STABILITY AND FLYING QUALITIES ASSESSMENTS OF A SMALL WING-IN-SURFACE-EFFECT TRANSPORT VEHICLE

Hendarko

Institute of Flight Systems
German Aerospace Center (DLR)
Lilienthalplatz 7, D-38108 Braunschweig, Germany

Keywords: *surface effect, stability, flying qualities*

Abstract

A wing-in-surface effect vehicle is a vehicle which flies in close proximity to a surface in most of its flight phases. It is predicted to be one of the future potential transportation means. Its high aerodynamic efficiency due to surface effect is very promising for such vehicles to be widely used.

The stability as well as flying qualities of a small wing-in-surface-effect transport vehicle in cruise flight for different cruise heights has been reported in this paper. The linear model is constructed in state-space form using small-perturbation theory and the vehicle's aerodynamic derivatives are computed using a semi-empirical USAF Datcom method.

Nomenclature

c	mean aerodynamic chord
C_L	lift coefficient
Cm	pitching moment coefficient
g	gravity acceleration
H	height
h	non-dimensional height ≡ H/c
I_y	moment inertia about the y-axis
m	mass of vehicle
M	pitching moment
q	pitch rate perturbation
u	horizontal velocity perturbation
U	horizontal velocity
w	vertical velocity perturbation
W	vertical velocity
X	horizontal force component
Z	vertical force component

Greek letters

α	angle of attack
θ	pitch angle

Subscripts

e	equilibrium, steady, or initial condition
h	non-dimensional height
u	horizontal velocity
w	vertical velocity
α	angle of attack

1 Introduction

Surface effects have been experienced by pilots when landing an aircraft ever since the beginning of manned flight. Just before touchdown it suddenly feels as if the aircraft does not want to go lower due to the air that is trapped between wings and runway, forming an air cushion.

In 1920's Wieselberger [1] has developed a theory that explained the increase of lift-to-drag ratio for a wing with an elliptic lift distribution if it is flown close to the surface.

As a wing flies in close proximity to a surface, the surface imposes a boundary condition on aerodynamic field that distorts the downwash from the wing and inhibits the formation of vortices, which result in two beneficial effects. There is a pressure increase on the lower wing surface due to the conversion of the dynamic pressure of the forward motion to static pressure, which results in a substantial increase in lift. At the same time there is a substantial reduction in (lift-induced) drag because the vortices and downwash are less and hence there is less energy stored in them. These surface effects hence increase the lift-to-drag ratio of the wing.

A wing-in-surface-effect (WISE) vehicle which flies in a high speed range close to the sea surface has attracted much attention worldwide to develop it as a future alternative marine transportation. Benefited from surface effect to reach high lift-to-drag ratio, such vehicle may be more economical compared with aircraft.

Stability plays an important role in designing a safe and efficient WISE vehicle due to its potential danger in sea surface proximity. Unlike an aircraft which flies out of surface effect, the pressure magnitude and distribution around the wings of a WISE vehicle vary with respect to distance from the surface even with a fixed angle of attack. This variation of pressure magnitude and distribution causes variation of lift and pitching moment. Therefore, the longitudinal stability characteristic of a WISE vehicle is quite different from that of an aircraft flying out of surface effect due to existence of lift and pitching moment derivatives with respect to height.

Table 1 General data of the small WISE transport vehicle

Length overall	15.0 m
Breadth overall	12.25 m
Height overall	5.2 m
Wing area	50.0 m2
Wing span	12.5 m
Mean aerodynamic chord	4.0 m
Aspect Ratio	3.125
Total Weight	4055 kg
Cruise speed	185 kmh

A small WISE transport vehicle with 8-10 passenger capacity is introduced in this paper.

In this paper the stability and flying qualities of the WISE vehicle in cruise flight are investigated. Since a WISE vehicle inherently possesses lateral stability [2] and the lateral-directional motions are influenced only moderately by surface effect [3], the assessments of stability and flying qualities in this paper are concerned with longitudinal motions.

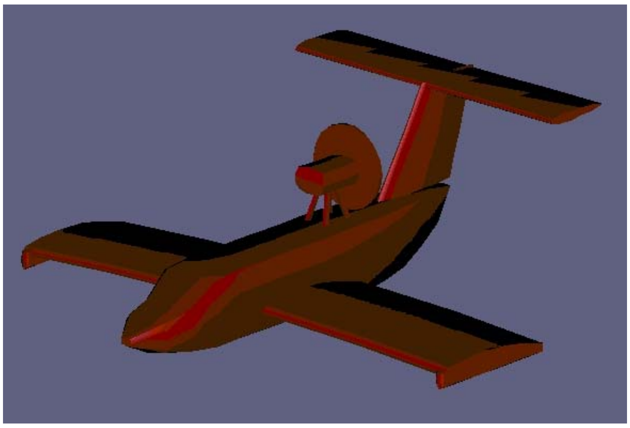

Fig.1 The small WISE transport vehicle

2 Longitudinal Stability

2.1 Longitudinal Static Stability

Generally, a vehicle is said to be statically stable if there exist a restoring force or moment which counteracts any disturbances from its initial stationary condition. Two different movements in the longitudinal direction can be recognized, i.e. pitch and height. For an aircraft flying out of surface effect height stability is irrelevant, but it is not the case for a WISE vehicle. A WISE vehicle must be stable in both height and pitch. Therefore, after a disturbance not only the pitch angle of the WISE vehicle, but also the height above the surface must be restored to their initial values.

2.1.1 Static Pitch Stability

Static pitch stability of a vehicle requires having moment about center of gravity in such a way that decreases angle of attack after a disturbance in angle of attack. Mathematically, this requirement is written as follows:

$$Cm_{\alpha} < 0 \qquad (1)$$

In other words it can also be said that the center of gravity position should be located upstream of the aerodynamic center of pitch.

2.1.2 Static Height Stability

Unlike an aircraft, height stability would be relevant to WISE vehicle since the force and moment of the WISE vehicle varies with respect to height change. The vehicle is said to have static height stability if it tends to return to the undisturbed condition after a disturbance in height, or in other words the lift should increase as the height decreases,

$$\left(\partial C_L / \partial h\right)\Big|_{C_m} < 0 \tag{2}$$

For the more general case, the concept of derivatives is used in the form

$$\begin{aligned} \Delta C_L &= C_{L\alpha}\Delta\alpha + C_{Lh}\Delta h \\ \Delta C_m &= C_{m\alpha}\Delta\alpha + C_{mh}\Delta h \end{aligned} \tag{3}$$

Then it follows that

$$\Delta C_L = \left[C_{Lh} - C_{L\alpha}\frac{C_{mh}}{C_{m\alpha}}\right]\Delta h + \frac{C_{L\alpha}}{C_{m\alpha}}\Delta C_m \tag{4}$$

Thus, the stability criterion (2) can be written as

$$C_{Lh} - C_{L\alpha}\left(C_{mh}/C_{m\alpha}\right) < 0 \tag{5}$$

2.2 Longitudinal Dynamic Stability

For more complete evaluation of flight stability in surface effect, it is necessary to consider the dynamic stability. The equations of motion are linearized using small-perturbation theory and the concept of derivatives is introduced where derivatives due to height, i.e. X_h, Z_h, and M_h, are included.

$$\begin{aligned} m\dot{u} - X_{\dot{w}}\dot{w} &= X_u u + X_w w + (X_q - mW_e)q - mg\theta\cos\theta_e + X_h h \\ m\dot{w} - Z_{\dot{w}}\dot{w} &= Z_u u + Z_w w + (Z_q + mU_e)q - mg\theta\sin\theta_e + Z_h h \\ I_y\dot{q} - M_{\dot{w}}\dot{w} &= M_u u + M_w w + M_q q + M_h h \end{aligned} \tag{6}$$

In addition, the following kinematics conditions are added.

$$\begin{aligned} \dot{\theta} &= q \\ \dot{h} &= -w + U_e\theta - W_e \end{aligned} \tag{7}$$

Equations (6) and (7) can be written in state space matrix form as follows:

$$M\dot{x} = Ax \tag{8}$$

Where M is the mass matrix, A is the state matrix, x is the state vector (i.e. $[u,w,q,\theta,h]^T$).

In order to investigate dynamic stability, the characteristic equation of the system needs to be evaluated by calculating the determinant of (sI-$M^{-1}A$). All the roots of characteristic equation must have negative values to ensure stability.

3 Flying Qualities

Flying qualities assessment of the WISE vehicle is based on the military specification [4] since the specifications are given in a numerical manner such that it gives the designer an analytical method by which to design towards achieving desired handling characteristics.

The small WISE transport vehicle can be classified in Class II Category B (See Ref.[4], [5] or [6]).

3.1 Short Period Pitching Oscillation (SPPO)

The short period pitching oscillation is clearly influenced by its natural frequency, ω_{nsp}, and damping ratio, ζ_{sp}. The minimum and maximum values of short period damping ratio for Class II Category B is shown in the following table.

Table 2 Flying qualities level requirement for SPPO in terms of damping ratio

Level	ζ_{sp} min	ζ_{sp} max
1	0.30	2.00
2	0.20	2.00
3	0.10	

Meanwhile, the role of short period natural frequency in flying qualities is expressed in a quantifiable measure of the anticipatory nature of the response, which called *Control Anticipation Parameter* (CAP). The formal definition of CAP is the amount of instantaneous angular pitching acceleration per unit of steady state normal acceleration [5], which formulated as:

$$CAP \equiv \frac{\dot{q}(0)}{n_z(\infty)} = \frac{mg\omega_{nsp}^{\;2}}{\frac{1}{2}\rho V^2 S C_{L_\alpha}} \tag{9}$$

The minimum and maximum values of CAP for Category B are shown in the following table.

Table 3 Flying qualities level requirement for SPPO in terms of CAP

Level	CAP min	CAP max
1	0.085	3.6
2	0.036	10
3	0.036	

3.1 Phugoid

Minimum and maximum values of phugoid natural frequency are not quantified. However, it is recommended that the phugoid and short period mode frequencies are well separated since handling difficulties may become obtrusive if the frequency ratio of the modes, $\omega_{nph}/\omega_{nsp}$> 0.1. Generally, the phugoid dynamics is acceptable provided the mode is stable and damping ratio limits are quantified as shown in table below [5]:

Table 4 Flying qualities level requirement for phugoid in terms of damping ratio

Level	ζ_{sp} min
1	0.04
2	0
3	Unstable, period T > 55s

4 The Stability and Flying Qualities Assessments

The longitudinal stability and flying qualities of the small WISE vehicle in cruise flight are investigated in variation of height.

The semi-empirical USAF Datcom method [7] is used to estimate the vehicle's aerodynamics derivatives. The Datcom method estimates aerodynamics derivatives based mostly on empirical data which requires some information about geometry and aerodynamics of the vehicle at the outset. The investigator then works through the estimation process, which involves calculation and frequent reference to graphical data and nomograms, to arrive at an estimate of the value of the derivative at the flight condition of interest. The sets of derivatives values for various heights used in the following investigation are summarized in Table 5.

Table 5 Derivatives of the investigated WISE vehicle

H	1.5m	2.0m	2.5m	Free air
Cx_u	-0.0440	-0.0460	-0.0460	-0.0500
Cx_α	-0.5678	-0.4510	-0.3765	-0.2014
Cx_z	0.0065	0.0033	0.0001	0
Cz_u	-1.0180	-0.9240	-0.8620	-0.6980
Cz_α	-6.0037	-5.6105	-5.3206	-4.4843
Cz_z	-0.4566	-0.3227	-0.1888	0
Cm_α	-2.0048	-1.8581	-1.7475	-1.3029
Cm_z	-0.1131	-0.0733	-0.0335	0
$Cm_{\dot\alpha}$	-5.6776	-5.6776	-5.6776	-5.6776
Cm_q	-8.4740	-8.4740	-8.4740	-8.4740

4.1 Static Stability Assessment

As explained in section 2.1 the requirements for longitudinal static pitch stability and longitudinal static height stability are given in Equation (1) and Equation (5) respectively, i.e:

Pitch Stability ≡ PS ≡ $Cm_\alpha < 0$

Height Stability≡HS≡ $C_{Lh} - C_{L\alpha}\left(C_{mh}/C_{m\alpha}\right) < 0$

The assessments of the longitudinal static stability of the small WISE vehicle are described in Table 6. Note that in this paper h is positive in upward direction and z is positive in downward direction.

Table 6 The static stability assessment

H	1.5m	2.0m	2.5m	Free air
$C_{L\alpha}$	5.9817	5.5875	5.2976	4.4593
Cm_α	-2.0048	-1.8581	-1.7475	-1.3029
C_{Lh}	-0.4566	-0.3227	-0.1888	-
Cm_h	0.1131	0.0733	0.0335	-
PS	-2.0048	-1.8581	-1.7475	-1.3029
HS	-0.1191	-0.1023	-0.0872	-

According to Table 6, the vehicle meets the requirements of static pitch stability and static height stability since the values of *PS* and *HS* are all negative. Meanwhile, in free air (out of surface effect) height stability is no longer relevant.

It can be clearly seen in Table 6 that the static pitch stability margin, |*PS*|, of this vehicle is larger (more stable) as the cruising height decreases. The reason for this is that as the vehicle approaches the surface, the variation of Cm_α is relatively larger than that of $C_{L\alpha}$, hence the aerodynamic center of pitch ($Cm_\alpha/C_{L\alpha}$) moves backward as the height decreases. The static height stability margin, |*HS*|, of this vehicle is also larger as the height decreases.

4.2 Dynamic Stability Assessment

By using linearized equations of motion and kinematics conditions, as explained in section 2.2, as well as aerodynamics derivatives calculations the longitudinal dynamic stability of the small WISE vehicle are investigated. The longitudinal root loci are shown in Fig.2.

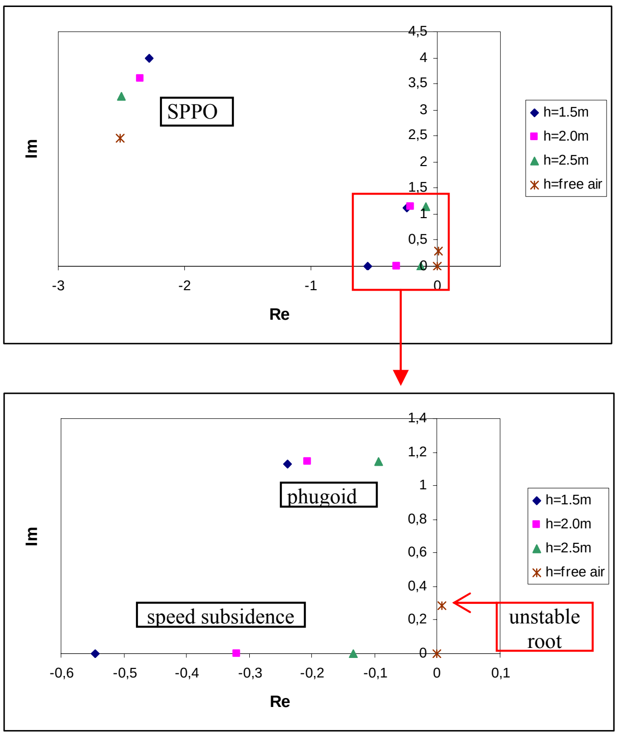

Fig. 2 The root loci in height variation

It can be seen in Fig.2 that all roots of longitudinal motion characteristics of this vehicle, except for phugoid mode in free air, lie in the left side of the imaginary axis which means dynamically stable. The phugoid mode of this vehicle in free air (out of surface effect) is slightly unstable. However, since this is a WISE vehicle, it is not recommended to operate out of surface effect due to efficiency reason.

It is generally known that ω_{nsp} in the SPPO mode is much influenced by $C_{L\alpha}$. As the vehicle approaches the surface, $C_{L\alpha}$ increases rapidly, resulting in increase in ω_{nsp}. In the phugoid mode, as the cruising height decreases, the damping ratio increases. This can be explained by the fact that in the surface proximity the air trapped between the surface and the underside of the wing acts as an air cushion resulting in an increase damping in phugoid mode.

4.3 Flying Qualities Assessment

Flying qualities of the small WISE vehicle are investigated analytically from its dynamic characteristics, i.e. by calculating the frequency and damping ratio of SPPO and phugoid modes.

The flying qualities assessments of the vehicle are summarized in Table 7 and Fig.3.

Table 7 Undamped natural frequencies, damping ratios, and CAP in height variation

H	Mode	
	SPPO	Phugoid
1.5m	ω_n= 4.5921 rad/s ζ= 0.4970 CAP=1.7578 rad/s^2	ω_n=1.1532 rad/s ζ= 0.2068
2.0m	ω_n= 4.3028 rad/s ζ= 0.5466 CAP=1.6521 rad/s^2	ω_n=1.1597 rad/s ζ= 0.1785
2.5m	ω_n= 4.1102 rad/s ζ= 0.6090 CAP=1.5900 rad/s^2	ω_n=1.1501 rad/s ζ= 0.0811

Comparing the values in Table 7 with the requirements in Tables 2, 3, and 4 it can be seen that the damping ratios of SPPO and phugoid mode as well as the CAP values of the WISE vehicle in the considered range of height lie within the requirements of Level 1 flying qualities.

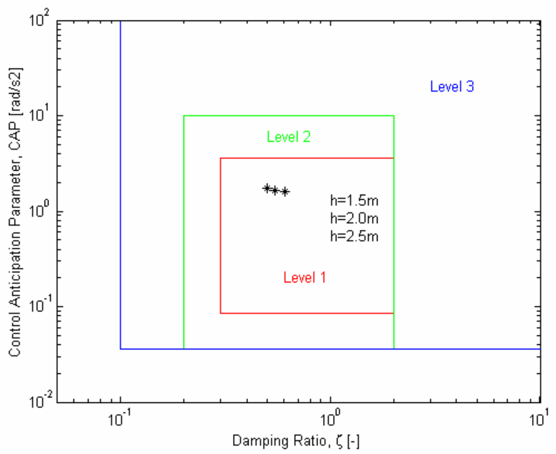

Fig. 3 Flying qualities level boundaries of SPPO in terms of CAP and damping ratio

5 Conclusion

The longitudinal stability and flying qualities criteria of WISE vehicle are discussed. Based on the semi-empirical USAF Datcom method the aerodynamic derivatives of the small WISE transport vehicle are estimated and the assessments of its static and dynamic stability as well as flying qualities are carried out. The assessments lead to a conclusion that the vehicle is stable to cruise in surface effect with flying qualities of Level 1. Out of surface effect the vehicle has slightly unstable phugoid.

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