TECHNICAL NOTE

STATIC STABILITY OF AERODYNAMICALLY SUPPORTED PLATFORMS MOVING ABOVE WATER

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SUMMARY

The motion stability is the most important problem of high-speed marine vehicles that utilize aerodynamic support. A simplified analysis and calculations of longitudinal static stability of several basic platforms moving above water are carried out in this study. The analysis is based on the extreme ground effect theory and the assumption of hydrostatic deformations of the water surface. Effects of the underlying surface type, Froude number, and several geometrical parameters on main aerodynamic characteristics, including the static stability margin, are presented. If the underlying surface is water instead of a rigid plane, the static stability worsens for platforms with flat or S-shaped lower surfaces, but it slightly improves for a horizontal platform with a flap. The static stability margin remains positive for S-shaped profiles at sufficiently low Froude numbers, while it is negative for other configurations.

NOMENCLATURE

c	Platform length (m)
C_L	Lift coefficient
F	Modified Froude number
g	Gravitational acceleration (m s^{-2})
h	Height of the center of gravity (m)
h_L	Height of the leading edge (m)
h_T	Height of the trailing edge (m)
L	Lift force per width (N m^{-1})
M	Moment per width (N)
p	Pressure (Pa)
p_0	Atmospheric pressure (Pa)
u	Airflow velocity (m s^{-1})
U	Incident airflow velocity (m s^{-1})
x	Horizontal coordinate (m)
x_{cg}	Position of the center of gravity (m)
X_h	Non-dimensional center of height
X_P	Non-dimensional center of pressure
X_θ	Non-dimensional center of pitch
ΔX	Non-dimensional static stability margin
y	Vertical coordinate (m)
y_p	Ordinate of the platform lower side (m)
y_w	Ordinate of the water surface (m)
y_1	Shape of S-profile (m)
θ	Platform pitch angle (rad)
ρ_a	Air density (kg m^{-3})
ρ_w	Water density (kg m^{-3})

1. INTRODUCTION

Very fast marine vehicles can benefit from application of unloading aerodynamic forces at high speeds. The contact with water and the water resistance of these vehicles are substantially reduced. A well-known example is a wing-in-ground (WIG) craft, which is completely supported by aerodynamic lift in a cruising regime. Other concepts of air-assisted marine craft are the vehicles with hybrid support: a part of the vehicle weight is unloaded aerodynamically, while the rest is supported hydrodynamically (and possibly hydrostatically). Examples of such concepts include several types of race boats, multi-hulls with a wing-shaped superstructure [1-3], and power augmented ram vehicles (PARV) [4-6].

Aerodynamics of a wing moving in the vicinity of an underlying surface may differ significantly from a flight in the free air. This difference is caused by several phenomena commonly referred to as the ground effect. For a broad class of wing shapes the lift can be increased and the induced drag can be reduced in the ground proximity. To calculate the wing-in-ground performance, even in operations above water, it is commonly assumed that the underlying surface can be treated as a rigid ground plane [7,8]. This assumption works well for usual WIG configurations in the cruising flight, when average clearances between the wing and water are 10-30% of the wing chord. Deformations of the water surface and their effects on WIG aerodynamics were found to be negligible for such cases [9,10]. However, on other types of air-assisted vehicles, such as PARV, as well as in the take-off regimes of conventional WIG craft, the height-to-chord ratio is often below 0.1, and effects of the deformable water surface can become substantial and must be accounted for. This regime is identified as the *extreme* ground effect.

A simple one-dimensional model for the airflow between the wing and water in extreme ground effect was proposed by Tuck [11] and later extended by Grundy [12]. They calculated water surface deformations and lift coefficients for several cases. However, no attention was paid to the influence of the deformable surface on the wing stability characteristics. The stability of WIG and ultra-fast air-assisted boats is the most significant operational problem of these vehicles. Frequent accidents with high-speed boats and WIG craft illustrate how easily these vehicles can become unstable. Sophisticated control systems are often required to achieve save flight in ground effect [13].

The main objective of this study is to demonstrate the influence of the water surface on stability characteristics of aerodynamically platforms. From previous WIG analyses above a rigid plane [8], it is known that usual single-element wings are often unstable in the ground effect. To achieve motion stability required for practical operations, many WIG craft utilize a large tail wing located outside the ground effect zone. The stability can be also attained by applying special wing profiles [14] and by the hull contact with an underlying surface on vehicles with hybrid support [15].

2. MATHEMATICAL MODEL

A two-dimensional platform flying close to the water surface is considered (Fig. 1). The extreme ground effect is assumed. This means that the clearance between the platform lower side and water is less than 10% of the platform length. In this regime the airflow in the under-platform channel is nearly one-dimensional, and the dominant component of the lift is due to increased pressure in the under-platform channel [8]. The pressure distribution under the platform can be found using the model proposed by Tuck [11]. The airflow is assumed to be incompressible and irrotational. The pressure at the trailing edge is atmospheric, and therefore, the airflow at this point equals to the incident airflow velocity $-U$ (sign minus is due to the selected x-axis direction shown in Fig. 1).

The continuity equation can be used to relate the local velocity $u(x)$ in the channel to effective channel height,

$$u\,(y_p - y_w) = -U\,h_T\,, \tag{1}$$

where y_p and y_w are the ordinates of the lower side of the platform and the water surface, respectively, and h_T is the distance between the platform trailing edge and the undisturbed water surface. The air pressure in the channel $p(x)$ is related to airflow velocity via Bernoulli equation,

$$p + \frac{1}{2}\rho_a u^2 = p_0 + \frac{1}{2}\rho_a U^2\,, \tag{2}$$

where ρ_a is the air density and p_0 is the atmospheric pressure. Assuming the dynamic pressure in the water to be much less than that in the air (in accordance with the "hydrostatic" assumption of Tuck [11]), the governing equation for the water surface elevation in the under-platform channel reduces to the following form,

$$p_0 = p + \rho_w g\, y_w\,, \tag{3}$$

where ρ_w is the water density and g is the gravitational acceleration.

Equations (1-3) can be transformed into a single cubic equation for the relative airflow velocity u/U,

$$\left(\frac{u}{U}\right)^3 - \frac{u}{U}\left(1 + \frac{2}{F^2}\frac{y_p}{h_T}\right) - \frac{2}{F^2} = 0\,, \tag{4}$$

where F is the modified Froude number,

$$F = U\sqrt{\frac{\rho_a}{\rho_w g h_T}}\,. \tag{5}$$

It was shown by Tuck (1984) that a positive solution of Eq. (4) continuous with the trailing-edge condition (Eq. 1) exists when the trailing edge is the lowest point of the platform and F is less than one.

After calculating the airflow velocity, the pressure in the channel and the water surface deformation are recovered from Eqs. (2,3). The overall lift coefficient and the non-dimensional center of pressure (with respect to the chord) are determined from the following expressions,

$$C_L = \frac{\int (p - p_0)dx}{\frac{1}{2}\rho_a U^2 c}\,, \tag{6}$$

$$X_P = \frac{\int (p - p_0)\; x\,dx}{C_L \frac{1}{2}\rho_a U^2 c^2}\,. \tag{7}$$

where the integration is carried along the platform, and c is the platform length. In an equilibrium state the center of pressure must coincide with the longitudinal center of gravity of a vehicle, if contributions of other forces are neglected.

To achieve stable motion, a vehicle must return into the equilibrium state after imposed deviations. While a general stability analysis of vehicles flying in the ground effect is rather complex, a good indication of the longitudinal stability characteristics can be given by the static stability margin ΔX,

$$\Delta X = X_h - X_\theta\,, \tag{8}$$

where X_h and X_θ are the non-dimensional centers of height and pitch, respectively,

$$X_h = \frac{1}{c}\frac{\partial M / \partial h}{\partial L / \partial h}, \quad (9)$$

$$X_\theta = \frac{1}{c}\frac{\partial M / \partial \theta}{\partial L / \partial \theta}, \quad (10)$$

where h is the height of the center of gravity (with respect to the undisturbed water surface), θ is the (small) pitch angle of the platform, M is the moment due to lift force with respect to the center of gravity, and L is the lift force. M and L (per unit width) are calculated as follows,

$$M = \int (p - p_0)(x - x_{cg})dx, \quad (11)$$

$$L = \int (p - p_0)dx, \quad (12)$$

where x_{cg} is the horizontal coordinate of the center of gravity.

The static stability is provided when restoring forces and moments appear upon a small deviation from an equilibrium state. In a constant-forward-speed regime on most WIG configurations the static stability is achieved when $\Delta X > 0$, implying that the center of height must be located in front of the center of pitch [8]. Although the static stability is not a sufficient condition for the overall stability, it is the most important when selecting a general configuration of a ground-effect craft. Dynamic stability, which is a subset of the static stability in a space of system parameters, can be usually achieved by adjusting mass distribution on the vehicle and deflections of control surfaces [16].

3. RESULTS

Three simple but practically important configurations of the platform lower surface are considered here: a flat plate at a positive attack angle (Fig. 1), a horizontal plate with a deflected flap (Fig. 2a), and an S-shaped profile, which is known for its superior stability characteristics (Fig. 2b). The variable parameters include the modified Froude number (Eq. 5) in the range where the above theory is applicable ($0 < F < 1$), the ratio of heights of the leading and trailing edges $H_L = h_L / h_T$, and the underlying surface type (rigid ground or deformable water). The ratio of the height of the leading edge above the undisturbed surface is taken to be 0.08 of the platform length. Additionally, the flap in the second case is selected to be 0.1 of the platform chord, and the shape of the zero-pitch S-profile with respect to the straight line connecting the leading and trailing edges is given by $y_1 = -0.002\, c \sin(2\pi\, x / c)$.

The calculated results for the flat plate without flap are shown in Fig. 3. The lift coefficient is higher at higher attack angle (or larger H_L) and greater above the water than over a rigid plane. The increment of C_L is more significant at higher Froude number F. These results are in agreement with Tuck's calculations [11]. The center of pressure moves back with increasing H_L and in case of water relative to the rigid plane. The static stability margin is zero for a flat plate moving over rigid surface in extreme ground effect, in accordance with previous findings [8]. When the underlying surface is water, the static stability margin becomes negative and decreases with increasing F. The instability is more pronounced for lower H_L. In order to counteract the instability, a stabilizing wing outside the ground effect zone (i.e., at a sufficient height) can be installed near the platform stern.

In the case of a horizontal plate equipped with a flap (Fig. 2b), the trends in the lift coefficients are similar to the previous case, but the magnitudes of C_L are higher for a flapped plate at the same H_L (Fig. 4). The centers of pressure are located closer to each other and to the platform midpoint. The static stability margin is negative and lower, implying even worse stability properties of a single platform of this kind. However, the effects of water and Froude number on stability are opposite to the case with a pitched flat plate. The deformable surface slightly improves stability in comparison with motion over a rigid plane.

Results for an S-shaped profile (Fig. 2b) are shown in Fig. 5. The lift coefficient is similar to the flat plate at the same H_L, while the center of pressure is moved forward. The effects of water on C_L and X_P are similar to those in previous cases. The static stability margin is positive for the selected S-profile above a rigid plane, implying statically stable motion of this system without additional stabilizing elements. The influence of water on stability is adverse. The static stability margin decreases with F and becomes negative at sufficiently high Froude numbers.

4. CONCLUSIONS

A simplified theory for the airflow under a platform above water is applied for estimating aerodynamic characteristics of the platform, including lift coefficient, center of pressure, and aerodynamic centers that define the longitudinal static stability. It is found that the lift coefficient increases above the water with respect to the ground up to the maximum Froude number at which the considered theory is applicable. The center of pressure displaces back to the trailing edge with increasing Froude number. The effect of water on the static stability depends on the platform shape. The static stability margin is found to decrease for a flat plate at a positive attack angle and for an S-shape profile with increasing Froude number, while it increases for a horizontal plate with a flap. The static stability margin is negative for flat plates with or without flap, but it is positive for an S-shaped profile at sufficiently low Froude numbers.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

1. DOCTORS, L. J., Analysis of the Efficiency of an Ekranocat: a Very High-Speed Catamaran with Aerodynamic Alleviation, *Proceedings of the International Conference on Wing In Ground Effect Craft, RINA, London, UK,* 1997.

2. DUBROVSKY, V., MATVEEV, K.I., Some Aspects of the Growth in Speed of Future Combat Ships, *International Journal of Maritime Engineering, Volume 146(1),* 2004.

3. COLLU, M., PATEL, M., TRARIEX, F., The Longitudinal Stability of an Aerodynamically Alleviated Marine Vehicle, a Mathematical Model, *Proceedings of The Royal Society A, Volume 466, pp 1055-1075,* 2010.

4. KRAUSE, F.H., The Power-Augmented-Ram Landing Craft Concept, *DTNSRDC/ASED Report 80/03, Bethesda, MD,* 1980.

5. KIRILLOVYKH, V.N., PRIVALOV, E.I., Transport Amphibious Platforms: a New Type of High-Speed Craft, *Proceedings of the Workshop on Ekranoplans and Very Fast Craft, University of New South Wales, Sydney, Australia,* 1996.

6. MATVEEV, K.I., Study of Power Augmented Ram Vehicles," *Proceedings of the SNAME Annual Meeting, Providence, RI,* 2009.

7. BENEDICT, K., KORNEV, N.V., MEYER, M., ELBERT, J., Complex Mathematical Model of the WIG Motion Including the Take-Off Mode, *Ocean Engineering, Volume 29, pp 315-357,* 2002.

8. ROZHDESTVENSKY, K.V., *Aerodynamics of a Lifting System in Extreme Ground Effect, Springer-Verlag, Heidelberg, Germany,* 2000.

9. MASUDA, S., SUZUKI, K., Simulation of Hydrodynamic Effects of Two-dimensional WIG Moving near the Free Surface, *Journal of the Society of Naval Architects of Japan, Volume 170, pp 83-92,* 1991.

10. BARBER, T., LEONARDI, E., ARCHER, D., Free Surface Deformation Caused by a Wing in Ground Effect over Water, *Proceedings of the Workshop "WISE up to Ekranoplan GEMs", Sydney, Australia, pp 90-101,* 1998.

11. TUCK, E.O., A Simple One-Dimensional Theory for Air-Supported Vehicles over Water, *Journal of Ship Research, 28(4), pp. 290-292,* 1984.

12. GRUDNY, I.H., Airfoils Moving in Air Close to a Dynamic Water Surface, *Journal of the Australian Mathematical Society, Series B, Volume 27, pp 327-345*, 1986.

13. NEBYLOV, A., WILSON, P.A., *Ekranoplanes: Controlled Flight Close to the Sea, WIT Press, Southampton, UK,* 2002.

14. STAUFENBIEL, R., KLEINEIDAM, G., Longitudinal Motion of Low-Flying Vehicles in Nonlinear Flowfields, *Proceedings of the Congress of International Council of Aeronautical Sciences, Munich, Germany, pp 293-308,* 1980.

15. MATVEEV, K.I., Modelling of Steady Motion of PAR Vehicle on Solid Surfaces, *International Journal of Aerodynamics, Volume 1(1), pp 52-63,* 2010.

16. KORNEV, N.V., MATVEEV, K.I., Complex Numerical Modelling of Dynamics and Crashes of Wing-in-Ground Vehicles, *Proceedings of the 41st Aerospace Sciences Meeting & Exhibit, Reno, NV, AIAA paper No. 2003-0600,* 2003.

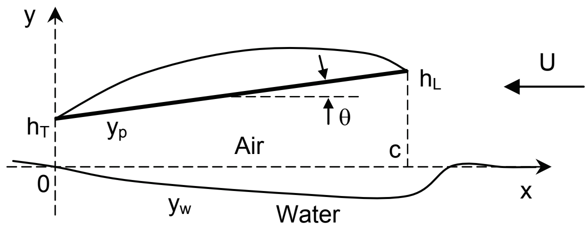

Figure 1: Platform with flat lower surface above water.

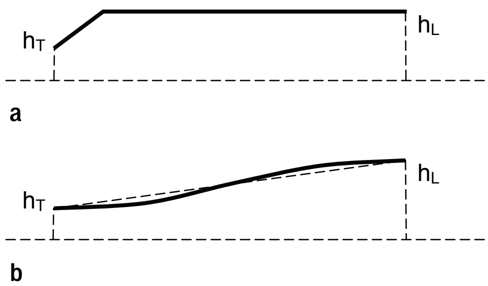

Figure 2: (a) Horizontal platform with flap. (b) S-shaped profile.

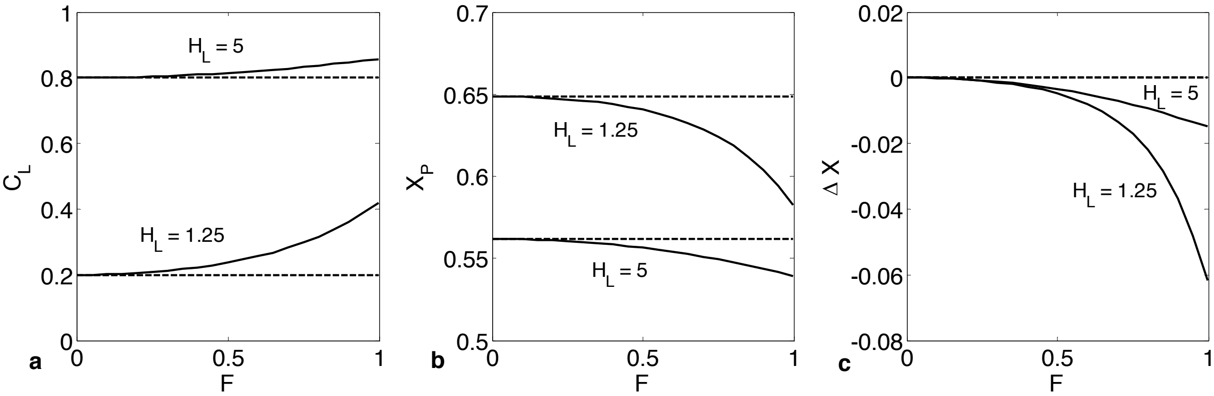

Figure 3: Results for pitched flat plate: (a) lift coefficient, (b) center of pressure, (c) static stability margin. Dashed and solid lines correspond to motion over rigid plane and water surface, respectively.

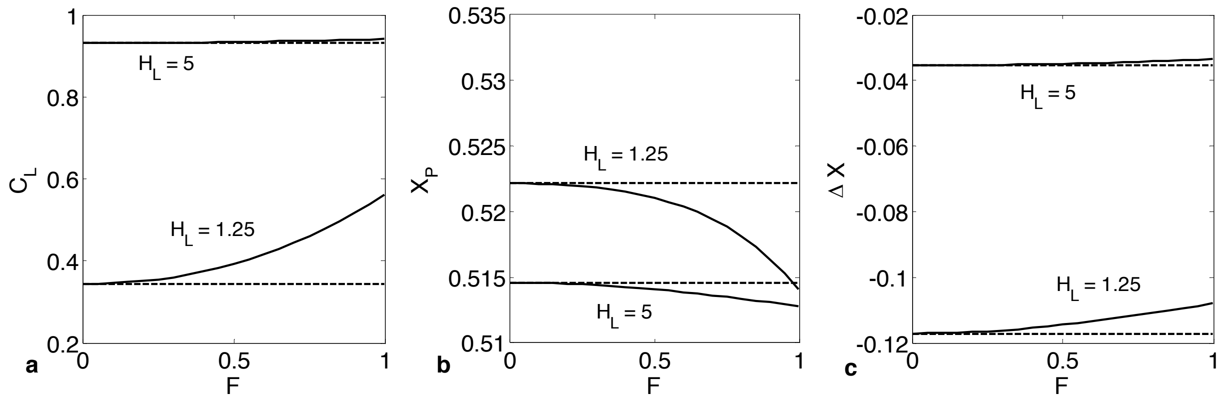

Figure. 4 Results for horizontal flat plate with flap: (a) lift coefficient, (b) center of pressure, (c) static stability margin. Dashed and solid lines correspond to motion over rigid plane and water surface, respectively.

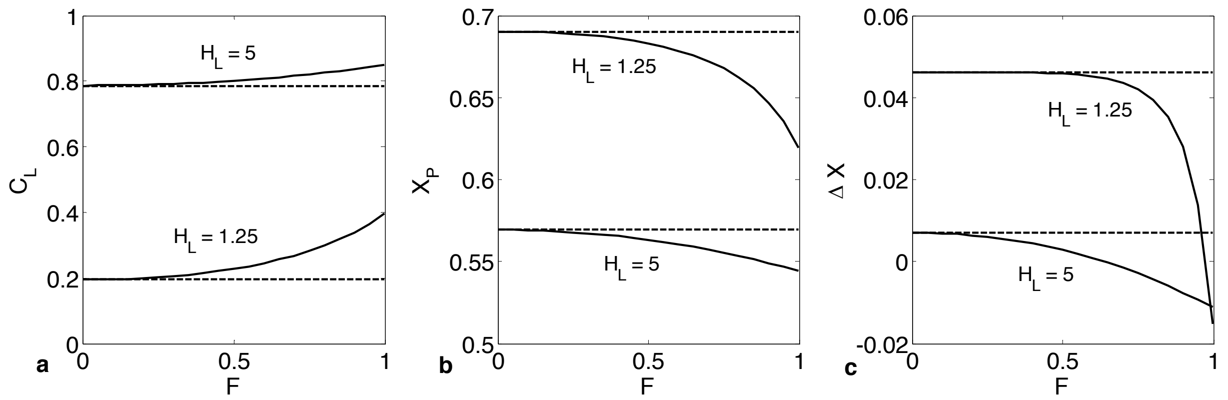

Figure 5 Results for pitched S-profile: (a) lift coefficient, (b) center of pressure, (c) static stability margin. Dashed and solid lines correspond to motion over rigid plane and water surface, respectively.

