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INVESTIGATION ON THE STABILITY OF A TRIMARAN WING IN GROUND EFFECT (WIG) CRAFT WITH ENDPLATE

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ABSTRACT

Longitudinal stability of Wing in Ground Effect Craft (WIG) is still the main concern of WIG craft designers and solutions are being sorted out to reduce this effect. In this research, investigations were conducted to determine the effect of flat ground and end plate proximity on the aerodynamic characteristics and stability criteria of NACA 6409 rectangular wing. The investigation were performed using vortex lattice method and examining the effects of flat ground and endplate on the performance of a trimaran WIG for relative ground clearances of $0.06 < h/c < 0.3$*, ratio endplate* $h_e/c = 0.1$ *on angles of attack between 0 and 8°, aspect ratio* $1 < AR < 2$ *Data is presented for lift coefficient with or without endplate, and static stability margin (SSM) versus angle of attack, and ground clearance. The result of the computation shows that the SSM was significantly affected with changing ground clearances with or without endplate. The results were also compared with experimental & CFD data from another research work.*

Keywords: *WIG trimaran, Longitudinal Stability, NACA 6409, vortex lattice method, endplate, ground effect*

NOMENCLATURE

A	Aspect Ratio (b/c)
b	Wing Span (m)
c	Chord length (m)
C_M	Moment Coefficient ($=L/0.5\rho AU^2_\infty$)
C_L	Lift Coefficient ($=L/0.5\rho AU^2_\infty$)
C_D	Drag Coefficient ($=D/0.5\rho AU^2_\infty$)
C_{Di}	Induced Drag Coefficient
h/c	Ground clearance
h_e/c	endplate ratio
N	Maximum number of element panel
c_c	cord along trailing leg of elemental panel (m)
α	Angle of attack (^{0})
ϕ	Dihedral angle (^{0})
σ	Ground Influence coefficient
φ	Endplate Influence coefficient
ψ	sweep Angle (^{0})
ρ	air density
Γ	vortex strength
F	Influence function geometry of single horshoe
S	wing area (m^2)
U	free stream velocity (m/s)
u	backwash velocity (m/s)
v	sidewash velocity (m/s)
w	downwash velocity (m/s)
r_1, r_2	vector distance
$\bar{x}, \bar{y}, \bar{z}$	body-axis system for plan form
$\hat{X}, \hat{Y}, \hat{Z}$	wind axis system
X, Y, Z	axis system for horsoe vortex
$\hat{x}, \hat{y}, \hat{z}$	distance along $\hat{X}, \hat{Y}, \hat{Z}$
x, y, z	distance along X, Y, Z
X_{ac}	distance center of aerodynamic from leading edge
X_{cg}	distance center of gravity from leading edge
X_h	distance center of height from leading edge

Subscript

u	backwash
v	sidewash
w	downwash
n	index for elemental panel
OGE	Out Ground Effect
IGE	In Ground Effect
E	With Endplate
WE	Without Endplate

1. INTRODUCTION

WIG craft is relatively new concept of transportation, can have a fruitful future as it is more efficient than equivalent aircraft and quicker than equivalent marine vessels. The advantages of the wing in ground effect craft come from additional lift provided by ground effect phenomenon. Wieselsberger [1], Reid [3] and Carter [4], theoretically and experimentally analyzed the effect of the ground on wings. Hemke [2] , analysis of experimental drag of wing with endplate shown effect endplate in aerodynamic characteristic. Absolutely, ground clearances and endplate ratio have influence in static stability margin (SSM). Kumar [5, 8], Irodov [6], Zhukov [9], and Staufenbiel [10, 11], Chun & Chang [13] all addressed the issue of pitch stability in ground effect, determining that the relative position of the aerodynamic centre in height and pitch influenced the nature of the pitch stability. Numerous studies have been conducted for analyzing the influence of the ground on wing performance. However, few largely overlooked. Rozhdestvensky [12, 14] presents a synopsis of research examining the influence of wing profile and platform on the positioning of the two aerodynamic centers.

In this paper, a trimaran WIG as shown in Figure 1 will be analyzed. The main wing of the WIG craft is of NACA 6409 section and the tail is of NACA 0012 section. The particulars of the craft are shown in table 1.

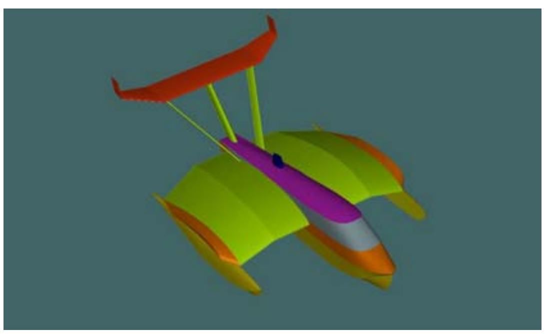

Figure 1.

Table 1. Principle dimension of WIG Catamaran

Length over all (LOA)	7.22 m
Breadth over all (BOA)	5.4 m
Hull breadth (B)	0.8 m
Side Hull breadth (B)	0.15 m
Span length (s)	5 m
Chord length (c)	4 m

2. NUMERICAL FORMULATION

2.1 Vortex lattice Method

The traditional representation for flat wing [7] is shown in Figure 2.

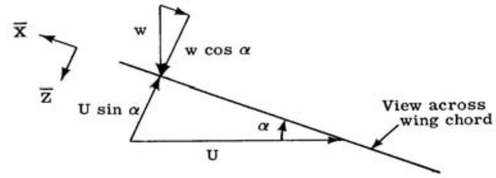

Figure 2.

$$w\cos\alpha - U\sin\alpha = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

The boundary condition is to be extended to represent wing with dihedral as in Figure 3.

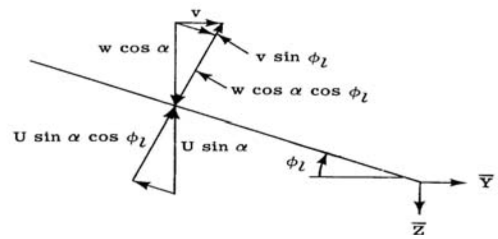

Figure 3.

$$w\cos\alpha\cos\phi - v\sin\phi - U\sin\alpha\cos\phi = 0 \quad \ldots (2)$$

The vortex lattice is located in a plane parallel to free stream as shown in Figure 4.

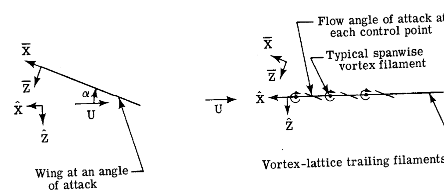

Figure 4.

Related from 0, equation (2) can be expressed for downwash influenced coefficient:

$$F_w(x', y, z, s, \psi, \phi') = \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

$$\frac{(y\tan\psi' - x')\cos\phi}{(x')^2 + (y\sin\phi)^2 + \cos^2\phi(y^2\tan^2\psi + z^2\sec^2\psi)' - 2z\cos\phi\sin\phi(y + x'\tan\psi')}$$

$$x\left\{\frac{(x' + s\cos\phi\tan\psi')\cos\phi\tan\psi'(y + s\cos\phi)\cos\phi + (z + s\sin\phi)}{\left[(x' + s\cos\phi\tan\psi')^2 + (y + s\cos\phi)^2 + (z + s\sin\phi)^2\right]}\right\}$$

$$-\left\{\frac{(x' - s\cos\phi\tan\psi')\cos\phi\tan\psi'(y - s\cos\phi)\cos\phi + (z - s\sin\phi)}{\left[(x' - s\cos\phi\tan\psi')^2 + (y - s\cos\phi)^2 + (z - s\sin\phi)^2\right]}\right\}$$

$$+\frac{(y + s\cos\phi)}{\left[(y + s\cos\phi)^2 + (z + s\sin\phi)^2\right]}\left\{\frac{x' + s\cos\phi\tan\psi'}{\left[(x' + s\cos\phi\tan\psi')^2 + (y + s\cos\phi)^2 + (z + s\sin\phi)^2\right]^{1/2}}\right\}$$

$$-\frac{(y - s\cos\phi)}{\left[(y - s\cos\phi)^2 + (z - s\sin\phi)^2\right]}\left\{\frac{x' - s\cos\phi\tan\psi'}{\left[(x' - s\cos\phi\tan\psi')^2 + (y - s\cos\phi)^2 + (z - s\sin\phi)^2\right]^{1/2}}\right\}$$

Sidewash influenced coefficient:

$$F_v(x', y, z, s, \psi, \phi') = \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(4)}$$

$$\frac{x'\sin\phi - z\cos\phi\tan\psi'}{(x')^2 + (y\sin\phi)^2 + \cos^2\phi(y^2\tan^2\psi + z^2\sec^2\psi - 2yx'\tan\psi')' - 2z\cos\phi\sin\phi(y + x'\tan\psi')}$$

$$x\left\{\frac{(x' + s\cos\phi\tan\psi')\cos\phi\tan\psi'(y + s\cos\phi)\cos\phi + (z + s\sin\phi)}{\left[(x' + s\cos\phi\tan\psi')^2 + (y + s\cos\phi)^2 + (z + s\sin\phi)^2\right]}\right\}$$

$$-\left\{\frac{(x' - s\cos\phi\tan\psi')\cos\phi\tan\psi'(y - s\cos\phi)\cos\phi + (z - s\sin\phi)}{\left[(x' - s\cos\phi\tan\psi')^2 + (y - s\cos\phi)^2 + (z - s\sin\phi)^2\right]}\right\}$$

$$+\frac{(y + s\cos\phi)}{\left[(y + s\cos\phi)^2 + (z + s\sin\phi)^2\right]}\left\{\frac{x' + s\cos\phi\tan\psi'}{\left[(x' + s\cos\phi\tan\psi')^2 + (y + s\cos\phi)^2 + (z + s\sin\phi)^2\right]^{1/2}}\right\}$$

$$-\frac{(y - s\cos\phi)}{\left[(y - s\cos\phi)^2 + (z - s\sin\phi)^2\right]}\left\{\frac{x' - s\cos\phi\tan\psi'}{\left[(x' - s\cos\phi\tan\psi')^2 + (y - s\cos\phi)^2 + (z - s\sin\phi)^2\right]^{1/2}}\right\}$$

Backwash influenced coefficient:

$$F_u(x', y, z, s, \psi, \phi') = \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(5)}$$

$$\frac{z\cos\phi - y\sin\phi}{(x')^2 + (y\sin\phi)^2 + \cos^2\phi(y^2\tan^2\psi + z^2\sec^2\psi - 2yx'\tan\psi')' - 2z\cos\phi\sin\phi(y + x'\tan\psi')}$$

$$x\left\{\frac{(x' + s\cos\phi\tan\psi')\cos\phi\tan\psi'(y + s\cos\phi)\cos\phi + (z + s\sin\phi)\sin\phi}{\left[(x' + s\cos\phi\tan\psi')^2 + (y + s\cos\phi)^2 + (z + s\sin\phi)^{1/2}\right]}\right\}$$

$$-\left\{\frac{(x' - s\cos\phi\tan\psi')\cos\phi\tan\psi'(y - s\cos\phi)\cos\phi + (z - s\sin\phi)\sin\phi}{\left[(x' - s\cos\phi\tan\psi')^2 + (y - s\cos\phi)^2 + (z - s\sin\phi)^{1/2}\right]}\right\}$$

The velocity induced by a straight vortex element can be calculated by Biot-Savart law which takes the form as :

$$U = \frac{1}{4\pi}\Gamma_n \frac{dl.r}{[r]^3} \quad \ldots\ldots\ldots \text{(6)}$$

Equation 6 can be integrated to give the induced velocity for a vortex segment of arbitrary length. This is done by Bertin & Smith. It takes the form of equation (7)

$$U = \frac{1}{4\pi}\Gamma_n \frac{r_1.r_2}{[r_1.r_2]^2}\left[r_0\left(\frac{r_1}{r_1} - \frac{r_2}{r_2}\right)\right] \quad \ldots\ldots \text{(7)}$$

From equations (3), (4), (5) and (7), downwash, sidewash and backwash velocity can be expressed as :

$$U_{u,v,w} = \frac{1}{4\pi}\Gamma_n F_{u,v,w}(x, y, z, s, \psi, \phi) \quad \ldots\ldots\ldots \text{(8)}$$

The coefficient along an elemental length of chordwise and coefficient divided by free stream dynamic pressure can be expressed to implement equation (8) in *Kutta-Joukowski* theorem which gives the following equation :

$$C_{L(OGE)} = 2\sum_n^{N/2}\left(\frac{2}{S}\Gamma_n c_c U_{u,v,w}\right) + \sum_n^{N/2}\left(\frac{2}{S}\Gamma_n 2b\right)$$

$$\left[(1 - U_{u,v,w}) + (U_{u,v,w}\tan\psi)\right]\cos\phi) \quad \ldots \text{(9)}$$

2.2 Effect of flat ground and endplate on aerodynamic characteristic

The theoretical treatment of ground effect presented by Wieselsberger [1] or predicting the reduction in induced drag for wing at various heights of the quarter chord of the wing above the ground. Experiments have conducted by Reid [3] & Carter [4]. The induced drag in ground effect is given by the equation

$$C_{Di(IGE)} = (1 - \sigma)\frac{C_L^{\,2} S}{\pi b^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(10)}$$

When $$\sigma = \frac{1 - 1.32\frac{h}{c}}{1.05 + 7.4\frac{h}{c}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(11)}$$

Equation (10) can be expressed:

$$C_{L(IGE)} = \sqrt{C_{Di}\pi\frac{b^2}{s}}\,\frac{1}{\sqrt{1 - \sigma}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(12)}$$

Using Equations (9), equation (12) can be rewritten as :

$$C_{L(IGE)} = C_{L(OGE)}\frac{1}{\sqrt{1 - \sigma}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(13)}$$

The frictional drag of the endplates can reduce induced drag, is sufficiently large to increase the efficiency of the wing. Analysis of experimental drag of wing with endplate is done by Hemke [2]

$$C_{Di(WE)} = (1 - \varphi)\frac{C_L^{\,2} S}{\pi b^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(14)}$$

When $$\varphi = \frac{1.66\frac{2h_e}{c}}{1 + 1.66\frac{2h_e}{c}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(15)}$$

Just like equation (13) coefficient with endplate could be shown:

$$C_{L(E)} = C_{L(WE)}\frac{1}{\sqrt{1 - \varphi}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(16)}$$

2.2 Longitudinal static stability

WIG should be stable in pitch like an airplane, if rigid body have been disturbed should be return to undisturbed position, and mathematically given as:

$$C_{M\alpha} < 0 \quad (17)$$

$$C_{M\alpha} = \frac{dC_m}{d\alpha} = \frac{dC_m}{dC_l} x \frac{dC_l}{d\alpha} < 0 \quad (18)$$

And derivatives could be written as:

$$C_{M\alpha} = \frac{dC_M}{dC_L} C_{L\alpha} < 0 \quad (19)$$

if $C_{L\alpha} > 0$, so $\frac{dC_M}{dC_L} < 0$ .... (20)

Where $\frac{dC_M}{dC_L} = \frac{X_{cg} - X_{ac}}{c}$ .... (21)

And derivatives could be written as:

$$\frac{dC_M}{dC_L} = \frac{X_{cg} - X_{ac}}{c} < 0 \quad (22)$$

From equation (22) it can be deducted the position of center of gravity (COG) of the craft should be located upstream of the aerodynamic center of pitch (ACP) (Rozhdestvensky [12]).

WIG also needs to have stability in the vertical dimension. The mathematical can be expressed as Kumar [5, 8]:

$$C_{Mh} < 0 \quad (23)$$

$$C_{Mh} = \frac{dC_m}{dh} = \frac{dC_m}{dC_l} x \frac{dC_l}{dh} < 0 \quad (24)$$

And derivatives could be written as:

$$C_{Mh} = \frac{\delta C_M}{\delta C_L} C_{Lh} < 0 \quad (25)$$

The derivatives of the lift coefficient with increasing height must be negative, mathematically have been expressed by Irodov [6] & Staufenbiel [10,11].

$$C_{Lh} < 0 \quad (26)$$

Referring to equation 21 derivatives could be written as:

$$\frac{\delta C_M}{\delta C_L} = \frac{X_{cg} - X_h}{c} > 0 \quad (27)$$

From equation (27) we can describe the position center of gravity (COG) craft located downstream of aerodynamic center in height (ACH) (Rozhdestvensky [12]).

After substituting equation (22) to equation (27), height stability equation can be derived

$$X_{ac} - X_h > 0 \quad (28)$$

The distance between the aerodynamic center in pitch and aerodynamic center in height are referred to as Static Stability Margin (SSM) Rhodes and Sayers [16]

$$SSM = X_{ac} - X_h > 0 \quad (29)$$

3. Computational result and discussion

Figures 5-10 draw a comparison of lift coefficient (C_L) for wing only carried out by VLM simulations, CFD simulation Maimun et al. [17], and experimental data Jung et al. [15]. The magnitude of lift coefficient increases with increment of aspect ratio, angle of attack, and ground clearance. According to Figure 5-10 lift coefficients of VLM at 0^o - 2^o angle of attack is less accurate than CFD results, where CFD is closer to experimental results. At 4^o - 8^o VLM results better than CFD results, because it's result near experimental results.

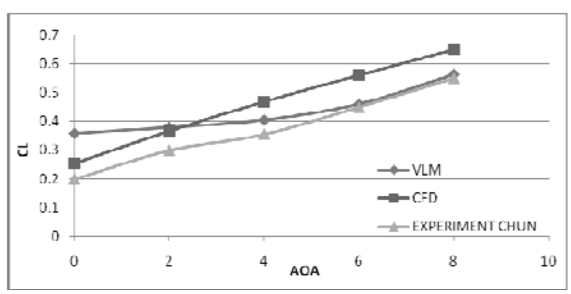

Figure 5. Lift Coefficient (C_L) versus angle of attack (α)for h/c= 0.1 and AR = 1

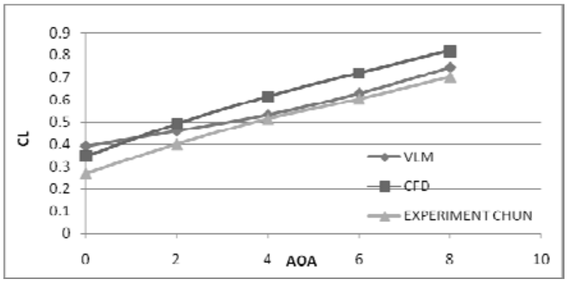

Figure 6. Lift Coefficient (C_L) versus angle of attack (α) for h/c= 0.1, AR = 1.5

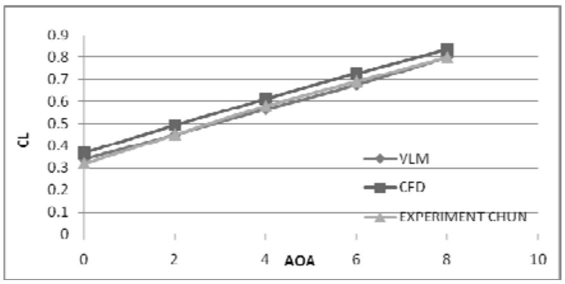

Figure 7. Lift Coefficient (C_L) versus angle of attack (α) for h/c= 0.1 and AR = 2

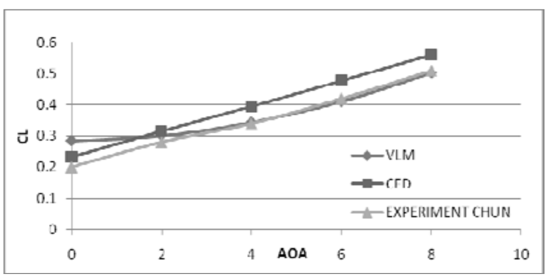

Figure 8. CL versus angle of attack for h/c= 0.3 and AR = 1

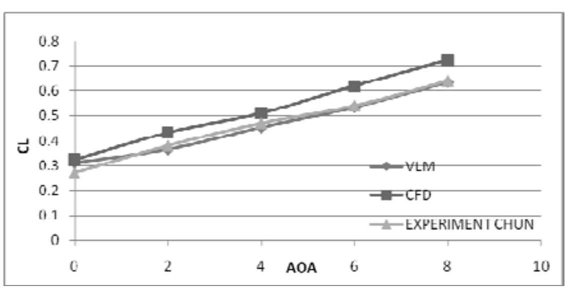

Figure 9. Lift Coefficient (C_L) versus angle of attack (α) for h/c= 0.3, AR = 1.5

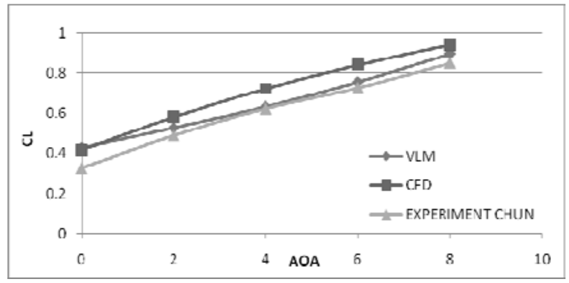

Figure 10. Lift Coefficient (C_L) versus angle of attack (α) for h/c= 0.3, AR = 2

Figure 11-15 shows the comparison of lift coefficient (C_L) for wing only with endplate due to VLM simulations, and experimental data Jung et al. [15] The magnitude of lift coefficient increases with increment of aspect ratio, angle of attack, and ground clearance. According to Figure 11-15 lift coefficients of VLM at 0^o - 2^o angle of attack is less accurate than experimental results. At 4^o - 8^o, VLM results near experimental results.

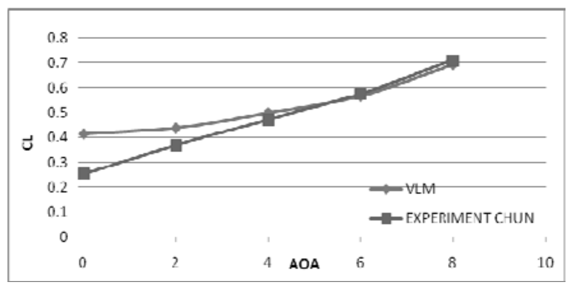

Figure 11. Lift Coefficient (C_L) versus angle of attack (α) for h/c= 0.1 and AR = 1, endplate he/c = 0.1

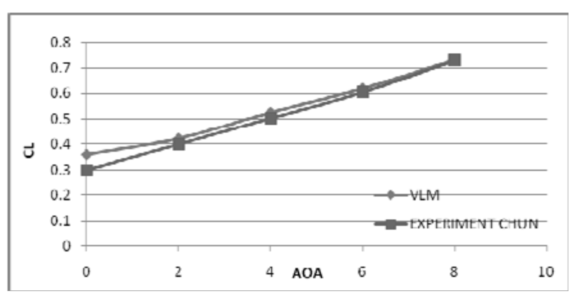

Figure 12. Lift Coefficient (C_L) versus angle of attack (α) for h/c= 0.1 and AR = 1.5, endplate he/c = 0.1

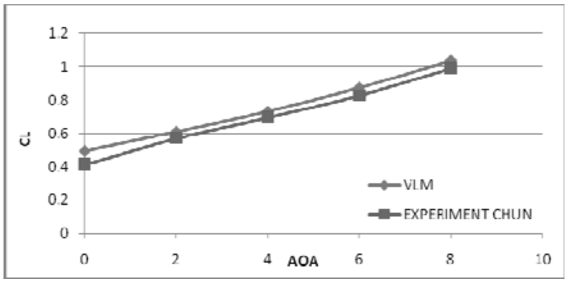

Figure 13. Lift Coefficient (C_L) versus angle of attack (α) for h/c= 0.1 and AR = 2, endplate he/c = 0.1

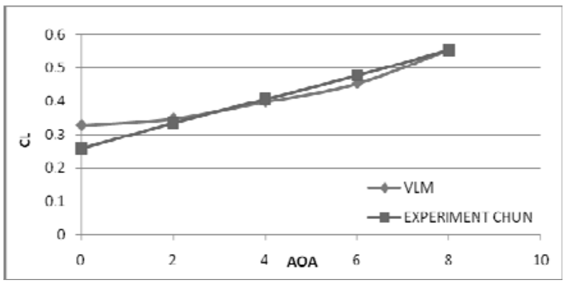

Figure 14. Lift Coefficient (C_L) versus angle of attack (α) for h/c= 0.3 and AR = 1, endplate he/c = 0.1

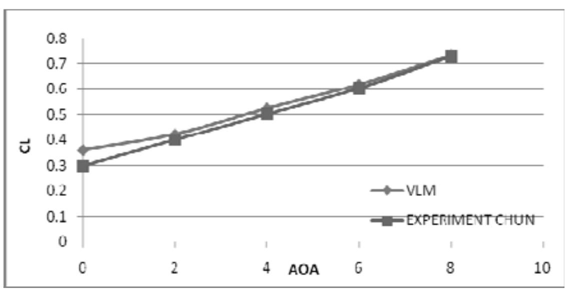

Figure 15. Lift Coefficient (C_L) versus angle of attack (α) for h/c= 0.3 and AR = 1.5, endplate he/c = 0.1

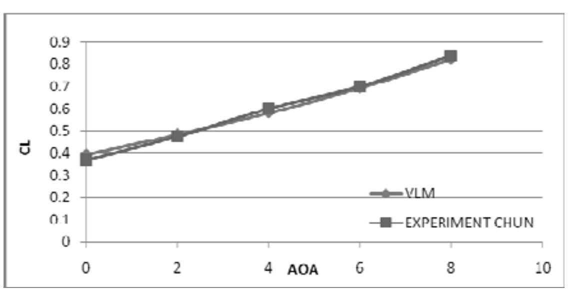

Figure 16. Lift Coefficient (C_L) versus angle of attack (α) for h/c= 0.3 and AR = 2, endplate he/c = 0.1

Regarding equation (29) the distance between the aerodynamic center in pitch and aerodynamic center in height must be greater than zero. 0 shows stability condition wing without endplate in variation ground clearance. At h/c = 0.06, SSM in stable condition, but when entering at h/c = 0.1, SSM becomes unstable, and after entering h/c = 0.3, SSM becomes stable again. The phenomenon occurred again in WIG with endplate (see 0). From Figures 17 and Figure 18 it can be concluded that there is not a stable phase between h/c = 0.06 and h/c = 0.3 and SSM decrease.

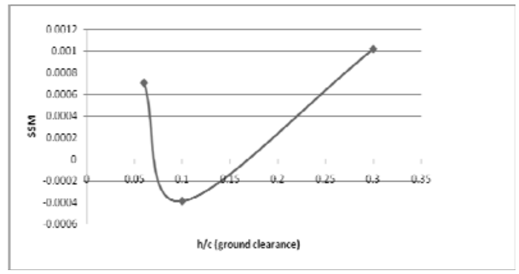

Figure 17. SSM wing w/o endplate, h/c= 0.06 - 0.3

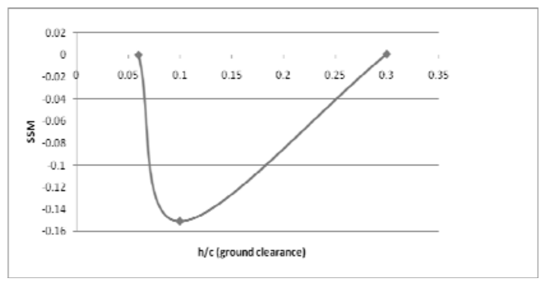

Figure 18. SSM wing with endplate, h/c= 0.06 - 0.3

4. Conclusion

In this work, traditional Vortex Lattice Method (VLM) has been modified by using much complex Flat Wing Theory [7] and then Wielselsberger Ground Effect Theory [2] has been used to calculate lift coefficient In Ground Effect (IGE). The results show values of Lift Coefficient (CL) are more close to experimental results for Angle of Attack (AOA) larger than 2 deg for different Aspect Ratio (AR) and Ground Clearances. Researchers suggest this procedure can be followed for initial estimation of Lift Coefficient for complex wing platform WIG.

It can be shown that using End Plate on the tip wing increases lift coefficient but reduces SSM. On this note, perhaps smart configuration of tail can solve this paradox which could be investigated later.

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