

Flight Dynamics of Unconventional Configurations

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ABSTRACT

Unconventional configuration aircraft are not often designed due to many problems, mainly with stability and trim. However, they could be very promising and these problems can be compensated by extraordinary performance characteristics. Therefore, despite the difficulties in the design process, they are chosen, giving a chance to design and build a truly competitive aircraft. Paper presents the analysis of flying qualities of most often used unconventional configurations: canard, flying wing, three surface tandem wing and box wing. The stability analysis is presented in terms of basic static stability and full 6 DoF dynamic analysis. The flying qualities based on airworthiness regulation and MIL specification are presented and commented. Examples of results related to real projects realized during the last decade are presented and discussed.

1. Introduction

Designing a new aircraft is always a challenge, especially when considering an unconventional configuration [1]. Unconventional configuration is usually the cause of many problems, however it can be very promising due to its remarkable properties - low drag, high performance etc. Nowadays methods of design and analysis allow to build the aircraft retaining the main advantages of unconventional configurations without causing typical problems. However, the flight dynamics characteristics are fundamental from the point of view of the pilot and potential customer and must be tested at the conceptual stage of the project [2]. The article presents an analysis of stability of unconventional configurations, with particular emphasis on dynamic stability and differences in comparison with a conventional configuration.

Conventional configuration is usually understood as a wing and tail plane arrangement, in which the tail plane is located behind the main wing. Unconventional configurations are different varieties of wings arrangements, in which one is the main wing and the other (if any) are designed to support the total lift force and to satisfy trim conditions [3]. The following configurations are presented in the paper:

- flying wing - only one wing, no extra wing to trim the aircraft,
- canard configuration - small(er) wing in front of the main wing,
- tandem wing - similar to canard but the size of the front wing comparable with the main wing,
- three surface - combination of canard and conventional configuration.
- box wing - two wings shifted as in tandem-wing, but joined by tips

1.1. Flying wing

The flying wing configuration is the most clean from an aerodynamic point of view. It does not have the sources of aerodynamic drag typical for conventional aircraft. The lack of fuselage and tail causes the so-called wetted area ratio to be the smallest in comparison to other layouts, which additionally reduces friction drag. Therefore, there were many attempts to build an aircraft in such a configuration. The most famous designers of flying wings in the history of aviation were Jack Northrop (Fig.1) and brothers Horten (Fig.2). Their aircraft however were not in serial production, only some prototypes and small number series were manufactured. In the next decades there were some attempts to design and build new gliders and aircraft in flying wing configurations, however without commercial success. The problems with stability and trim, high sensitivity on balance caused that the potential advantages were dramatically decreased, not giving the expected results. Currently only one aircraft (Northrop Grumman B2 Spirit - Stealth Bomber) built in flying wing configuration, probably the most costly in the aviation history, is in service. However, the configuration is still

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Figure 1: Northrop YB-49 (1947)

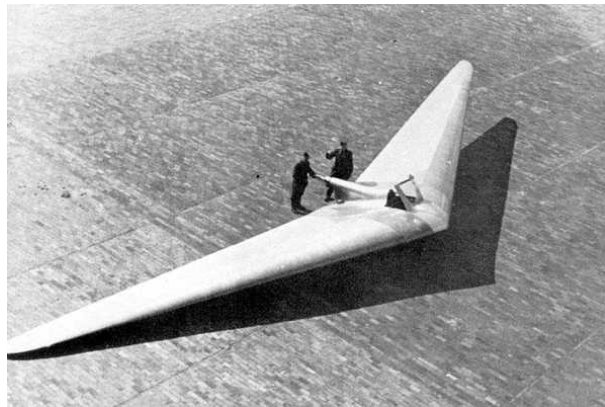


Figure 2: Horten - Ho IIIe (1944)

tested, particularly for such purposes as aircraft of reduced radar signature [4] or special mission UAVs [5, 6]. The configuration also becomes more popular in case of small UAVs [7], including Mars mission vehicles [8] and its flying qualities are under study [9, 10] taking into account lateral characteristics [11, 12].

1.2. Canard configuration

The first aircraft in aviation history - Brother Wright Flyer (1903) was built in canard configuration (Fig.3). The small wings (in biplane form) were located in front of the main wings. Such a configuration satisfied the controllability which was a key problem for the first airplanes, but caused the stability problems that resulted in an accident on the fourth flight. The main advantage of canard configuration is the fact that this small front wing (canard) gives extra aerodynamic lift force compared to the conventional layout. This was a reason why many designers tried to build new airplanes in canard configuration despite potential problems with stability. There are some examples of such attempts made during WWII: SAI-Ambrosini "S.S.4" (1939), Curtiss-Wright XP-55 Ascender (1943), Kyushu J7W1 Shinden (1945), but none of them lived up to expectations. Over the next decades, attempts were made to build canard planes, mostly general aviation aircraft or small planes, even home-built, the best known being those designed by Burt Rutan (Fig.4). It is worth adding that the success was the result of in-depth research, including experimental one in a wind tunnel [13], where various configurations of the lifting surfaces were tested. Currently, the canard configuration is often considered as promising for small business aircraft, including supersonic aircraft [14, 15].

1.3. Tandem wing

The concept of the Tandem wing configuration is derived from canard configuration but the proportion of areas of both wings is different. While in case of canard configuration front wing is rather small and only supports satisfying the equilibrium condition, while giving positive lift force, in case of tandem wing the front wing area is quite big and



Figure 3: Brothers Wright Flyer (1903)



Figure 4: Burt Rutan's VariEze(1975)



Figure 5: Miles Liebellula M.35 (1942)

comparable to the main wing, reaching even equal value, taking an essential role in the lift force generation. A very big enthusiast of tandem wing was British designer George Herbert Miles [16, 17]. Only few tandem wing aircraft (Fig.5) designed by Miles were built, however they were not well received by pilots, due to serious problems with flying qualities.

Also, nowadays this configuration is of interest to aircraft designers and researchers [18, 19, 20] but only a few of them finished with success. A good example of tandem wing configuration aircraft is Quickie by B.Rutan (Fig.6). However, the most successful tandem wing configuration aircraft ever built is Rutan's Model 133 ATTT [21] (Fig.7). The idea was born in 1987, initiated and supported by DARPA (Defense Advanced Research Projects Agency). It was assumed, that the maximum take-off weight (MTOW) would be equal to 25 tons (including 5 tons of payload). The computed maximum L/D ratio was about 20 and maximum lift coefficient was equal to 3.55. Only a scaled technology demonstrator (0.62) was built. The project was very promising but it was canceled due to unclear reasons.



Figure 6: Quickie Q2 (Courtesy of Scaled Composites, LLC.)



Figure 7: Model 133 ATTT (Courtesy of Scaled Composites, LLC.)

1.4. Three surfaces configuration

In the pioneering years of aviation, many aircraft were flown with both front and aft support surfaces. The issue of horizontal stability was poorly understood and usually the pitch control was realized by the front surface. The rear surface also gave positive lift force which resulted in longitudinal instability, similarly as in case of canard configuration. Nowadays three surfaces configuration is a chance to join the canard advantages with conventional aircraft, which can give extra lift force without, usual for canard configuration, problem with instability [22]. It requires a thoughtful fuselage arrangement and weight distribution however, to be able to benefit from the advantages of this configuration. The configuration is still of interest to engineers and researchers as it has the potential to obtain very good results by optimizing the front and rear horizontal surfaces [23] and could be widely used in passenger airliners [24]. A successful example of such layout is P.180 Avanti (Fig.8).

1.5. Box wing

Box wing or Joined wing was suggested by Ludwig Prandtl as a wing that under certain conditions, might provide the minimum induced drag for a given lift and wingspan. Therefore it was designed as two offset wings joined by vertical surfaces on the wing tip (Fig.9). Sometimes it is defined as "an airplane that incorporates tandem wings arranged to form diamond shapes in both plan and front views" [25]. Despite the potential advantages, the configuration was not met with wide recognition among engineers and aircraft manufacturers, however it is still a subject of research and study [26, 27, 28]. The comprehensive review of ideas related to this configuration is presented in [29]. Recently so-called inverted joined wing is also a subject of investigation. In this layout the front wing is on the top and the rear wing is at the bottom, which is an interesting take on the box wing [30, 31]. Generally, box wing layout combines the potential advantages of minimizing induced drag with the stability problems typical for canard or tandem wing



Figure 8: P.180 Avanti - Three Surfaces aircraft



Figure 9: Joined wing demonstrator – MOSUPS [31]

configuration.

2. Static stability

The basic factor that characterizes longitudinal stability is static margin. It is defined as the distance between neutral point and center of gravity. The neutral point of stability can be defined as the point which satisfies the condition, that pitching moment coefficient is constant versus angle of attack or lift coefficient:

$$\frac{\partial C_{m,N}}{\partial C_z} = 0 \quad (1)$$

Fig.10 presents the simplified scheme of the forces acting on the aircraft. Notice, that the aerodynamic forces and moment of forces shown in Fig.10 do not present the physical direction but the positive direction according the assumed convention, where positive force is directed up and pitching moment is positive when nose is going up. The equilibrium state is determined by pitching moment equation:

$$\Sigma M_{CG} = M_Y - P_Z x_{CG} - P_{ZH}(x_H + x_{CG}) = 0 \quad (2)$$

After extension it will have the following form:

$$\Sigma M_{CG} = \frac{1}{2} \rho S V^2 C_a \left(C_{m(W+B)} - C_z \frac{x_{CG}}{C_a} - \frac{S_H}{S} \frac{V_H^2}{V^2} C_{zH} \frac{x_H + x_{CG}}{C_a} \right) = 0 \quad (3)$$

Dimensionless coefficients of the lift force acting on the main wing and horizontal tail can be written as follows:

$$C_Z = a(\alpha - \alpha_0) \quad \text{where:} \quad a = \frac{\partial C_z}{\partial \alpha} \quad (4)$$

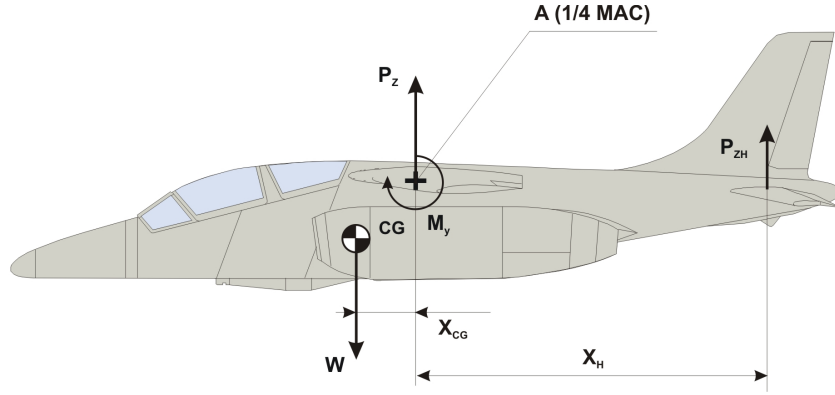


Figure 10: The longitudinal equilibrium - simplified forces scheme (conventional configuration)

$$C_{ZH} = a_1 \alpha_H + a_2 \delta_H + a_3 \delta_T \quad (5)$$

where:

δ_H – elevator deflection,

δ_T – deflection of elevator servo tab,

a_1, a_2, a_3 – derivatives of the lift force coefficient with respect to: angle of attack, elevator deflection, tab deflection (accordingly).

Differentiating both sides of equation (3) with respect to the lift coefficient the following relation is derived:

$$\frac{\partial C_{M_{CG}}}{\partial C_z} = \frac{\partial C_{m(W+B)}}{\partial C_z} - \frac{x_{CG}}{C_a} - \frac{S_H}{S} \frac{V_H^2}{V^2} \frac{x_H + x_{CG}}{C_a} \frac{\partial C_{zH}}{\partial C_z} \quad (6)$$

Assuming that the stick is fixed, only the first component of formula (5) depends on lift coefficient and it can be written as follows:

$$a_1 \alpha_H = a_1 (\alpha - \epsilon) = a_1 \left(\alpha - \frac{\partial \epsilon}{\partial \alpha} \alpha - \epsilon_0 \right) = a_1 \left(1 - \frac{\partial \epsilon}{\partial \alpha} \right) \alpha - a_1 \epsilon_0 \quad (7)$$

Therefore derivative of lift coefficient on the tail has the form:

$$\frac{\partial C_{zH}}{\partial C_z} = \frac{\frac{\partial C_{zH}}{\partial \alpha}}{\frac{\partial C_z}{\partial \alpha}} = \frac{a_1}{a} \left(1 - \frac{\partial \epsilon}{\partial \alpha} \right) \quad (8)$$

Assuming that center of gravity is the neutral point of stability ($X_{CG} = X_N$), pitching moment derivative from equation (6) is equal to zero. Additionally taking relation (8) the position of the neutral point of stability can be derived in the form:

$$\bar{X}_N = \frac{X_N}{C_a} = \frac{\frac{\partial C_{m(W+B)}}{\partial C_z} - \frac{S_H}{S} \frac{V_H^2}{V^2} \frac{x_H}{C_a} \frac{a_1}{a} \left(1 - \frac{\partial \epsilon}{\partial \alpha} \right)}{1 + \frac{S_H}{S} \frac{V_H^2}{V^2} \frac{a_1}{a} \left(1 - \frac{\partial \epsilon}{\partial \alpha} \right)} \quad (9)$$

The positive value of $\bar{X}_N$ denotes that neutral point is located in front of the center of gravity, which results in the aircraft being not stable. The second component of numerator has a crucial role to satisfy sufficient value of static margin and depends on the horizontal tail characteristics, where the horizontal tail volume and lift derivative of the horizontal tail with respect to angle of attack play the most significant role (Fig.11). This second term takes a different form in case of unconventional configurations. The value of the first term is pitching moment derivative of wing-body configuration, which depends mainly on the fuselage and has positive value. The value of denominator is usually close to one and doesn't have a big role in the analysis.

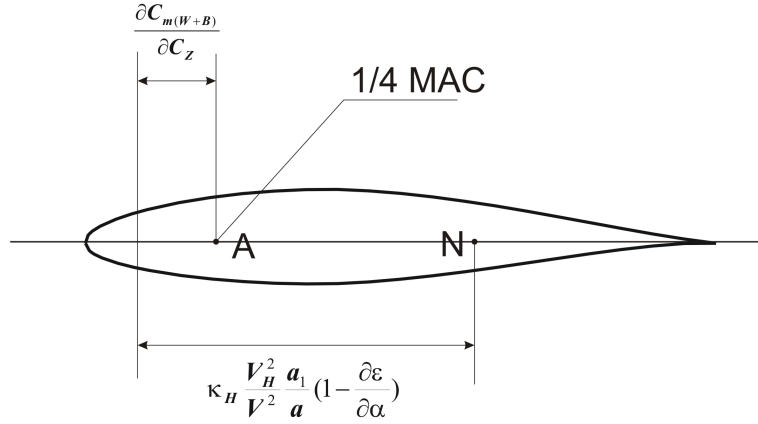


Figure 11: The role of basic terms of equation (9) for neutral point position

2.1. Flying wing

The neutral point position in case of a flying wing configuration depends only on wing and fuselage, if it exists. Therefore, the equation (9) reduces to one term, that represents derivative of pitching moment coefficient of wing and fuselage with respect to lift coefficient. This usually forces a swept wing with stable reflexed airfoil, which is not very effective from aerodynamic point of view. Moreover, the range of possible CG positions is very limited due to the fact that the stability requirement (front CG position) is contradict to equilibrium needs (aft CG position).

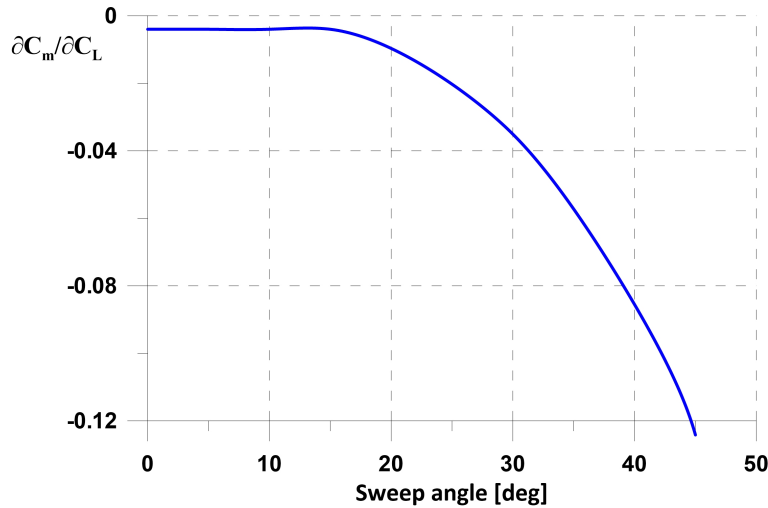


Figure 12: Pitching moment derivative with respect to lift coefficient versus sweep angle
- separate wing AR=13.3, taper ratio 0.5

Figure 12 presents pitching moment coefficient derivative with respect to lift coefficient versus sweep angle. Pitching moment is given with respect to the point of 1/4 of MAC (Mean Aerodynamic Chord). The presented graph shows that neutral point of stability moves backwards for higher values of sweep angle (computed using 3D panel method [32, 33]), which suggests to increase it. However, higher sweep angle also causes negative effects, reducing the lift force and causing some structural problems.

Even a big wing sweep cannot prevent an additional reduction of the lift force caused by control forces. Classical airfoils give a negative pitching moment, which implies the need to balance the moment by elevator. While in the classical configuration forces at the elevator act on a large arm, in case of flying wing, the arm of elevator, most often in the form of elevons, is limited by the wing sweep. Therefore, so-called reflexed airfoils were often applied in such

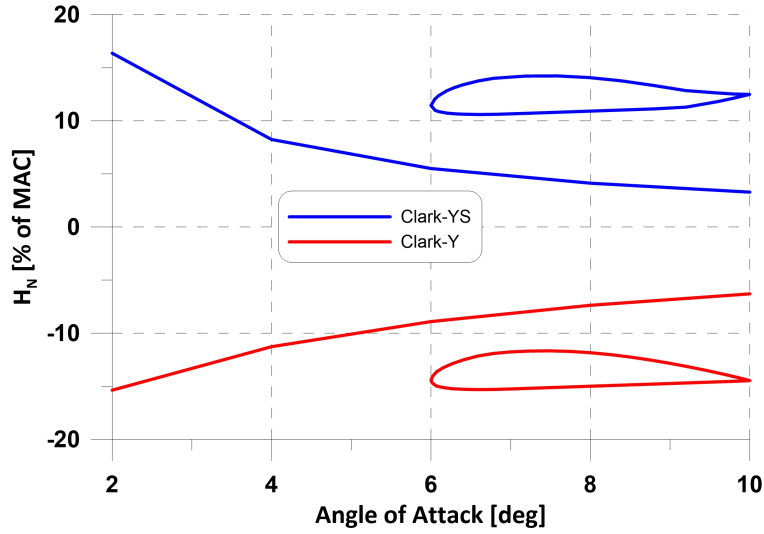


Figure 13: The distance between aerodynamic center and center of pressure [% of MAC]

configuration. Figure 13 presents the distance between aerodynamic center and center of pressure for classical airfoil Clark-Y and its reflexed equivalent Clark-YS. The graph shows that if CG is placed in pressure center, the static margin is positive in case of reflexed airfoil and negative otherwise. This indicates that the use of reflexed profiles is reasonable, however not ideal as their aerodynamic efficiency is usually worse than the non-reflexed equivalent.

2.2. Canard configuration

The analysis of canard configuration is similar to the general analysis presented at the beginning of this chapter and is also nicely presented by Gudmundsson [34] in the Appendix. The main difference is that canard is in the clean flow and the flow on the main wing is disturbed by downwash from the canard, while in the conventional configuration main wing is in the undisturbed flow and horizontal stabilizer is in main wing downwash. Therefore Eq. (2) takes a form (10).

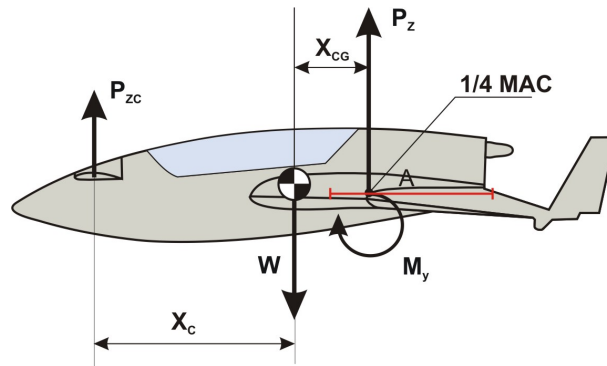


Figure 14: Canard configuration equilibrium - simplified forces scheme

$$\Sigma M_{CG} = M_Y - P_Z x_{CG} - P_{ZC} x_C = 0 \quad (10)$$

After extension it will have the following form:

$$\Sigma M_{CG} = \frac{1}{2} \rho S V^2 C_a \left(\frac{V_W^2}{V^2} C_{m(W+B)} - \frac{V_W^2}{V^2} C_z \frac{x_{CG}}{C_a} - \frac{S_C}{S} C_{ZC} \frac{x_C}{C_a} \right) = 0 \quad (11)$$

Dimensionless coefficients of the lift force acting on the main wing and horizontal tail take the following form in this case:

$$C_Z = a(1 - \frac{\partial \epsilon}{\partial \alpha}) \alpha, \quad C_{ZC} = a_1 \alpha + a_2 \delta_C + a_3 \delta_T \quad (12)$$

Equation (11) can be transformed to a form similar to that of a conventional configuration (9) in order to obtain the position of the neutral point:

$$\bar{X}_N = \frac{X_N}{C_a} = - \frac{\frac{\partial C_{m(W+B)}}{\partial C_z} + \frac{S_C x_C}{S C_a} \frac{a_1}{a(1 - \frac{\partial \epsilon}{\partial \alpha})}}{\frac{V_W^2}{V^2} + \frac{S_C}{S} \frac{a_1}{a(1 - \frac{\partial \epsilon}{\partial \alpha})}} \quad (13)$$

The meaning of particular terms of Eq. (9) is clarified in Fig. 15.

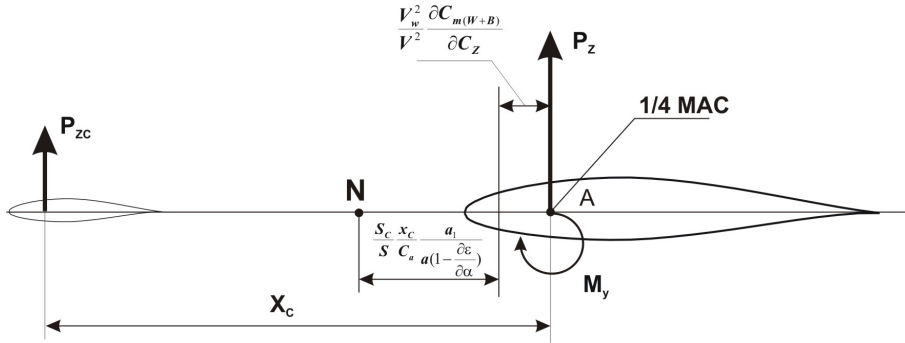


Figure 15: Canard configuration - neutral point position

The presented relations show that there is a fundamental contradiction between balance and stability. Due to the significant forward shift of the neutral point, the center of gravity must be located even further forward. Strongly forward position of the gravity center forces greater lift force acting on the canard to satisfy trim condition which in turn leads to increased area of canard and then, in consequence to an even greater forward shift of the neutral point and the transformation of the canard configuration into a tandem wing. Therefore, selection of the correct proportions of the lifting areas and their aerodynamic characteristics is essential to the success of the canard configuration airplane design.

The analysis for tandem-wing or box-wing configurations is similar to that presented above. A nice comparison of different two surfaces configurations is presented by McGeer and Kroo in [35] and they noted the high value of the optimization approach in designing unconventional configurations [36].

2.3. Three surfaces configuration

Three Surfaces Aircraft (TSA - Fig.16) is a kind of compromise between conventional layout and canard configuration [37]. The presence of a small but effective canard supports the trim and causes that negative force on the horizontal tail is significantly reduced without resorting to extreme relaxation of static longitudinal stability [38], so it might seem that it is an ideal configuration. Unfortunately, this is not the case and the designer must very precisely select both the lifting areas and the fuselage layout, focusing on the weights breakdown. An example of such problems is nicely described by T. Antoniewski [39], where the arrangement of four seats, luggage, landing gear and the whole structure resulted in such configuration design.

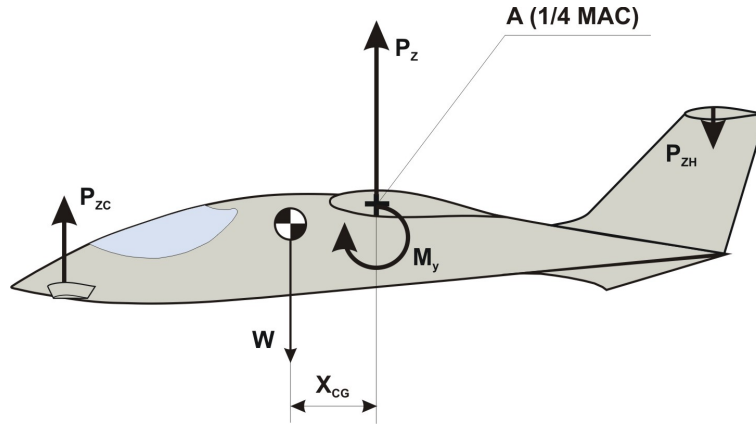


Figure 16: TSA configuration equilibrium - simplified forces scheme

2.4. Lateral stability

Static stability considerations would not be complete without at least a concise lateral stability analysis. The static lateral stability is characterized by two quantities: derivative of the yawing moment with respect to sideslip and derivative of the rolling moment with respect to sideslip. The first one is more important and is responsible for directional stability. Generally, it must have positive sign and depends on vertical stabilizer area, fuselage side area, fuselage's position relative to the wing and wing sweep angle. In case of a conventional configuration, the vertical tail usually plays a dominant role in meeting this requirement. For unconventional configurations there are different solutions depending on specific design. In case of flying wing usually the sufficient sweep angle plays the most important role. Sometimes the small vertical surfaces mounted on the trailing edge support directional stability (Fig.1). The most interesting however, are strongly coupled configurations, where the downwash from the front wing (canard, tandem, boxwing) causes unsymmetrical load distribution on the main wing (Fig.17). This asymmetry, in turn, results in a rolling moment that increases sideslip, which may cause lateral instability.

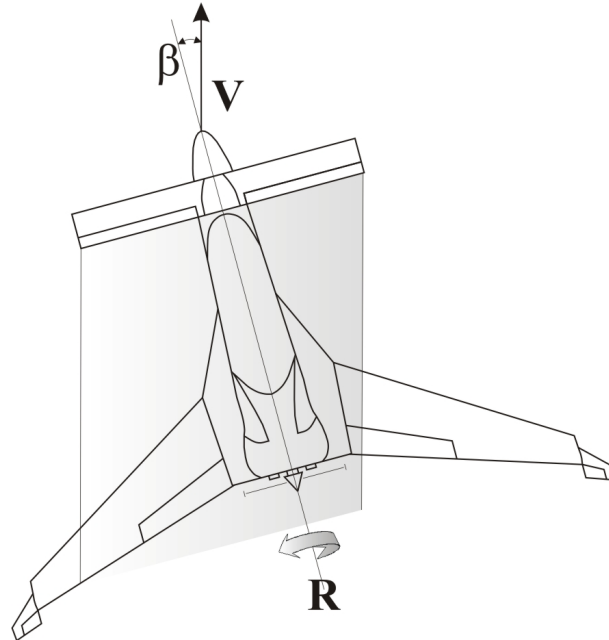


Figure 17: Canard configuration in side flow

3. Dynamic stability

The dynamic stability of an aircraft is represented by five typical modes of motion. Usually there are two longitudinal periodic modes (phugoid, short period) and three lateral modes (periodic Dutch roll and non-periodic spiral and roll). However, in case of unconventional configuration, some typical modes can change form and typically periodic mode can be decoupled while non-periodic modes can be coupled and become a new periodic mode. Relatively often such an effect is noted in case of lateral modes, when roll and spiral couple in one roll-spiral mode.

The dynamic analysis of an aircraft must be preceded by the definition of a physical and mathematical model that is well described in many books and papers on flight dynamics [40, 41, 42, 43, 44, 45]. A brief summary of the physical and mathematical models is provided below.

3.1. Physical Model

The physical model of an aircraft for motion analysis, especially for flight simulation and stability analysis, is based on the following assumptions:

- aircraft is a rigid body with six degrees of freedom:
- 3 translations along the axis - x, y, z
- 3 rotations - pitch, roll, yaw,
- control surfaces are movable but can not perform free vibrations,
- aerodynamics are quasi-steady,
- atmosphere is not disturbed and windless - atmosphere is conformable with standard atmosphere.

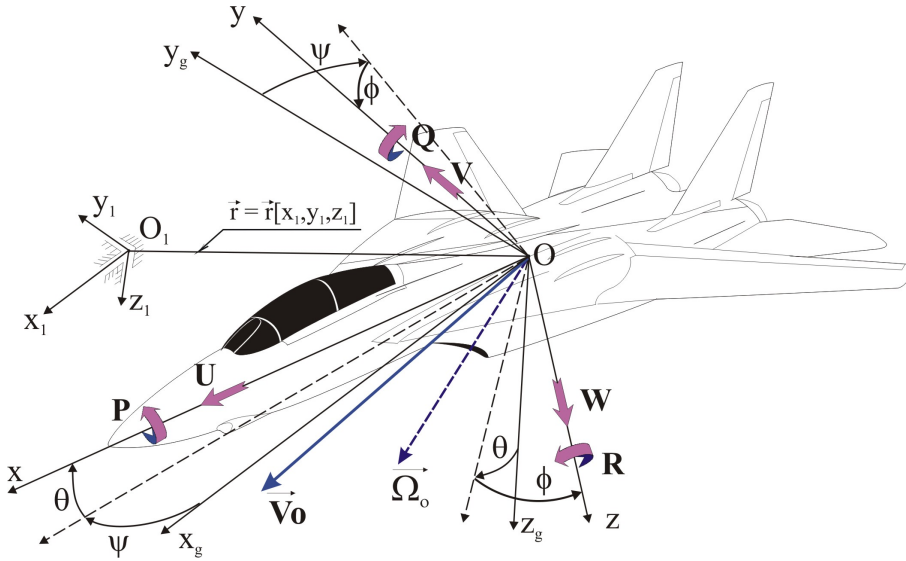


Figure 18: Coordinate systems used to describe the position and the attitude of an aircraft

3.2. Coordinate systems and Kinematic Relations

To describe the motion of an aircraft, the following coordinate systems are necessary (Fig.18):

- fixed gravity coordinate system $(O_1x_1y_1z_1)$,
- movable coordinate system $(Ogxgygzg)$ parallel to the gravity coordinate system; the origin of this system is placed usually in point defined by 1/4 of MAC,
- body axis system; the origin of this system is the same as in the previous one; axis Ox is parallel to the MAC and pointed forward, axis Oz is pointed down, and axis Oy is pointed to the right wing. Transformation from the $Ogxgygzg$ axis system to the body axis system is defined by three rotations performed in the following order:
 - rotation around the Ozg axis - yaw angle ψ ,
 - rotation around the new Oy axis (after yaw rotation) - pitch angle θ ,
 - rotation around the new Ox axis (after yaw and pitch rotation) - roll angle ϕ .

The components of main velocity vector V_O (U,V,W) and main angular velocity vector Ω (P,Q,R) are defined in the body axis system (Fig.18).

Such defined axis systems facilitate to formulate indispensable kinematic relations. Equation (14) presents the relation between coordinates of the gravity inertial system and linear velocities defined in the body axis system.

$$\begin{bmatrix} \dot{x}_1 \\ \dot{y}_1 \\ \dot{z}_1 \end{bmatrix} = A_V \begin{bmatrix} U \\ V \\ W \end{bmatrix} \quad (14)$$

where transformation matrix A_V has the following form:

$$A_V = \begin{bmatrix} \cos \theta \cos \psi & \cos \psi \sin \theta \sin \phi - \cos \phi \sin \psi & \sin \theta \cos \phi \cos \psi + \sin \phi \sin \psi \\ \cos \theta \sin \psi & \sin \psi \sin \theta \sin \phi + \cos \phi \cos \psi & \sin \theta \cos \phi \sin \psi - \sin \phi \cos \psi \\ -\sin \theta & \sin \phi \cos \theta & \cos \phi \cos \theta \end{bmatrix} \quad (15)$$

Equation (14) presents relation between the quasi-Euler angles and angular velocities:

$$\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = A_\Omega \begin{bmatrix} P \\ Q \\ R \end{bmatrix} \quad (16)$$

where

$$A_\Omega = \begin{bmatrix} 1 & \sin \phi \tan \theta & \cos \phi \tan \theta \\ 0 & \cos \phi & -\sin \phi \\ 0 & \sin \phi / \cos \theta & \cos \phi / \cos \theta \end{bmatrix} \quad (17)$$

3.3. Mathematical model of an aircraft motion

Dynamic equations of motion are derived from fundamental laws of mechanics: the balance of momentum theorem and the balance of the angular momentum theorem:

$$\frac{\partial \bar{\Pi}}{\partial t} + \bar{\Omega} \times \bar{\Pi} = \bar{F} \quad (18)$$

$$\frac{\partial \bar{H}_0}{\partial t} + \bar{\Omega} \times \bar{H}_0 + \bar{V}_0 \times \bar{\Pi} = \bar{M}_0 \quad (19)$$

Expressions on the right side of Eq. (18) and (19) represent the generalized forces acting on the airplane, including aerodynamic loads, gravity, forces from control, propulsion, landing gear, etc. Usually, aerodynamic, gravity, control and propulsion forces are taken into account for the stability analysis, with the first two playing the dominant role. The mathematical model of the aerodynamics, assumed for stability analysis is quasi-steady aerodynamics. Therefore, aerodynamic forces can be expanded into the infinite Taylor series [43]. Such a form is not convenient for the analysis. Fortunately, almost all terms of higher order are not significant, so only primary aerodynamic derivatives are important with the exception of derivatives of vertical and side components of acceleration. Then the generalized aerodynamic forces $F_a = \{X_a, Y_a, Z_a, L_a, M_a, N_a\}$ have the following form:

$$\begin{aligned} X_a &= X_{ae} + \frac{\partial X}{\partial u}u + \frac{\partial X}{\partial v}v + \frac{\partial X}{\partial w}w + \frac{\partial X}{\partial p}p + \frac{\partial X}{\partial q}q + \frac{\partial X}{\partial r}r + \frac{\partial X}{\partial \dot{u}}\dot{u} + \frac{\partial X}{\partial \dot{v}}\dot{v} + \frac{\partial X}{\partial \dot{w}}\dot{w} \\ Y_a &= Y_{ae} + \frac{\partial Y}{\partial u}u + \frac{\partial Y}{\partial v}v + \frac{\partial Y}{\partial w}w + \frac{\partial Y}{\partial p}p + \frac{\partial Y}{\partial q}q + \frac{\partial Y}{\partial r}r + \frac{\partial Y}{\partial \dot{u}}\dot{u} + \frac{\partial Y}{\partial \dot{v}}\dot{v} + \frac{\partial Y}{\partial \dot{w}}\dot{w} \\ &\dots \\ M_a &= M_{ae} + \frac{\partial M}{\partial u}u + \frac{\partial M}{\partial v}v + \frac{\partial M}{\partial w}w + \frac{\partial M}{\partial p}p + \frac{\partial M}{\partial q}q + \frac{\partial M}{\partial r}r + \frac{\partial M}{\partial \dot{u}}\dot{u} + \frac{\partial M}{\partial \dot{v}}\dot{v} + \frac{\partial M}{\partial \dot{w}}\dot{w} \\ N_a &= N_{ae} + \frac{\partial N}{\partial u}u + \frac{\partial N}{\partial v}v + \frac{\partial N}{\partial w}w + \frac{\partial N}{\partial p}p + \frac{\partial N}{\partial q}q + \frac{\partial N}{\partial r}r + \frac{\partial N}{\partial \dot{u}}\dot{u} + \frac{\partial N}{\partial \dot{v}}\dot{v} + \frac{\partial N}{\partial \dot{w}}\dot{w} \end{aligned} \quad (20)$$

The form of equations (18) and (19) is not convenient for further analysis, therefore it should be transformed to the useful form. Taking notation shown in Fig.18 momentum and angular momentum can be written as follows:

$$\bar{\Pi} = m(\bar{V}_0 + \bar{\Omega} \times \bar{r}_c) \quad (21)$$

$$\bar{H}_0 = I_0 \bar{\Omega} + m \bar{r}_c \times \bar{V}_0 \quad (22)$$

where:

m - aircraft mass,

$\bar{r}_c$ - center of gravity in body axis system (vector),

I_0 - inertia tensor.

Taking definitions (21) & (22) the equation of motion can be written in form:

$$\frac{\partial \bar{\Pi}}{\partial t} + \bar{\Omega} \times m(\bar{V}_0 + \bar{\Omega} \times \bar{r}_c) = \bar{F} \quad (23)$$

$$\frac{\partial \bar{H}_0}{\partial t} + \bar{\Omega} \times I_0 \bar{\Omega} + m \bar{r}_c \times \bar{V}_0 + \bar{V}_0 \times m(\bar{V}_0 + \bar{\Omega} \times \bar{r}_c) = \bar{M}_0 \quad (24)$$

Equation (24) can be expanded to the form:

$$\frac{\partial \bar{H}_0}{\partial t} + \bar{\Omega} \times (I_0 \bar{\Omega}) + m \bar{\Omega} \times (\bar{r}_c \times \bar{V}_0) + m \bar{V}_0 \times \bar{V}_0 + m \bar{V}_0 \times (\bar{\Omega} \times \bar{r}_c) = \bar{M}_0 \quad (25)$$

Using the Jacobi identity it can be written as:

$$\bar{\Omega} \times (\bar{r}_c \times \bar{V}_0) + \bar{r}_c \times (\bar{V}_0 \times \bar{\Omega}) + \bar{V}_0 \times (\bar{\Omega} \times \bar{r}_c) = 0 \quad (26)$$

which simplifies equation (25):

$$\frac{\partial \bar{H}_0}{\partial t} + \bar{\Omega} \times (I_0 \bar{\Omega}) + \bar{r}_c \times m(\bar{\Omega} \times \bar{V}_0) = \bar{M}_0 \quad (27)$$

The first terms of equations (23) & (27) are the partial derivatives with respect to time while next terms represent so-called body forces which can be written as follows:

$$\bar{F}_m = - \left[\begin{array}{c} \bar{\Omega} \times m(\bar{V}_0 + \bar{\Omega} \times \bar{r}_c) \\ \bar{\Omega} \times (I_0 \bar{\Omega}) + \bar{r}_c \times m(\bar{\Omega} \times \bar{V}_0) \end{array} \right] \quad (28)$$

Taking into account the model of aerodynamic forces presented above, the equation of an aircraft motion can be written as follows:

$$\frac{ds}{dt} = A^{-1} \bar{F}(s, \dot{s}, t) \quad (29)$$

where:

s - state vector:

$$s = \{u, v, w, p, q, r\} \quad (30)$$

A - inertia matrix:

$$A = \begin{bmatrix} m - X_{\dot{u}} & -X_{\dot{v}} & -X_{\dot{w}} & 0 & S_z & -S_y \\ -Y_{\dot{u}} & m - Y_{\dot{v}} & -Y_{\dot{w}} & -S_z & 0 & S_x \\ -Z_{\dot{u}} & -Z_{\dot{v}} & m - Z_{\dot{w}} & S_y & -S_x & 0 \\ -L_{\dot{u}} & -S_z - L_{\dot{v}} & S_y - L_{\dot{w}} & J_x & -J_{xy} & -J_{xz} \\ -S_z - M_{\dot{u}} & -M_{\dot{v}} & -S_x - M_{\dot{w}} & -J_{xy} & J_y & -J_{yz} \\ -S_y - N_{\dot{u}} & S_x - N_{\dot{v}} & -N_{\dot{w}} & -J_{xz} & -J_{yz} & J_z \end{bmatrix} \quad (31)$$

For the stability analysis, state vector is extended with two attitude angles: roll and pitch. Then equation (31) is linearized to the form [46]:

$$\frac{ds_8}{dt} = A_8^{-1} \overline{F_8}(s_8, t) \implies \frac{ds_8}{dt} = J_8 s_8 \quad (32)$$

where:

$$s_8 = \{u, v, w, p, q, r, \varphi, \theta\} \quad (33)$$

$$J_8 = \left\{ \frac{\partial(A_8^{-1} \overline{F_8})_{i,j}}{\partial s_j} \right\} \quad (34)$$

The J_8 matrix - the Jacobian (34) of the right hand side of equation (2) is computed numerically. Then the eigenvalue problem can be formulated:

$$[J_8 - I\lambda]s_8 = 0 \quad (35)$$

The solution of the eigenvalue problem gives directly the frequency and damping coefficients, while solving of the eigenvector problem allows to identify the modes of motion [46].

$$\lambda = \xi + i\eta \quad (36)$$

where:

ξ - damping coefficient

η - frequency coefficient

The frequency and damping coefficients are the first measures of flying qualities, however, damping ratio and undamped natural frequency are more useful. They can be found using:

$$\omega_n = \sqrt{\xi^2 + \omega_D^2} \quad (37)$$

$$\zeta = \frac{-\xi}{\omega_n} \quad (38)$$

The period of oscillation and time of damping to the half of amplitude (or double time) can be computed as follows:

$$T = \frac{2\pi}{\eta} \quad (39)$$

$$T_{1/2} = -\ln(2)/\xi \quad \text{for } \xi < 0, \quad T_2 = \ln(2)/\xi \quad \text{for } \xi > 0 \quad (40)$$

The measures presented above can be used to assess the flying qualities. The civilian airworthiness regulations (e.g. [47]) do not give precise answer, relying on general recommendations (e.g. 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 ..."). Much more complete criteria are included in MIL-F-8785-C [48] specification, which involves linking the Cooper-Harper scale [49] with physical coefficients. Therefore MIL specification criteria are used within next considerations about flying qualities of aircraft built in unconventional configurations.

3.4. Comments to the mathematical model

The mathematical model presented above is a general model. In most cases it can be simplified. The first premise to simplify the model is geometrical and mass symmetry of most of designed aircraft, even those in unconventional configurations. Therefore, the first moment of mass (static moment) S_y is reduced to zero as well as inertia products J_{xy} and J_{yz} . The second question is related to the so-called apparent masses, i.e. stability derivatives with respect to acceleration components. Although most of these derivatives are not significant, except for derivatives with respect to $\dot{w}$, unconventional configurations force an unconventional approach, so in each case it should be carefully considered

if particular derivative may be neglected. It should be remembered that due to the different possibilities of positioning the aerodynamic surfaces (wings, stabilizers, winglets, etc.) in unconventional configurations, it is not possible to form universal rules in this respect, i.e. which derivative may be neglected and which must be considered and very popular semi-empirical methods to estimate stability [50, 51] must be considered very carefully. Generally an individual approach must be applied. On the other hand, some derivatives lose or change their meaning. Classical interpretation of derivatives with respect to $\dot{w}$ [40], i.e. a delay of downwash from main (front) wing, causing temporary increase of the horizontal stabilizer effectiveness cannot be applied to the unconventional configurations presented above. In case of flying wing such an effect does not appear at all. In case of canard or any front (but not main) wing the effect is usually significantly reduced due to the smaller area of front wing in comparison with the main one. A similar situation can be present in case of conventional configuration but with components of abnormal size as fuselage of Guppy and Beluga aircraft [52] or in case of specific engine location [53].

The presented model represents a pure case without any system to artificially improve flight stability. Natural stability is the key to understanding the dynamic properties of the aircraft, especially in the case of an unconventional configuration where even the intuition of an experienced engineer can fail. Currently, autopilots and even simple SAS (Stable Augmentation Systems) are often installed on UAVs, making them easier to pilot. However, in the case of unstable or less stable configurations, fine-tuning the autopilot controls can be troublesome. Therefore, it is important to be aware of the actual handling qualities of the aircraft being designed.

3.5. Data necessary for numerical calculations

The mathematical model presented above requires many different data, the most important of which are aerodynamic, mass and inertial data. To use this model for flight simulation, control system data also are needed, however stability analysis needs control surfaces only to find the trimmed flight conditions without strong influence on stability merits, unless the analysis is performed for controlled aircraft.

3.5.1. Aerodynamic data

Aerodynamic data can come from a variety of sources. They may be the result of experimental research in a wind tunnel. They can be determined by simplified, semi-experimental methods, e.g. using ESDU reports [54]. Aerodynamic characteristics can finally be computed using CFD methods. There are many methods, starting from potential code (VLM, 3D panel method), through Euler to full Navier-Stokes model. The development of CFD methods and big increase of the computers' power caused that Euler or Navier-Stokes models are used more often, and potential methods could be seen as obsolete. However, despite many simplifications, methods based on the potential code are still attractive due to the significantly lower cost and easy to use. The question is the sensitivity of dynamic model on the quality of aerodynamic data [55]. Aerodynamic data quality studies have been extensively conducted as part of the SimSAC [56, 2] project, one of the two main objectives of which was to develop a simulation environment, CAESIOM [57], for conceptual design sizing and optimization suitably knitted for low-to-high-fidelity S&C analysis. Numerous benchmarking [58, 59] showed possibility to use mixed data, obtained from different sources. The discussion about application different quality CFD methods to derive aerodynamic data presented in [60] shows attractiveness of potential methods despite numerous simplification of mathematical model and problems with estimation of the friction drag. Moreover, it is worth noting that the stability analysis uses a linearized model (32), so the non-linearities of the aerodynamic data do not have a great influence on the results of calculations of flight qualities.

3.5.2. Mass & Inertia data

The second group of data that is crucial for stability analysis is mass and inertia data. The mass analysis is one of the basic procedures conducted within each stage of design. During the conceptual and preliminary design so-called hand-book methods are in use [61]. The semi-empirical formulas are not too easy, so it is much more convenient to estimate the masses of structure elements within even initial structural analysis [32]. Different methods of estimating mass and inertia data were presented in [62] and the influence on dynamic characteristics were shown in [63].

4. Results of the analysis (test cases)

This chapter presents several examples of the stability analysis of unconventional configurations in which the author was involved. They regard projects that have been realized and those that were only in the design phase. All the cases have shown that a dynamic stability analysis is necessary at a very early stage of the design. The following cases are presented:

- flying wing:
 - tailless configuration study for HALE project [5],
 - flying wing being a flying laboratory [63] for NORD project (Numerical Optimization Research Demonstrator [64]),
- canard - lightweight aircraft project [65],
- three surfaces aircraft (TSA) - lightweight aircraft project developed and waiting for maiden flight [39],
- tandem wing personal plane [66] designed within PPLANE [67] project ,
- box wing - lightweight demonstrator designed within MOSUPS project (inverted joined wing) tested numerically [68, 69] and experimentally as well [70]

4.1. Computational issues

Reliability of data and software used for analyzes is of great importance for the credibility of the presented results. Within the analysis of the cases presented below different software was used (Table1). To prepare aerodynamic data mostly potential code was in use - commercial (VSAERO[71]) and homemade (PANUKL[33] and KK-Aero[72]) as well. For tandem-wing configuration initially used potential methods were completed with commercial Euler code[73] analysis. In case of canard configuration initially used ESDU based methods were verified using PANUKL software.

Stability analysis was performed using homemade software STB[74], which was tested in many projects [51] and SDSA[75] which was validated[46] i.a. within SimSAC project. In case of canard configuration initially homemade FISH program to analyze the lateral stability [65] was in use and next stability analysis was completed and verified with SDSA software.

Table 1

Methods and software used for analysis the test cases

Test case	model used to collect aerodynamic data	CFD software	S&C Software
HALE PW-114	potential code with integral boundary layer	VSAERO	STB
NORD	potential code	PANUKL	SDSA
Canard	ESDU based methods	verified by PANUKL	FISH/SDSA
TSA	potential codes	PANUKL/KK-Aero	SDSA
TANDEM WING	Euler code	MGAERO	SDSA
MOSUPS (boxwing)	potential code	PANUKL	SDSA

It is worth to emphasis that several of the presented cases (NORD, TSA, MOSUPS) were verified in test flights, and the results confirmed previously conducted computational studies. The stability modes of motion characteristics obtained during tests flights conducted according to the standard procedures [76]. The subjective opinion of test pilot is well presented in case of NORD flying wing UAV[63].

4.2. Flying wing

Two examples represent a completely different approach to design. The first UAV HALE aircraft designed within the CAPECON project is an example of the search for the best configuration using the classic iterative design methodology. The second example of a flying wing is the result of a numerical optimization of a UAV designed from scratch in this configuration.

4.2.1. HALE PW114 project

The HALE PW-114 was designed within the CAPECON UE project [77] dedicated civilian application of UAVs. PW-114 version was preceded by former versions – PW-111, PW-112 and PW-113 aircraft (Fig.19).

The analysis of the PW-111 concept led to a list of main drawbacks which had to be corrected in order to improve the concept. PW-111 was CANARD, a naturally unstable configuration. HALE PW-112 received a modified, higher aspect ratio canard. Moreover, fuselage and engine nacelle geometry were modified. Lower front fuselage section had to be enlarged because front leg of landing gear was moved forward to the fuselage nose. Previously, front landing gear leg had been located behind EO/IR sensor. Nacelles had to be enlarged after final engine selection. Nevertheless, the configuration was still unstable. Canard was abandoned to create version PW-112A, which was the beginning of tailless configuration. For next PW-113 configuration new, larger outer wing was designed with smaller taper ratio. New configuration analysis revealed satisfactory longitudinal stability (Fig.20). Unfortunately lateral stability appeared

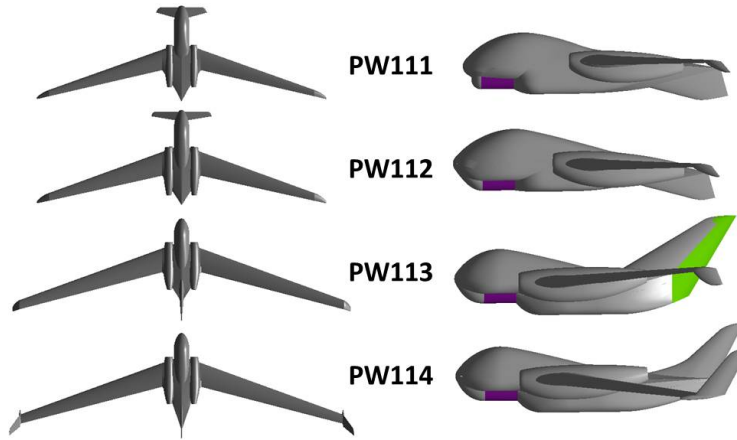


Figure 19: PW HALE - changes of the configuration [5]

not to be satisfactory. Vertical stabilizer with rudder was located at the top of the fuselage. Calculations suggested better qualities for negative dihedral. As a result the PW-114 configuration with negative wing dihedral was endowed with a modified fin in the rear fuselage section together with wingtips to provide sufficient directional stability.

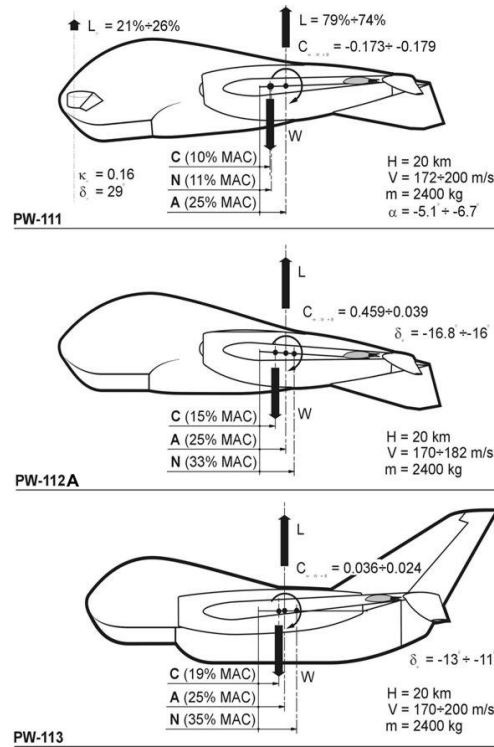


Figure 20: PW HALE - longitudinal trim analysis

Further detailed stability analysis showed that although the configuration is generally stable, the lateral stability, especially Dutch Roll mode is barely on the verge of acceptability. The Dutch Roll characteristics of two last versions (PW-113 and PW-114) are presented against the background of MIL F-8785C [48] criteria in Fig.21. PW-113 is unstable, while PW-114 is only in the 3rd level of acceptance.

PW-HALE is an example of the aircraft design using classical iterative approach - so called design spiral, which

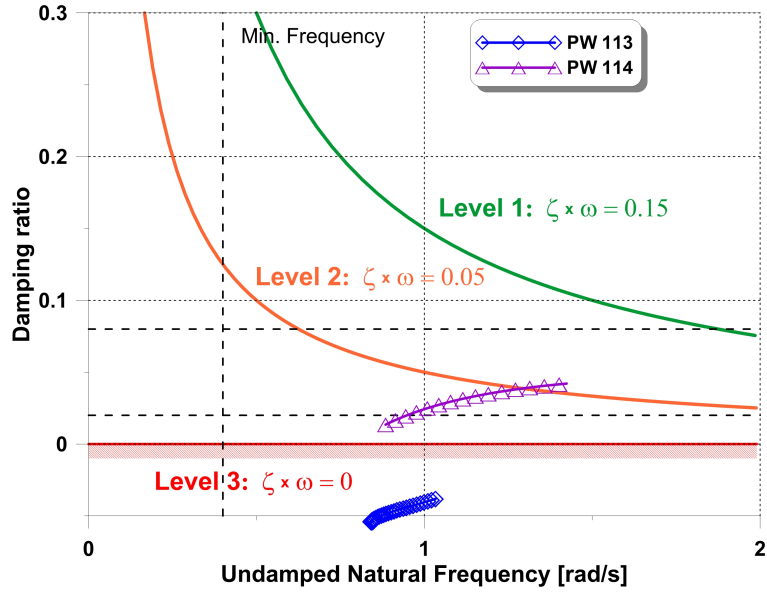


Figure 21: PW HALE - Dutch Roll mode of two last versions

does not guarantee success, especially in case of unconventional configuration. The problem with stability is often a reason of failure of the project.

4.2.2. NORD project

Another example of a flying wing configuration is the result of the NORD (Numerical Optimization Research Demonstrator) - Fig.22. The UAV was designed using an iterative procedure in which the dynamic stability analysis is embedded [69, 78]. This approach allows to avoid problems with subsequent versions of the project, especially if the structural analysis is turned on within the optimization process [79, 80]. A similar approach to optimization of the wing-body configuration is presented in [81], however the stability analysis is limited to the static longitudinal part.

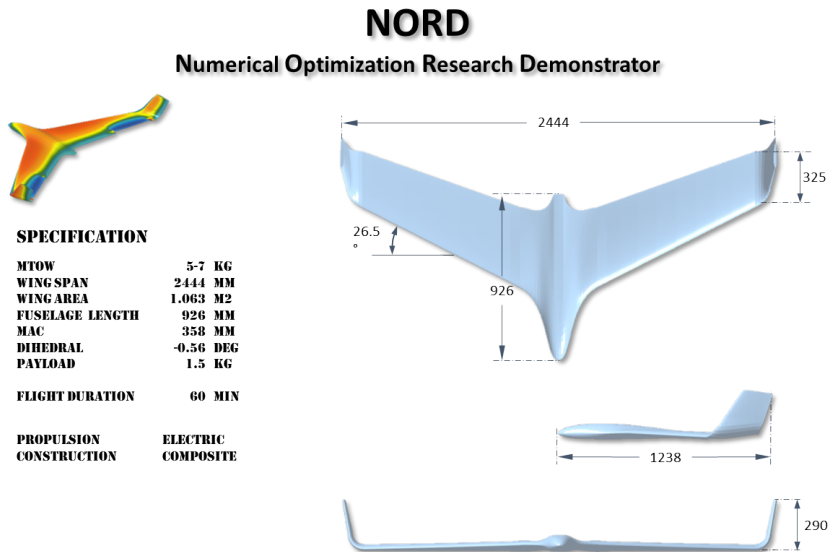


Figure 22: NORD - 3 projections view

The idea of an MDO (Multidisciplinary Design Optimization) system combining several existing applications is presented in [82, 83] and is still being developed. MDO process implemented during design of "NORD" took into account aerodynamics [33], structure analysis, performance characteristics and stability criteria as the optimization constraints [75]. The scheme of this approach is presented in Fig.23. Such an approach allowed to obtain very good flying qualities, which were validated during test flight campaign [63]. In comparison with the previous example, what stands out is big vertical surface of the winglets and relatively low front part of the fuselage.

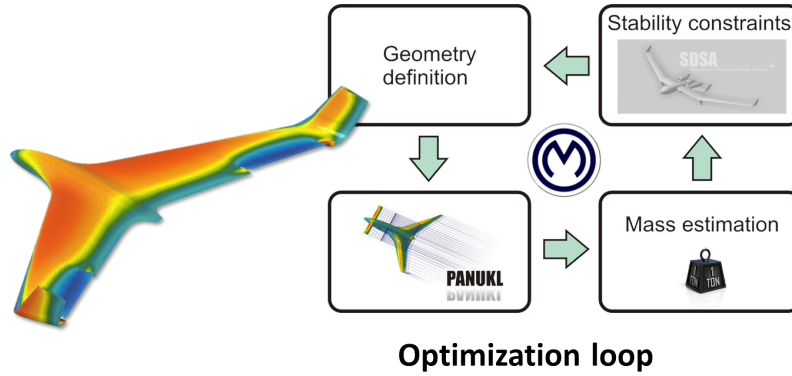


Figure 23: MDO loop scheme

An approach to apply stability constraints in case of flying wing is presented in [84], however only for one of longitudinal modes using simplified formulas [85]. Considering the dynamic stability criteria for all modes during the preliminary and even within the conceptual stage of design allowed to avoid the typical problems in the flying wing configuration. All characteristics, longitudinal and lateral as well, are satisfactorily damped. Fig.24 and Fig.25 present dynamic longitudinal characteristics against the background of MIL-8785C specification [48] - Short Period damping ratio and Phugiod time to double (negative value of time to double means that the mode is stable and denotes time to half damping in fact). Both characteristics are satisfactory, which was next proved during test flights [63]. The typical problems for flying wing configuration didn't appear. Trimming and dynamic stability met very good pilot opinions.

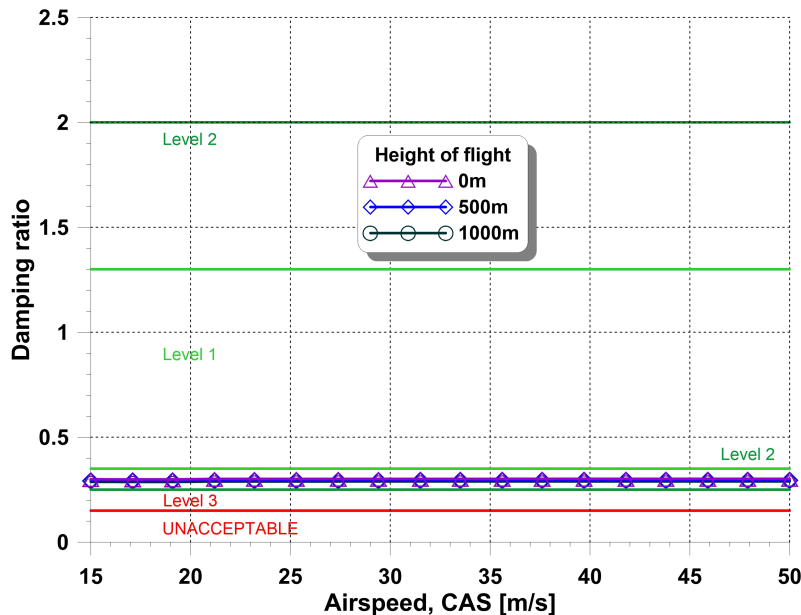


Figure 24: NORD - Short Period damping ratio against background of MIL-8785C specification [48]

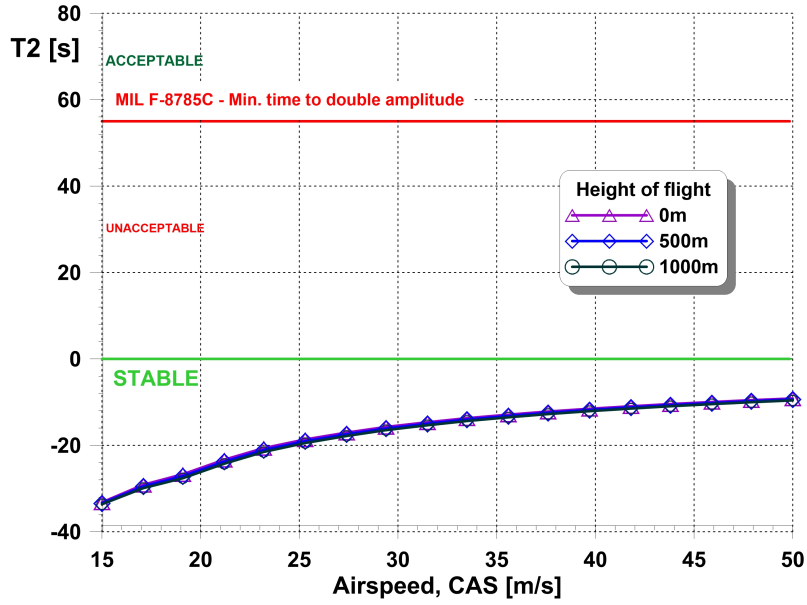


Figure 25: NORD - Phugoid time to double against background of MIL-8785C specification [48]

Lateral characteristics were also very good. Combined yawing-rolling oscillation (Dutch roll), which is treated most severely by regulations, satisfied EASA CS-23 regulations (Fig.26) and MIL specification as well (Fig.27). Also spiral characteristics (Fig.28), which are usually not critical, are stable, resulting in a very good pilot opinion. Both "Dutch roll" and spiral variables stabilize at higher flight airspeeds.

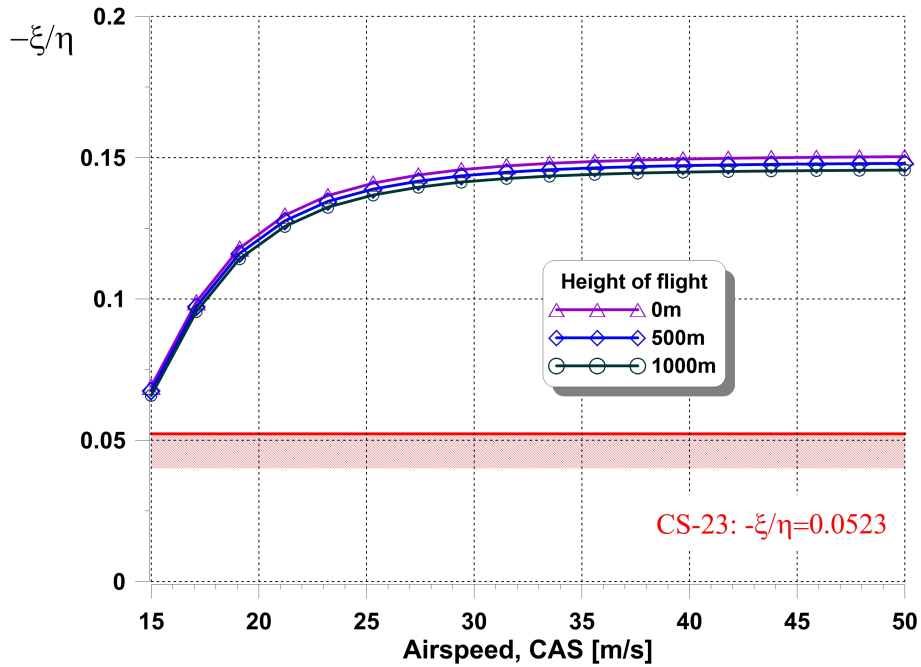


Figure 26: NORD - Dutch roll characteristics time to double against background CS23 requirements [47]

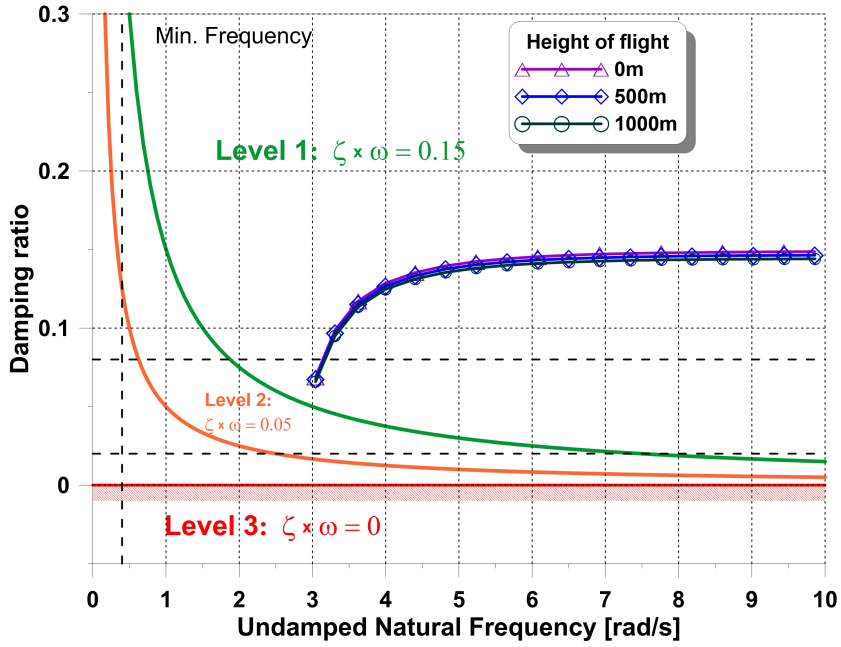


Figure 27: NORD - Dutch roll characteristics against background of MIL-8785C specification [48]

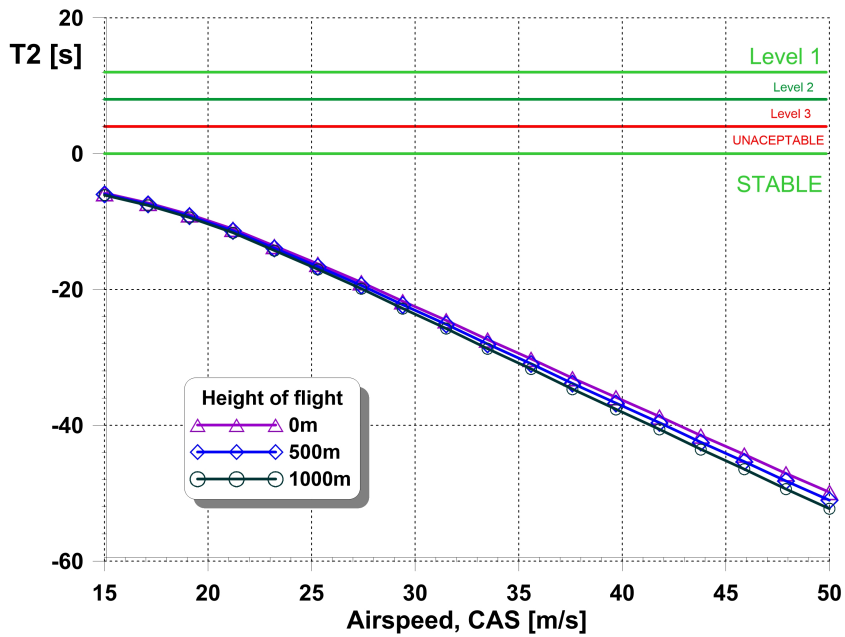


Figure 28: NORD - Spiral time to double against background of MIL-8785C specification [48]

4.3. Canard configuration

The canard configuration chosen for analysis is a two-seat light aircraft (Fig.29), designed by the author.

Analysis of the configuration begun with estimation of the canard area and center of gravity to satisfy trim and static margin requirements. Next, dynamic analysis was done, taking into account four variables: vertical tail area (S_v), dihedral angle of main wing (γ), and CG position (x and z).

The results of dynamic analysis have shown that for longitudinal stability, from four mentioned parameters, the

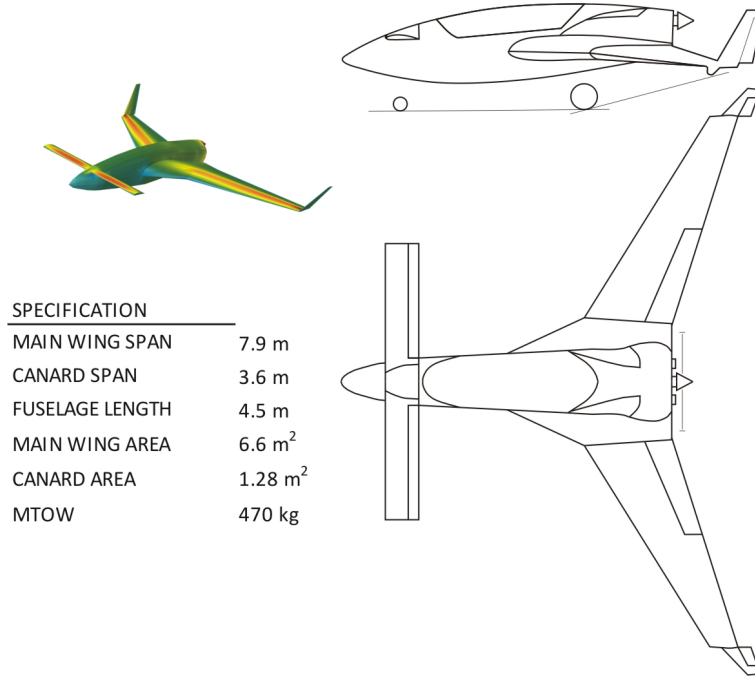


Figure 29: Canard configuration aircraft.

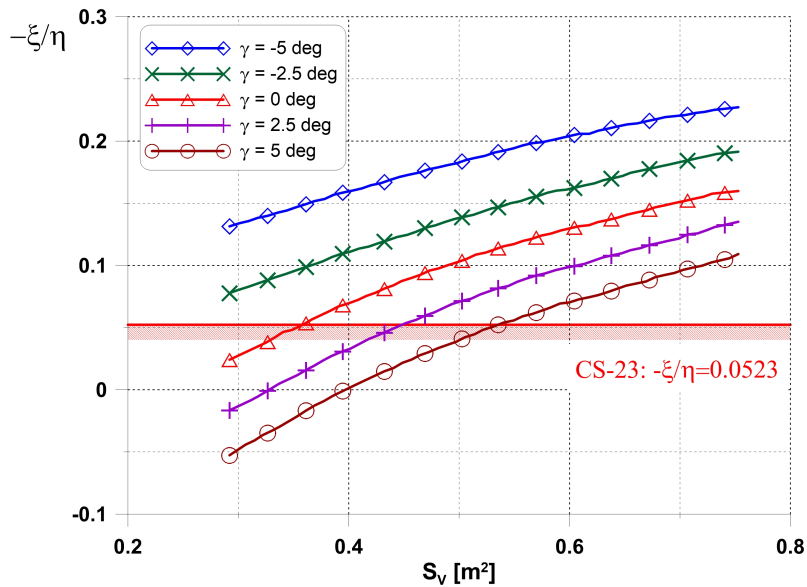


Figure 30: Dutch roll characteristics versus vertical tail area and dihedral angle.

most important are both coordinates of CG. In case of lateral modes the most important are: vertical position of the main wing with respect to the body, dihedral angle and vertical tail area. An increase of the dihedral angle, a decrease of the fin and rudder area as well as shifting the wing upward prolong the times to double of the Spiral mode, which is advantageous from stability point of view. Either a decrease of the dihedral angle when the fin and rudder area is constant or an increase of the fin and rudder area when the dihedral angle is constant can be compensated by shifting the main wing toward high-wing configuration.

The Dutch Roll mode damping increases with an increase of the fin and rudder area as well as with a decrease

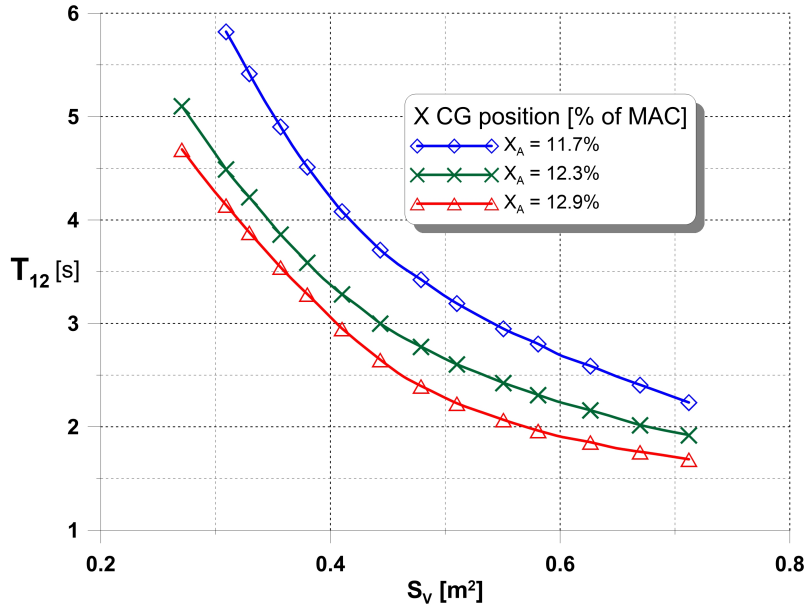


Figure 31: Dutch roll time to half amplitude versus vertical tail area ($\gamma = 0$ deg).

of the dihedral angle (Fig.30). Shifting the mass center forward, improving the longitudinal static stability, slightly worsens the stability of the Dutch Roll mode increasing the time to half amplitude of an oscillation (Fig.31).

4.4. Tandem wing

The presented example of airplane designed in the tandem wing configuration, which was developed within PPLANE project [67] as a concept for personal plane. The aircraft was designed as a quad-tilt rotor vehicle with two tandem-wings with almost equal areas (Fig.32) to be able to fly as an aircraft, when all rotors give thrust forward, or as a multicopter when all rotors give thrust upward.

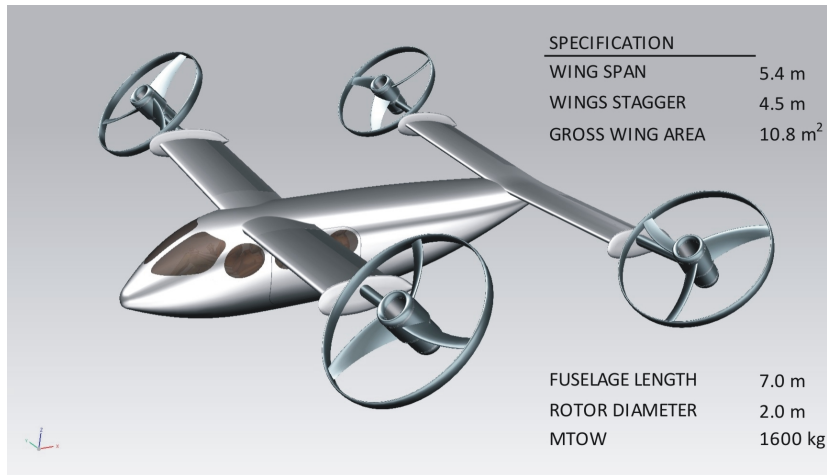


Figure 32: Tandem wing as a quad-tilt rotor configuration [66]

The configuration seemed to be very attractive despite potential problems with the flying qualities. The appropriate arrangement of the fuselage interior allows to satisfy trim and static margins. Dynamic stability analysis showed that phugoid characteristics do not raise any objections (Fig.33) however Short Period parameters are on the verge of acceptability for lower airspeed (Fig.34).

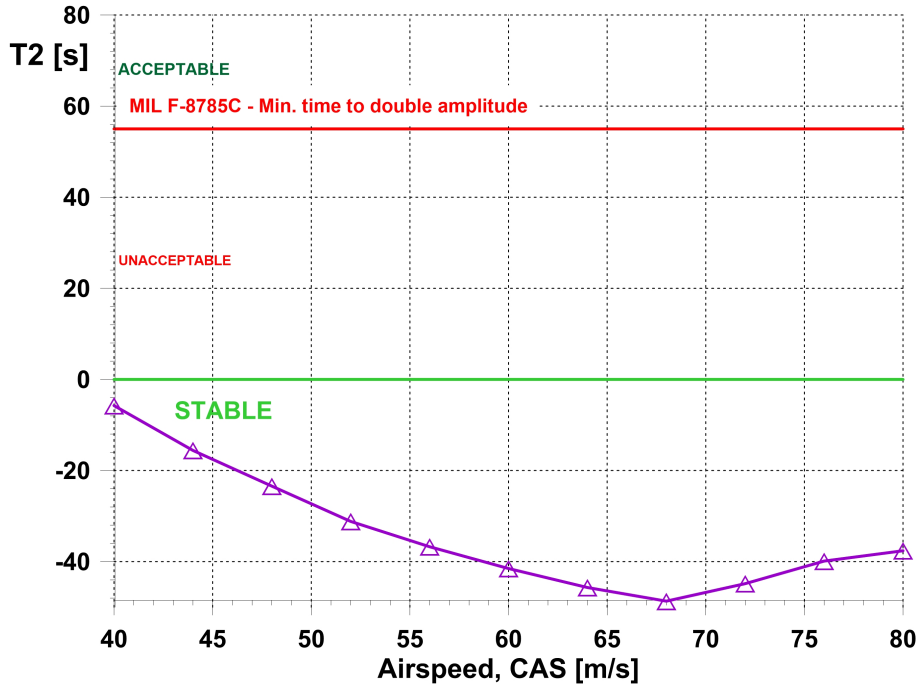


Figure 33: Tandem wing phugoid time to double vs. airspeed

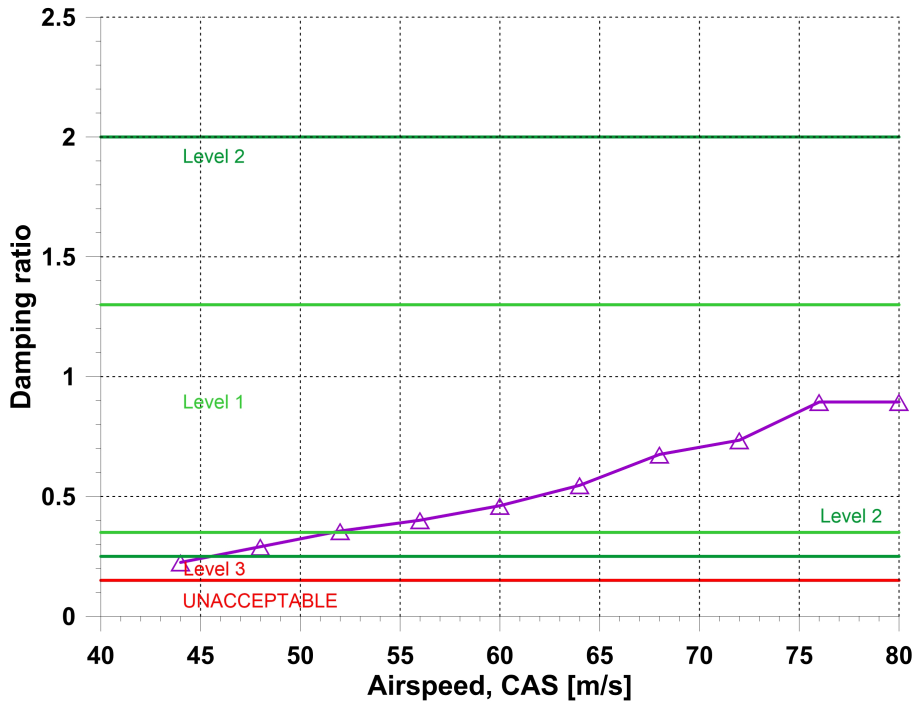


Figure 34: Tandem wing Short Period damping ratio vs. airspeed

The analysis of the lateral modes yielded unexpected results. The configuration without vertical tail was directionally unstable, which was not too surprising, but a second periodic mode of motion appeared - the spiral-roll mode (Fig.35). The roll and spiral modes, both stable, were uncoupled at lower airspeed and they coupled at the airspeed

close to 55m/s. The Dutch roll was unstable almost for whole airspeed range, also for higher airspeed, for which Dutch roll was uncoupled into two non-periodical modes.

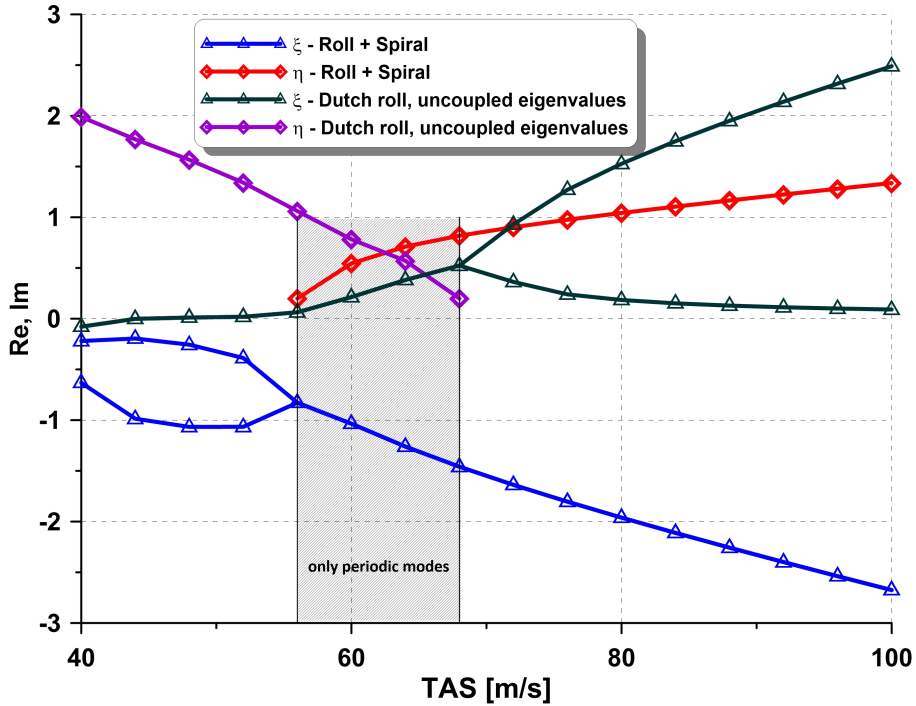


Figure 35: Lateral modes of motion for configuration without vertical tail

The results of the lateral stability analysis indicated the necessity to modify the configuration. It was decided to add a classic vertical stabilizer. The other assumptions of the project remained unchanged, except for a slight rearrangement of the interior of the fuselage so that the position of the center of gravity remains the same. Both configurations, original and modified one are presented in Fig.36.

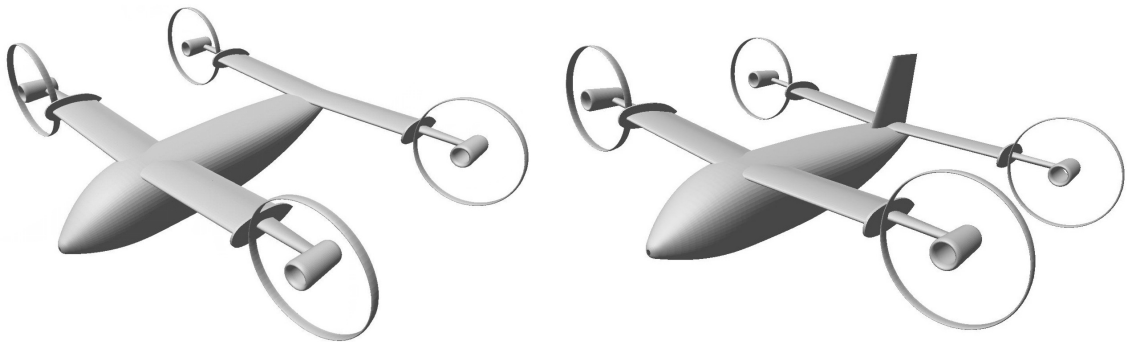


Figure 36: Tandem wing - the original and modified configuration

The modified configuration was stable in the whole range of airspeed, however still roll and spiral were coupled at higher airspeed (above 80m/s) - Fig.37. For the lower airspeeds at which the roll and spiral are decoupled, both modes of motion are sufficiently damped.

Despite the unusual modes of motion both modes satisfied criteria defined by MIL specification. It is worth noting that the MIL specification also provides criteria for the spiral-roll mode of motion, although it occurs extremely rarely and practically does not come in the case of conventional configurations.

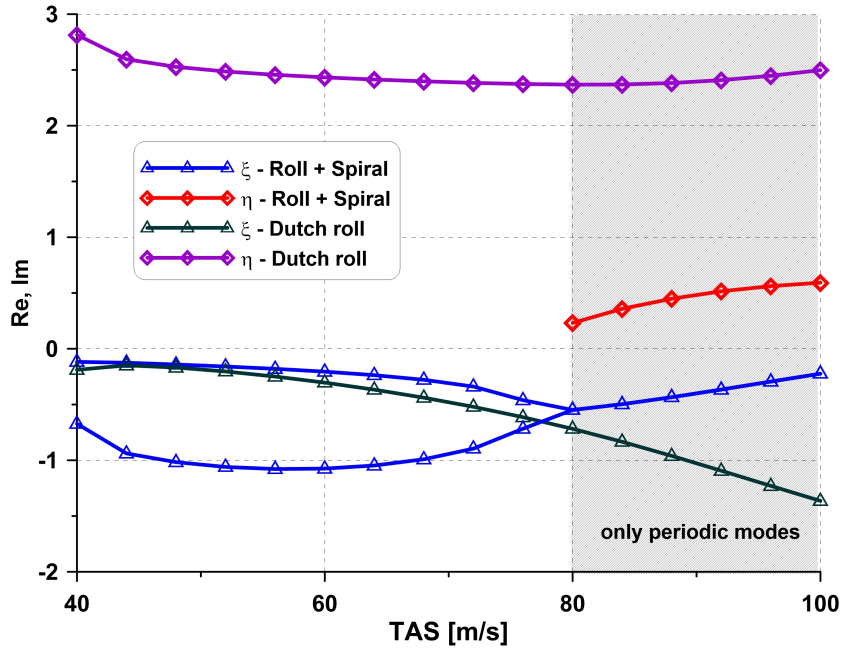


Figure 37: Lateral modes of motion for configuration without vertical tail

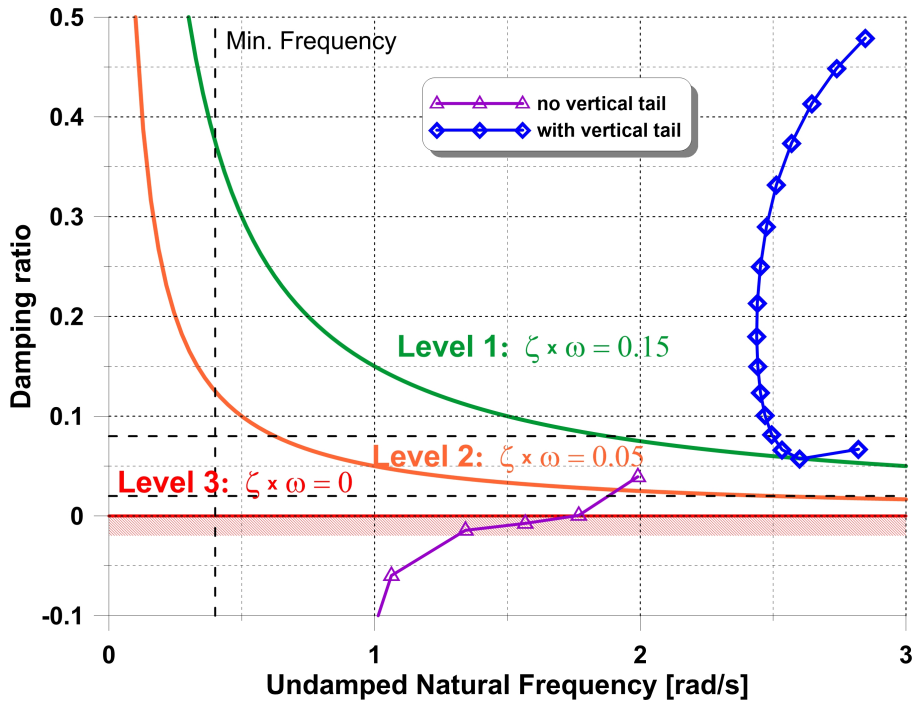


Figure 38: Tandem Wing - Dutch roll characteristics against the background of MIL criteria [48]

Fig.38 presents Dutch roll characteristics against background of figures of merit based on MIL-F-8785C criteria. Fig.39 presents Roll-spiral mode with appropriate MIL rating. The rating of both lateral modes (especially Dutch-roll) is high (1st level), Spiral-roll characteristics for higher airspeed are a little worse.

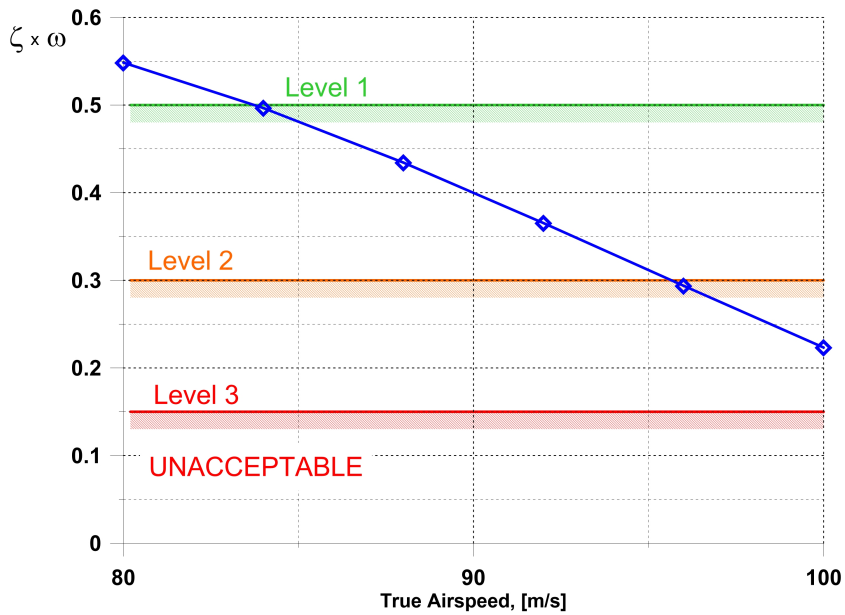


Figure 39: Tandem Wing - roll-spiral characteristics for final configuration against the background of MIL criteria [48]

4.5. Three surfaces configuration (TSA)

Presented example of TSA configuration shows how the results of the dynamic stability test results can influence the shape of the geometry of the airplane, even it was initially well designed, including trim and static stability analysis. The presented aircraft was designed as a four seat, twin engine light aircraft (Fig.40).

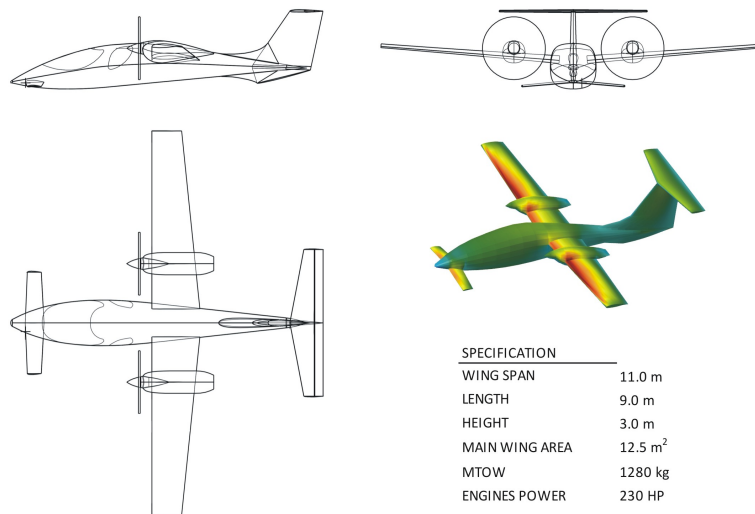


Figure 40: AT-6 - main specification

Initially, the starting point was the ergonomics of the cabin. The cabin needed to be free of other elements to ensure overall comfort, and also because the cross-sectional area should be kept as small as possible as it has a big impact on performance. Thus, the main spar and landing gear were lifted out of the cabin. The visibility from the cabin had to be similar to the visibility from the helicopter cabin, not like a small Cessna, so it should be a fully glazed cabin.

Next - easy entry for each pilot and passenger, so one large glazed door for pilots and two "gull-wing" doors for each passenger. Due to these requirements, the wheelbase of the landing gear was increased, and most importantly, the wing was moved to the rear, which placed the center of gravity in front of the leading edge of the wing. Such extreme position of the center of gravity requires an additional lifting surface at the front of the fuselage (canard) in order to satisfy the trim and reduce a very big negative force on the horizontal tail.

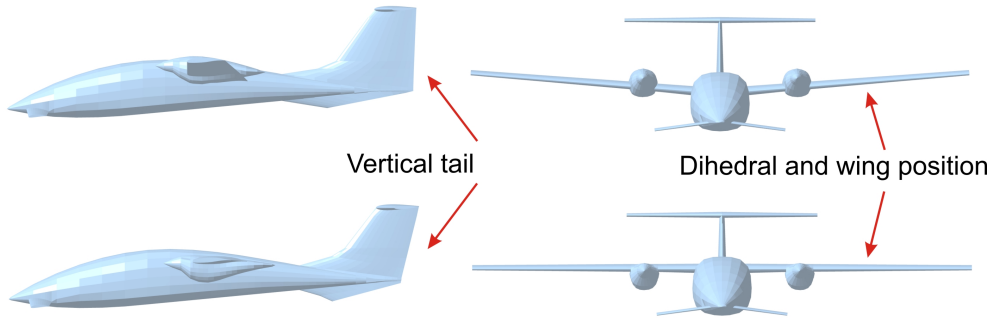


Figure 41: AT-6 - changes of the configuration [39]

These design priorities allowed the size and proportions of three main lifting surfaces to be determined. The longitudinal stability was good enough, however lateral characteristics were not satisfactory. The preliminary version assumed positive dihedral of the main wing to satisfy good spiral characteristics, which are not critical according to airworthiness regulation but generally important from flying qualities point of view. To satisfy Dutch roll requirements big vertical tail was designed.

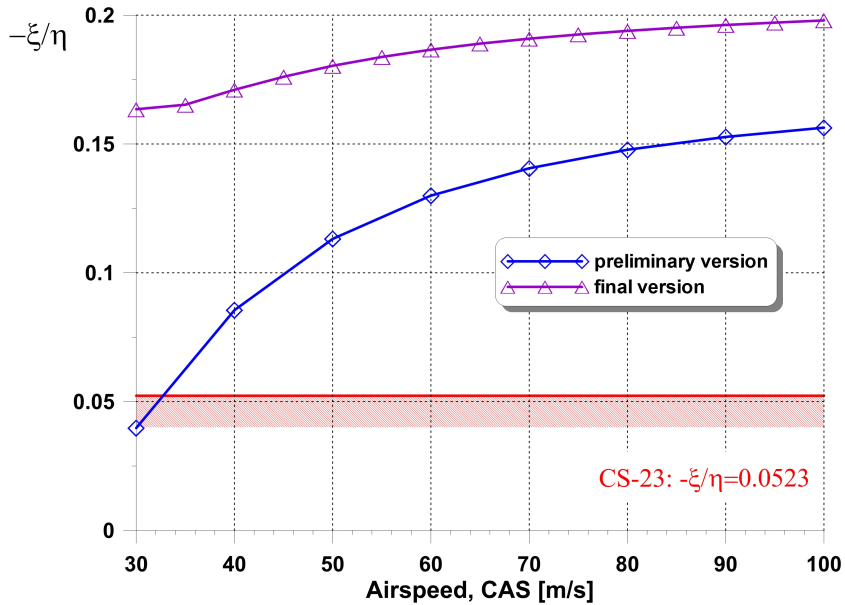


Figure 42: AT-6 - Dutch roll characteristics against the background of the CS-23 criteria [47]

Unfortunately Dutch roll characteristics didn't satisfy CS23 [47] requirements (Fig.42) and also MIL 8785C [48] criteria indicated insufficient damping at lower airspeeds (Fig.43).

Unsatisfied results forced the changes in configuration presented in Fig.41. The main wing has been shifted upwards, setting at the same time the dihedral of wings to zero. Therefore the position of engines remained unchanged with respect to the geometry of the entire aircraft. Initial estimation of Dutch roll after applying no dihedral main wing pointed out that the vertical stabilizer area can be reduced, which caused it's weight reducing and forces acting on it.

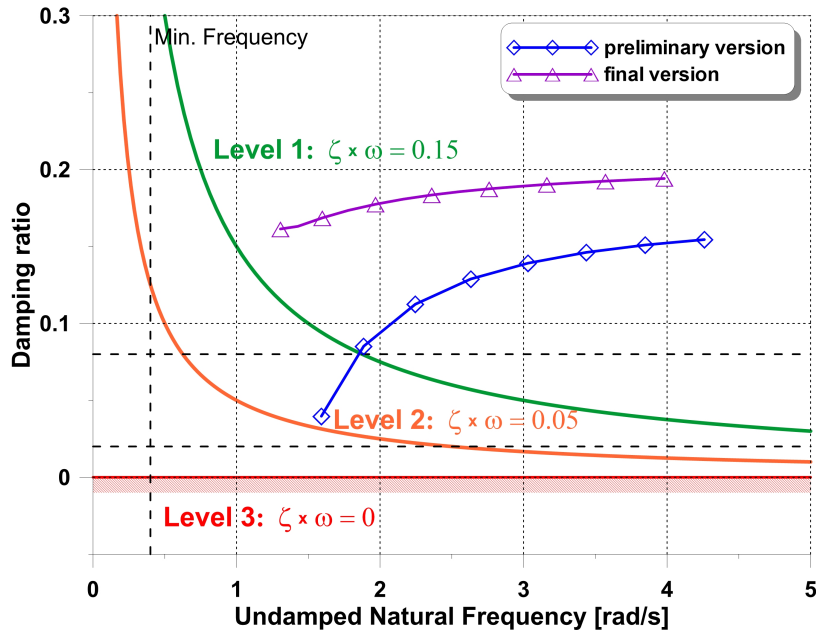


Figure 43: AT-6 - Dutch roll characteristics against the background of MIL-8587C criteria [48]

Additionally, the reduction of the vertical stabilizer improved spiral characteristics after eliminating the wing dihedral. Despite the fact that the damping after the changes is weaker, it is still sufficient and is in the first level of acceptance according to the MIL 8785C specification (Fig.44).

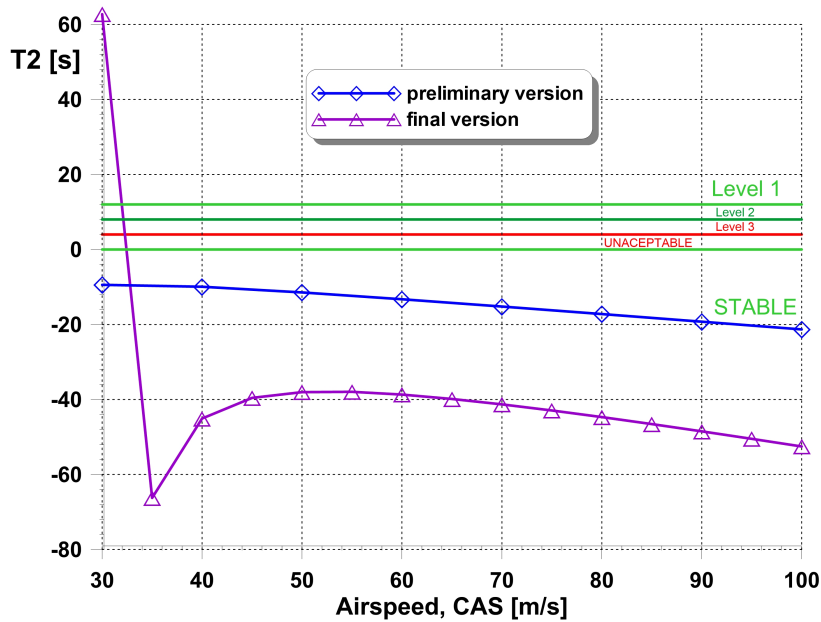


Figure 44: AT-6 - Spiral characteristics against the background of the MIL-8587C criteria (time to double) [48]

The effectiveness of the changes was confirmed by flight tests of the scaled demonstrator (Fig.45). The recorded flight parameters matched with the computation results [39] and the pilot's opinions indicated a high rating according to the Cooper-Harper scale.



Figure 45: AT-6 - flight tests of scaled demonstrator (courtesy AT-P AVIATION)

4.6. Box wing

The example of Box wing presented in this paper is MOSUPS project (Fig.46), which was tested numerically very thoroughly, already within the preliminary stage of the project [68, 86, 87, 88].

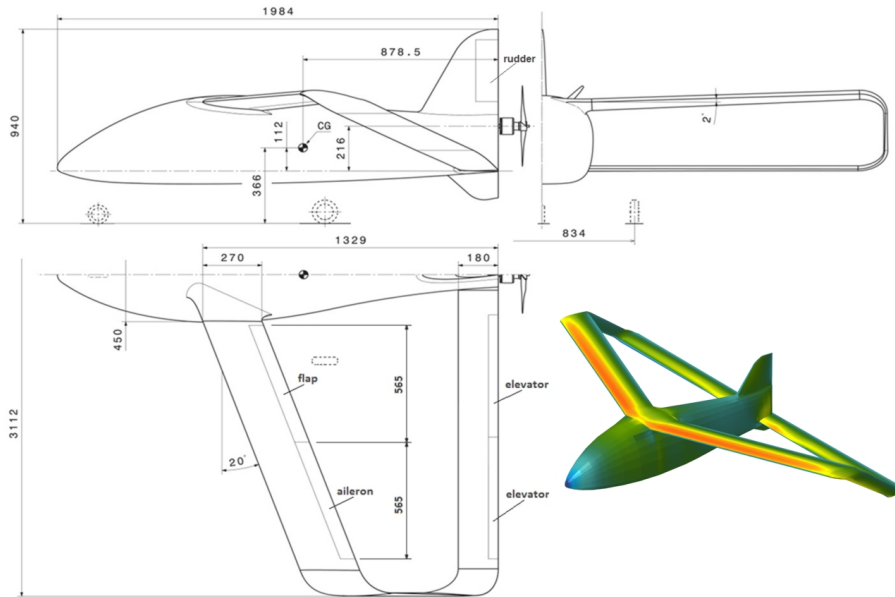


Figure 46: Inverted Box Wing configuration - main specification of MOSUPS project

The analysis allowed to find the appropriate position of gravity center versus both wings configuration (sweep angle, relative position: stagger and gap) to satisfy good flying qualities. To find this, the methodology presented in the case of the NORD [69] project was used, which gave good results and allowed to meet conflicting requirements.

The first problem concerned the longitudinal characteristics and was common for canard and tandem wing configurations. This is a problem of reconciling the requirements of ensuring equilibrium and longitudinal stability, which are contradictory due to the destabilizing role of the front wing. The position of CG corresponding to approximately 90% of MAC of the front wing was satisfactory for trimming and allowed to obtain very good parameters of short period oscillations (Fig.47).

The joined wing configuration is exceptionally strongly aerodynamically coupled, thus all decisions made to solve longitudinal trimming and stability problem affect the lateral characteristics. Relatively large vertical surfaces which join the wing tips allow to reduce the vertical stabilizer saving good Dutch Roll characteristics. Fig.48 presents Dutch Roll characteristics (damping to frequency ratio) against the background of CS-23 criteria and Fig.49 presents damping ratio versus undamped natural frequency for this mode against the background of MIL-8587C criteria. Both criteria

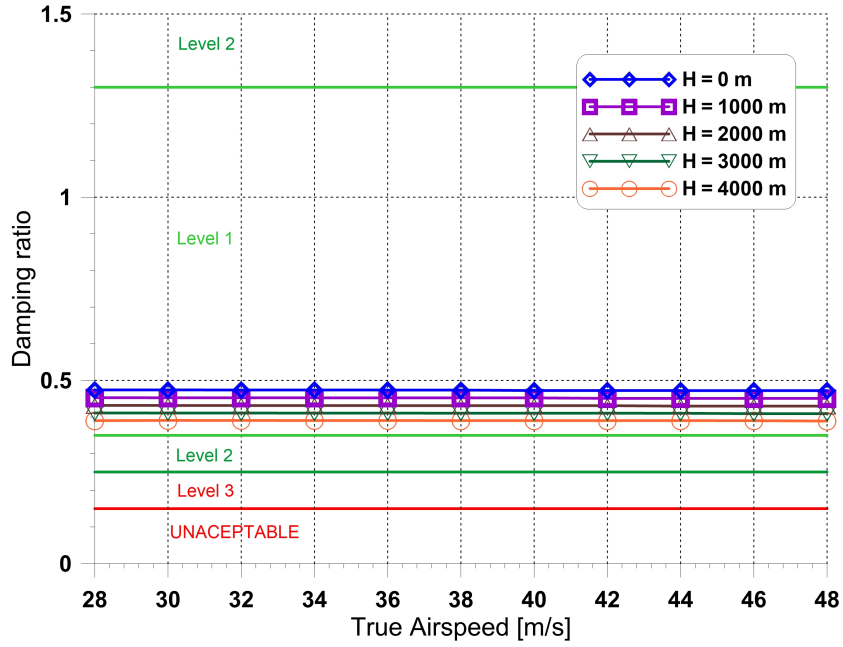


Figure 47: MOSUPS - Short period damping ratio against the background of MIL-8587C criteria [48]

are satisfied putting the result in the highest level of acceptance (MIL specification).

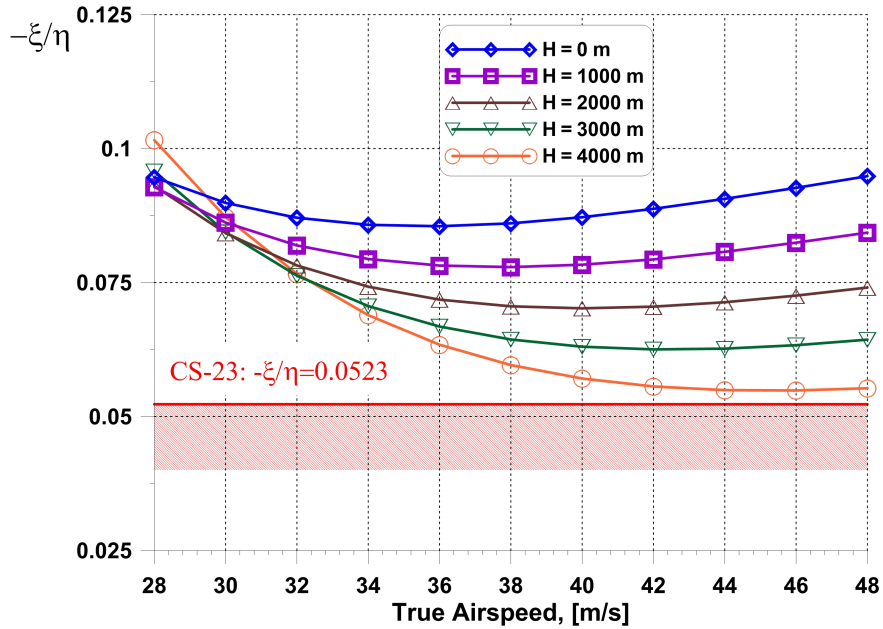


Figure 48: MOSUPS - Dutch roll characteristics against the background of the CS-23 criteria [47]

Satisfying Dutch Roll characteristics often results in unstable spiral mode, especially in case of high aspect ratio wing (e.g. sailplanes) or strongly aerodynamically coupled unconventional configuration. In case of presented joined wing configuration both main lateral modes, Dutch Roll and spiral, are stable. Spiral mode time to double versus airspeed, against background of MIL-8587C criteria, is presented in Fig.50.

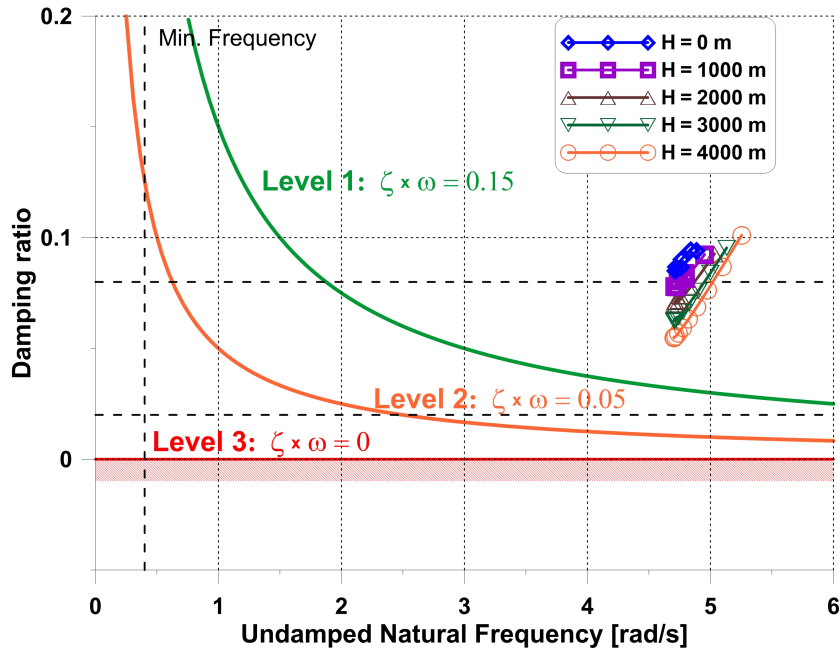


Figure 49: MOSUPS - Dutch roll characteristics against the background of MIL-8587C criteria [48]

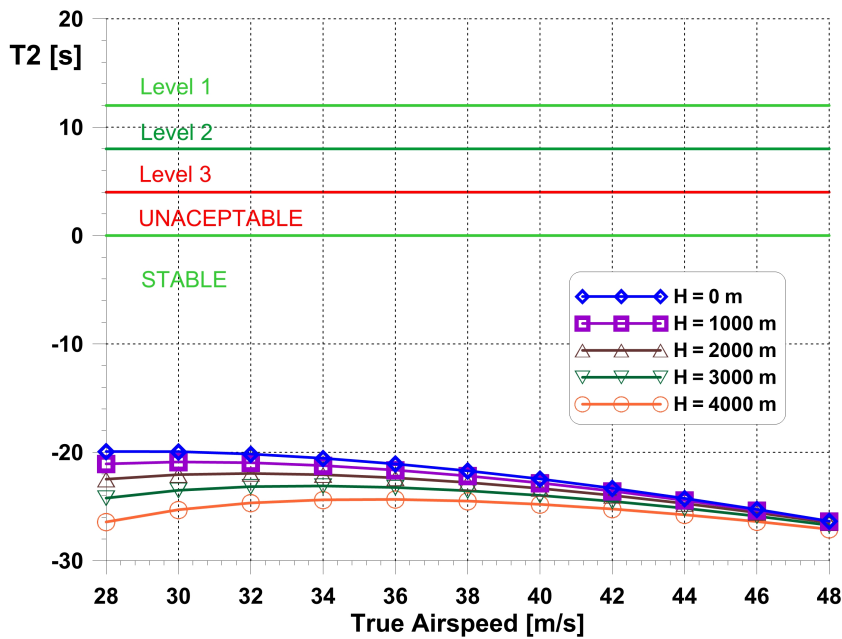


Figure 50: MOSUPS - Spiral time to double against the background of MIL-8587C criteria [48]

4.7. Stability evaluation - lessons learned

The evaluation of stability characteristics follows from analysis of the dynamics for small perturbations from some reference state, here straight and level flight. The results – the time constants of the different eigenmodels – are plotted together with assessment of the pilot “opinions” according to the Cooper-Harper scales and MIL standard, where applicable. These plots take up a substantial fraction of the space. The accompanying text would do well to point out what was learnt about parameter trade-offs, envelope limits, or necessary design modifications.

5. Concluding remarks

The presented examples of aircraft designed in unconventional configurations show numerous problems related to the static and dynamic stability. The main reasons are greater sensitivity to the shift of the center of gravity and the stronger aerodynamic coupling compared with conventional layout. In a conventional configuration, the role of the horizontal and vertical tail is usually clearly defined, i.e. to provide trim, stability and controllability. In the case of unconventional configurations, due to the above-mentioned stronger aerodynamic coupling, the tail, if it exists, does not fulfill its role and must be replaced by other solutions. One of the methods to improve stability are very popular stability augmentation systems (SAS) present in autopilots used to control the UAVs. However, despite their great capabilities, they cannot replace a naturally stable configuration. Therefore, the effort to design and develop a stable configuration is important. Current design methods with the use of MDO procedures, similar to those presented in [89], allow to use the advantages of unconventional configurations while minimizing their typical problems. However, it is good to be aware of the main problems and advantages before using automatic design methods. The attempt to summarize main of them comparing with conventional layout is presented in table below:

Table 2

Comparison of main design advantages (A) and problems (P) between conventional and unconventional configurations

Feature/design component	Conventional	Unconventional
CG position	relatively wide range of shifting the center of gravity (A)	high sensitivity to the CG shift (P)
fuselage	equal proportions of the front and aft parts of fuselage - moderate influence on stability derivatives (A)	usually the greater part of the fuselage in front of the main wing (canard, TSA, box-wing), which causes reducing of longitudinal and directional stability (P)
horizontal tail (HT)	negative lift force, high force from control (P) provides good longitudinal stability (A)	low negative (TSA) or positive lift force (tandem, box-wing) lower loads from control (TSA) (A) lack of horizontal tail reduces longitudinal stability and limits CG shift (P)
vertical tail (VT)	provides directional stability (A)	VT arm is usually reduced that forces increasing of VT area (P)

The comparison in the table shows overall advantages of the conventional configuration, but does not include the other benefits of unconventional configurations, related to aerodynamic and performance characteristics mentioned in the brief descriptions of each. Almost all of them give a chance to develop really competitive aircraft, omitting their typical problems. The way to achieve this is dynamic analysis done in very early design stage, complemented with MDO methods that gives stable configuration, regardless of it being conventional or unconventional.

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