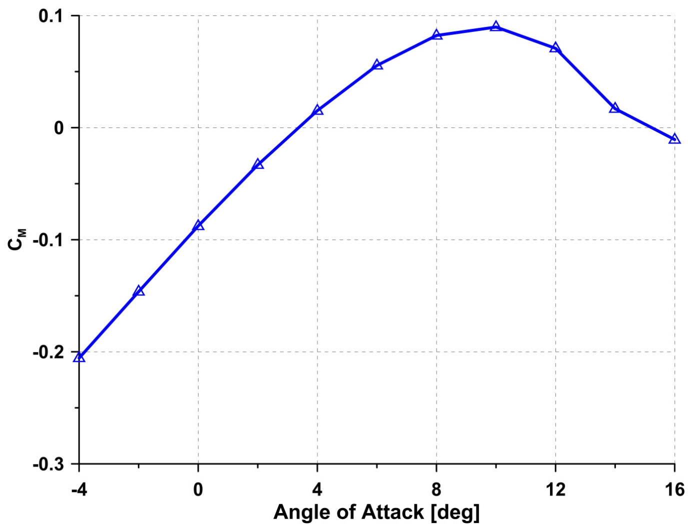

Figure 10: Lift Coeficient versus angle of attack

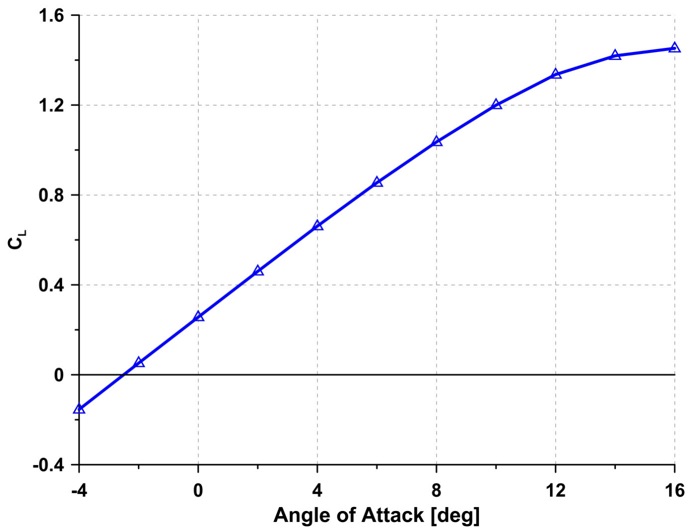

Figure 11: Pitching moment versus angle of attack

2.3.2 Stability derivatives:

To determine the stability derivatives a number of cases had to be computed. Symmetrical cases were considered to obtain the longitudinal derivatives and unsymmetrical cases to compute lateral derivatives. It should be noted, that lateral cases are more time consuming due to their asymmetry. Minimum three cases should be computed for each stability derivative. Tables 2 & 3 present the selected stability derivatives computed for both models. Longitudinal cases were computed only for basic model (without vertical tail) because the influence of vertical stabilizer on longitudinal aerodynamic characteristics can be neglected.

Table 2 Longitudinal stability derivatives

Stability derivatives	Value
Cdw	0.186
CLw	5.855
CLq	-0.734
Cmw	1.650
Cmq	-2.725

Table 3 Lateral stability derivatives

Stability derivatives	Basic Model	Aircraft with vertical stabilizer
Cyv	-0.853	-1.287
Cyp	0.072	0.097
Cyr	-0.052	-0.1
Clv	-0.636	-0.785
Clp	-0.254	-0.262
Clr	0.017	0.018
Cnv	-0.468	-0.281
Cnp	-0.021	-0.017
Cnr	-0.061	-0.092

2.3.3 Control derivatives:

Stability analysis requires first to find equilibrium state. Classical longitudinal trim problem is to find the following variables: angle of attack, required thrust and elevator deflection. The elevator role is fulfilled by rear wing flap in presented aircraft. Therefore a few additional computational cases with different deflection of flap were analyzed. The result are control derivatives – lift force and pitching moment derivative with respect to flap deflection. They allow to solve the trim problem.

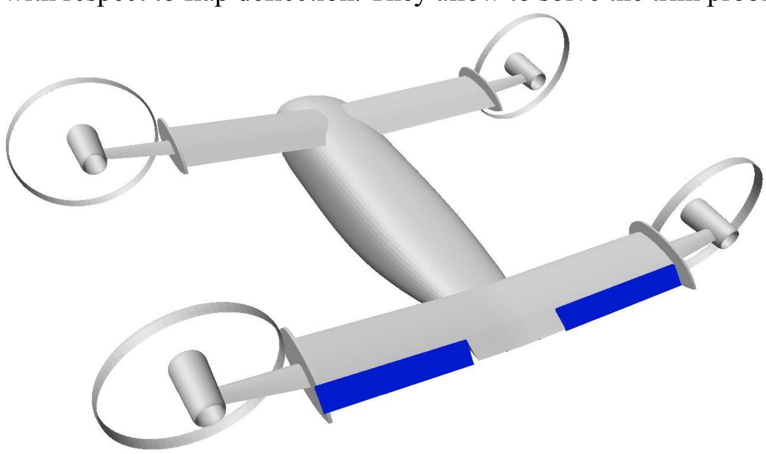

Figure 12: Control surface for VTOL – rear wing flap

3 Stability analysis

Stability analysis of presented tandem-wing aircraft was performed by use of SDSA (Simulation and Dynamic Stability Analysis) package [7]. The package was developed first of all to analyze the stability of an aircraft. It can compute stability characteristics of uncontrolled (fixed controls) and controlled (pilot in the loop) aircraft as well. It has also embedded 6 DoF desktop flight simulator, LQR based FCS, Performance module, etc. The SDSA was designed to use the same nonlinear model [8]-[12] of the aircraft motion for each functionality. For eigenvalues analysis, the nonlinear model was linearised numerically by computing the Jacobian matrix of the state derivatives in the equilibrium (trim) point. It allowed the construction of the stability analyser using the same set of equations as in the flight simulation. The flight simulation module, based on mathematical model with six degrees of freedom, can be used to do the test flights in order to record flight parameters in time. Next they can be used for identification of typical modes of motions and their parameters (period, damping coefficient, phase shift). The stability analysis results are presented on the figures of merits based on JAR/FAR, ICAO, MIL [13] regulations.

3.1 Configuration without vertical tail (original design)

In the first stage, the stability characteristics were calculated for original configuration, without vertical tail. The vertical stabilizer doesn't influence on longitudinal modes, so only lateral modes were analyzed and compared for both configurations.

3.1.1 Longitudinal modes

Both longitudinal modes proved to be stable. Figure 13 presents the period and time to half damping for phugoid mode. The results show, that although mode is stable, the time to half damping is long and could be longer than period which could give not high pilot rating. Figure 14 presents the same variables for short period mode. The mode is stable however time to half damping is comparable with period for low airspeed, which could be not acceptable.

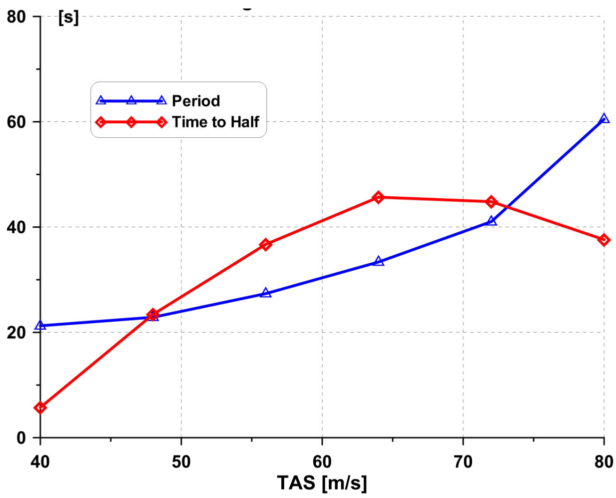

Figure 13: Phugoid characteristics: period and time to half damping

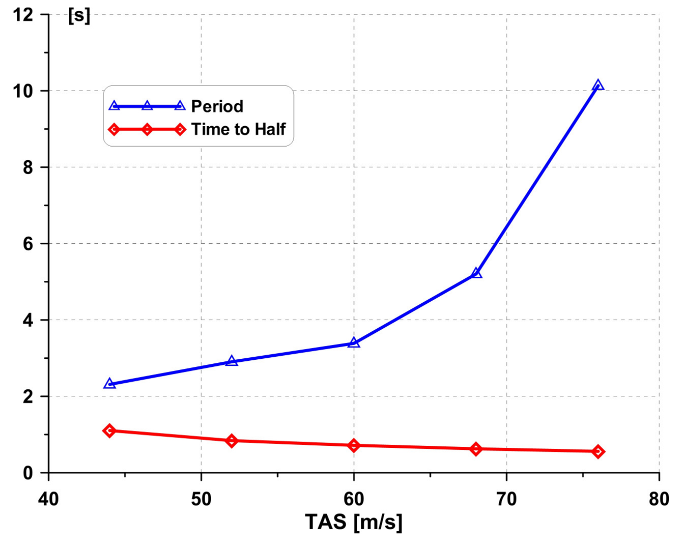

Figure 14: Short period characteristics: period and time to half damping

3.1.2 Lateral modes

The original design has not any vertical stabilizer, which causes, that lateral derivatives with respect sideslip angle show, that configuration could be not stable. Especially derivative of yawing moment with respect to sideslip angle is strongly negative, which is not good from stability point of view. Two tilt-rotors mounted on the wing tips could improve lateral characteristics, however flight should be stable also in case of engine are off (e.g. engines failure).

Figure 15 presents lateral eigenvalues, imaginary part versus real one. The results are interesting and not typical. In a range of airspeeds (Figure 16), there are two periodic modes – Dutch roll and so called Roll-Spiral, in other all modes are uncoupled.

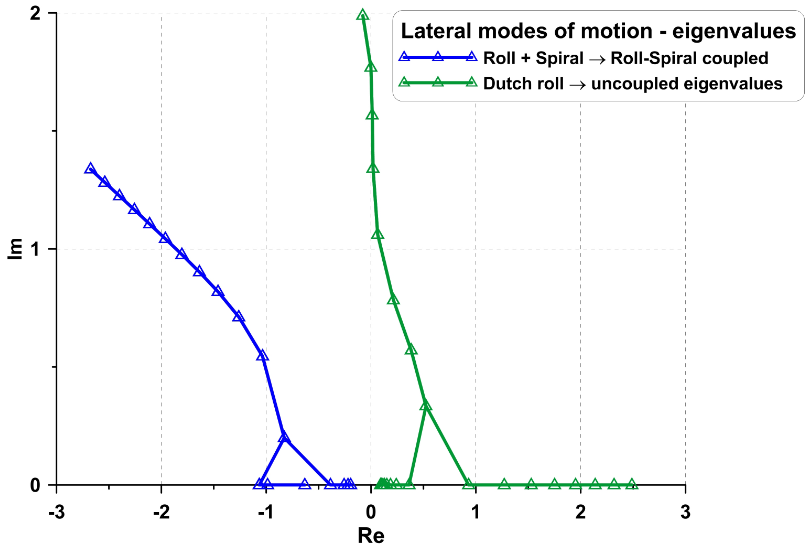

Figure 15: Lateral modes –eigenvalues

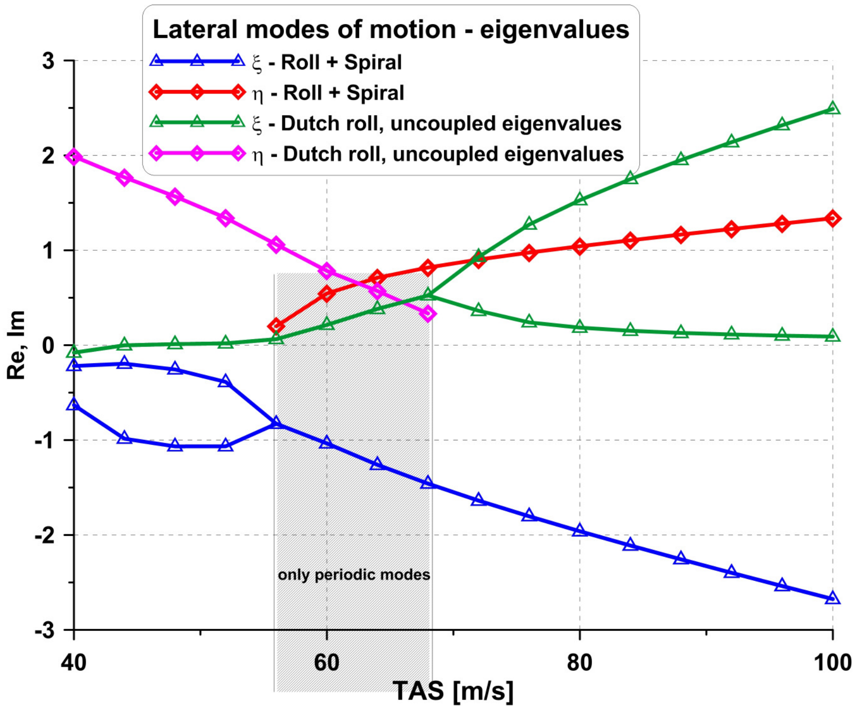

Figure 16: Lateral modes – real and imaginary parts of eigenvalues

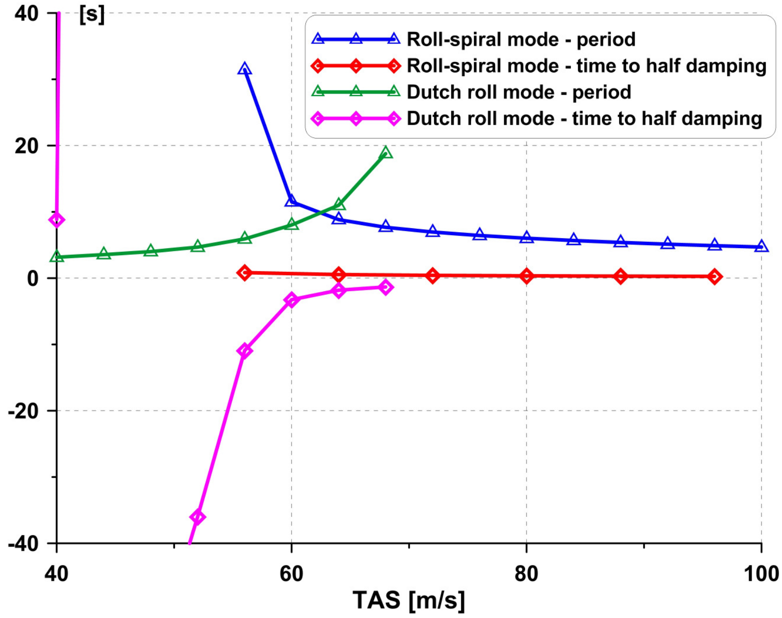

Figure 17: Lateral periodical modes – period and time to half damping

Unfortunately the lateral characteristics are not good. Dutch roll is not well damped and in some extend even unstable (Figure 17). The Roll-spiral mode is also very poorly damped. These results show, that some improvements had to be made to satisfy stability criteria for lateral modes of motion.

3.2 Improvements

The results of stability analysis of the original design showed that configuration has to be improved. The longitudinal modes of motion should be better damped, while lateral modes, especially Dutch roll, must be stabilized at all. The longitudinal characteristics were improved by control system – simply Stability Augmentation System (SAS). The lateral modes were improved by additional vertical stabilizer.

3.2.1 Improvement of flying qualities by control system

The longitudinal modes of motion, especially short period mode needed to be improved. It was assumed, that SAS will be applied to increase damping. First tests carried out in the SDSA have confirmed that this approach should be effective. Figures 18 & 19 present the results of stability analysis performed for both configurations: with and without SASA system. Presented figures of merit show, that the pilot rating for aircraft with SAS is significantly better and quite satisfied.

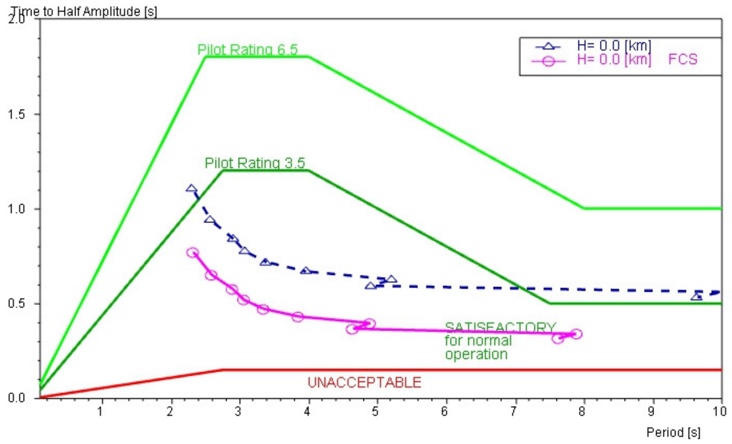

Figure 18: Short period characteristics:
ICAO based figure of merit – time to half damping versus period – without and with SAS system

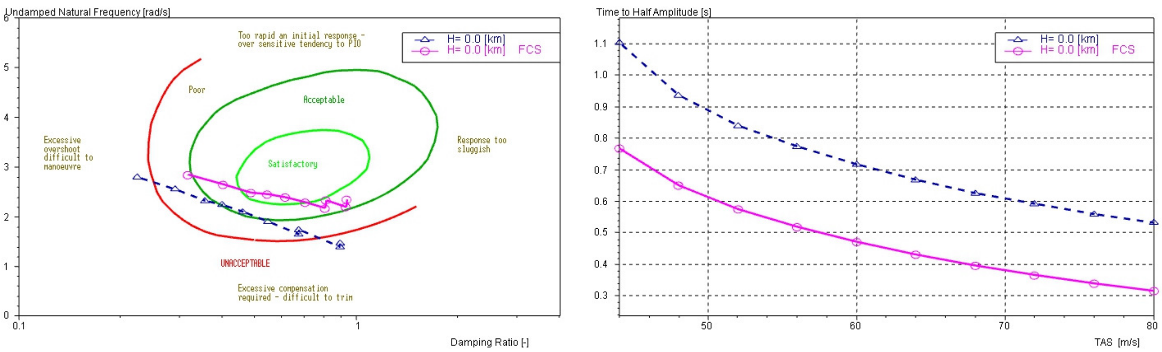

Figure 19: Short period characteristics:
ESDU based figure of merit and time to half damping – without and with SAS system

3.2.2 Improvement by geometry modification

The original design was strongly unstable configuration, which was described before. The addition of the vertical stabilizer improved lateral characteristics to satisfied level. Figure 20 presents eigenvalues of lateral modes of motion (real and imaginary part). It shows, that all modes are stable, however still in some range two periodical modes are present. Figure 21 presents period and time to half damping for both periodical modes of motion.

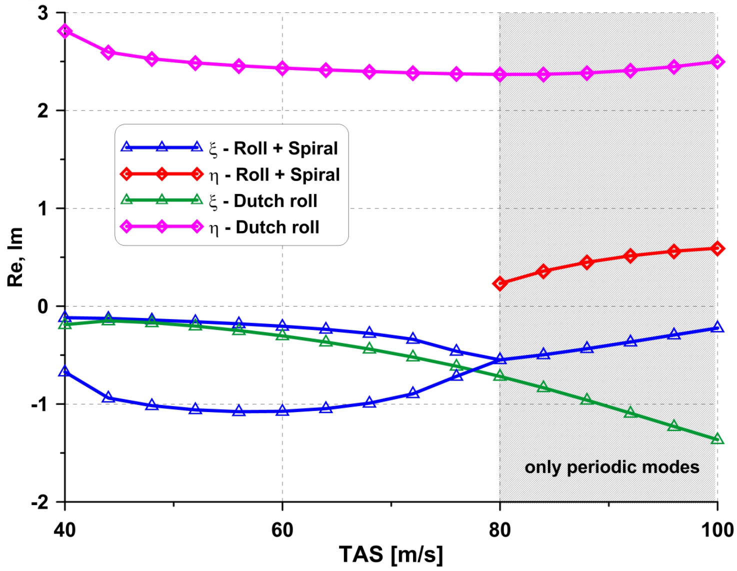

Figure 20: Lateral modes – real and imaginary parts of eigenvalues

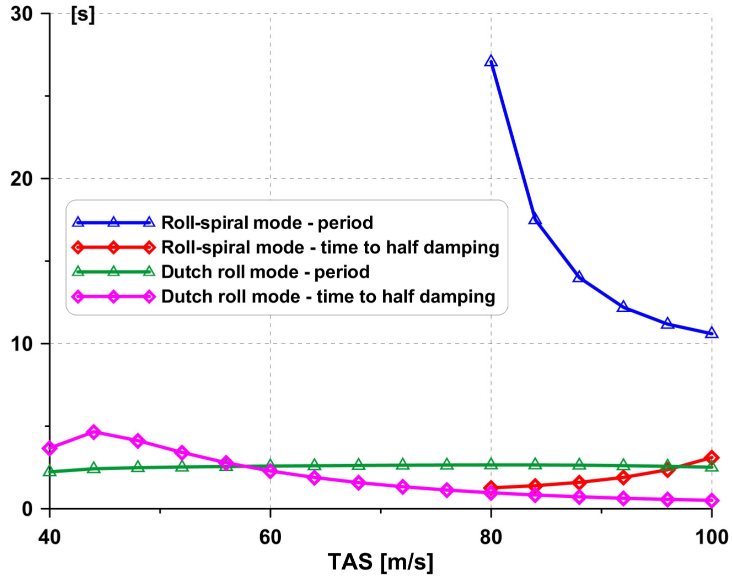

Figure 21: Lateral periodical modes – period and time to half damping

Figure 22 presets Dutch roll characteristics against background of figures of merit based on CS-23 regulation and MIL-F-8785C criteria. Also MIL criteria was used to rate Roll-spiral mode - Figure 23. The rating of both lateral modes (especially Dutch-roll) is high (1st level), however Spiral-roll for higher airspeed a little worse.

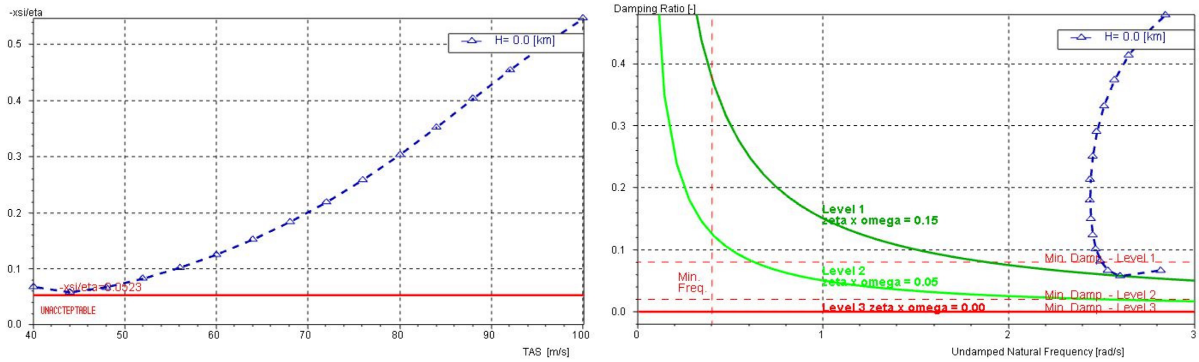

Figure 22: Dutch roll mode –figures of merit based on: CS-23 (left) and MIL-F-8785C (right) criteria

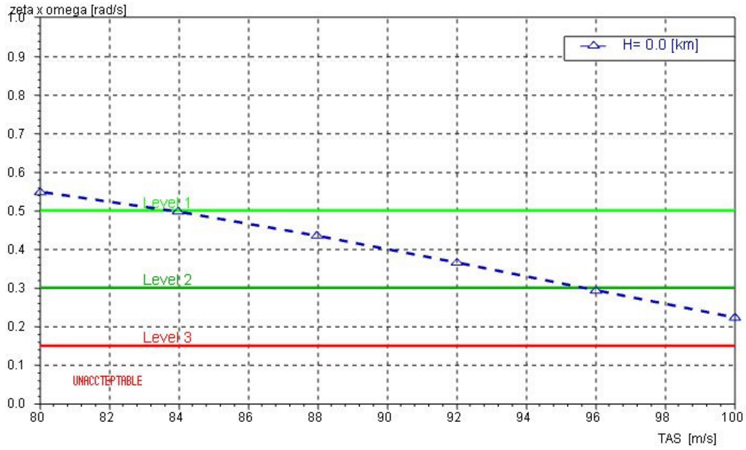

Figure 23: Roll-spiral mode –figure of merit based on MIL-F-8785C criteria

Figure 24 presents desktop simulator embedded in SDSA during simulation of lateral modes of presented aircraft. Figure 25 presents results of the simulation. The initial equilibrium state was disturbed by initial sideslip angle. Presented graph shows strongly damped Dutch roll and after that, visible long period Spiral-roll mode.

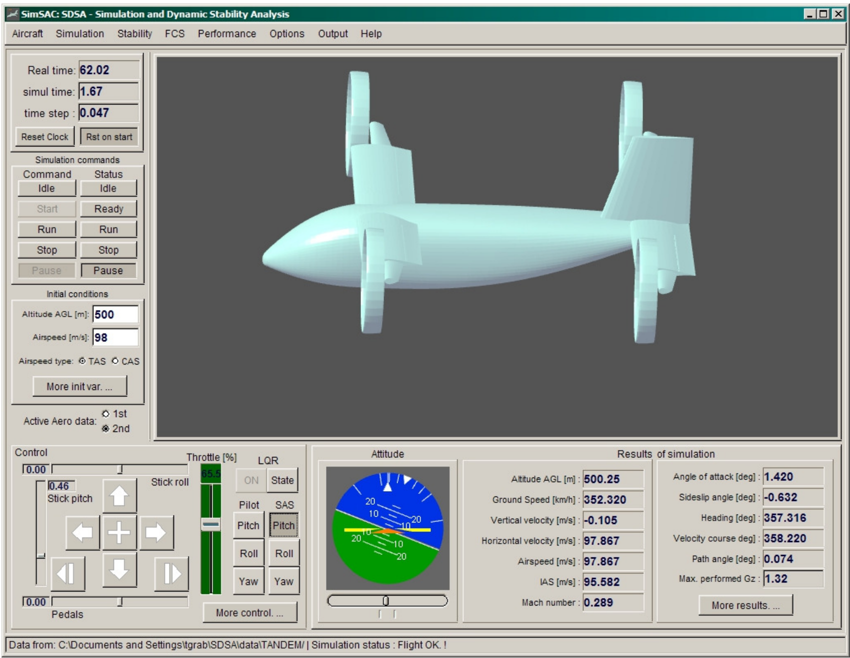

Figure 24: Flight simulation of analyzed aircraft

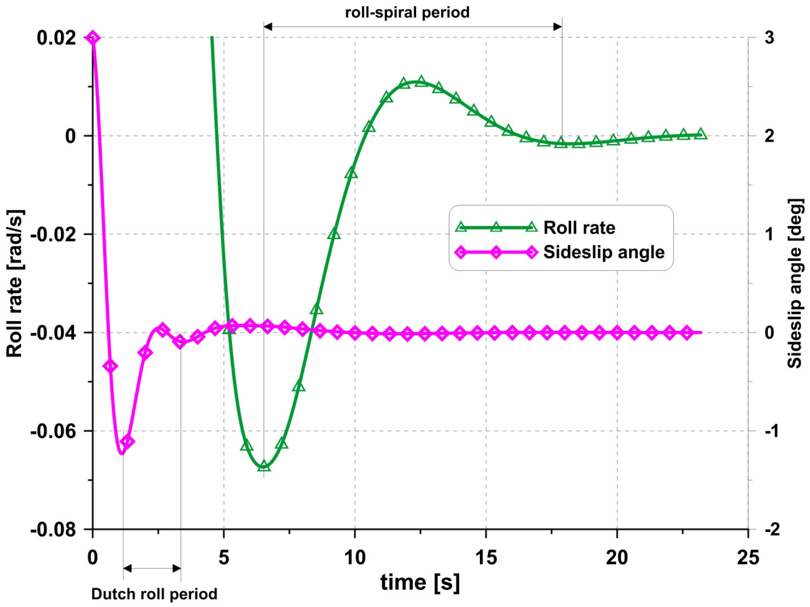

Figure 25: Flight simulation results of lateral oscillations

4 Concluding remarks

The results of aerodynamic analysis show that the presented configuration is very interesting. It is a promising concept, but the results of stability analysis indicate the possibility of having certain problems in flying qualities area. The unconventional configuration gives unconventional behavior, for example two lateral periodic modes. Some modification, made as result of stability analysis, gave quite good improvement of stability characteristics. The sufficient flight control system should be a good solution to obtain well rated pilot opinion.

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