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Stability Analysis of a Wing in Ground Effect Craft

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Abstract: Analysis of dynamic stability is practically very important where the critical condition might occur during take-off of a Wing in Ground (WIG) craft. The change of hull resistance from the water to the air can make a sudden reduction in resistance. It is also strongly influenced by the pressure on the lower wing boundary layer which becomes greater due to air pressure reflections from the ground or water surface to the wings. The change of the pressure and resistance influenced the stability of the WIG significantly. In this research, dynamic stability of WIG craft during cruise and time domain analysis during take-off are conducted to study the WIG performance. A mathematical model was developed in time-domain (incorporating heave, pitch and surge motions) with varying parameters to analyze the WIG responses at the critical situation during take-off.

Key words: WIG craft, Panel Method, Stability, Time domain.

1. Introduction

The development of ground effect craft originated from observations made of the landing performance of aircraft in 1920's. A theoretical understanding of ground effect was achieved soon after, in 1921. USA and the USSR, became interested in attempting to exploit the potential benefits of ground effect. 1960's saw a number of experimental craft designed by these countries. The USA abandoned efforts to produce ground effect craft in the mid 1960's as they were more interested in Surface Effect Ship development. Germany began work in the late 1960's using the designs of Alexander Lippisch. However USSR was the undisputed leader, in research and development of WIG up to the late 1980's. Under these circumstances the Ministry of Science, Technology and Innovation (MOSTI) Malaysia was providing fund to develop a WIG, first of its kind here in Malaysia. To understand the nature of Wing in ground effect craft it is very important to know its definition. A lifting system that has increased lift-to-drag ratio due to flying very near to the ground is termed as "the ground effect (GE)" [1]. The GE is a phenomenon where aerodynamic, aero elastic and aero acoustic impact on a body that cruises while keeping very close distance to a surface [2]. If relative ground clearances is less or equal than 10% of the chord of the main wing then it is known as extreme ground effect (EGE) [3]. A wing-in-ground (WIG) effect craft is heavier than air craft that is using GE efficiently by operating just above an underlying surface. Number of terms used to define this type of craft, for example from the French word *e´kran* the name *ekranoplan* was derived, or the name *ekranolet* was originated from Russia, another name *nizkolet* which means low flying means of transportation [4]. Nevertheless WIG is a popular term that describes the ground effect vehicle. It also referred as WISES which means wing in surface effect ship, or GEM that is GE Machine, Gunther Jorg (Germany) used the term. Flaircraft, Tandem-Aerofoil Boat. The vehicles of Techno Trans (Germany) are known as Hydrowing(s). S. Hooker (Aerocon, USA) introduced Wingship to define WIG vehicles of massive size[6]. WIG needs huge power to take-off; it is the most important obstacle to the growth of the

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know-how. WIG requires about 2–3 times more power than it uses while cruise [4]. The foremost aspect of WIG drag forces is once the craft has taken off from the water surface into ground effect the drag becomes lower which allows it achieve higher cruise speed than other fast marine crafts but also to maintain speed over waves. This is a major plus for the WIG than other fast marine craft, another important feature of WIG drag before take-off it faces higher drag compared with other high-speed craft because of its planing hull, calculation of WIG drag at speeds below take-off are not simple rather complex, surprisingly researches on this area that is calculation of WIG drag at speeds below take-off are not done to the same depth [7]. During the take-off the wetted area of the WIG hull changes drastically ranging from a slender planing hull at initial stage of run to a planing surface of moderate aspect ratio just before the take-off [8] which can have a detrimental effect on longitudinal stability during take -off. Unlike aircraft, when a WIG with a fixed angle of attack fly near ground, its force and moment vary due to the ground effect. Therefore, the longitudinal stability characteristics of the WIG are quite different from that of conventional aircraft due to the existence of force and moment derivatives with regard to height. These stability characteristics play an important role in designing a safe and efficient WIG due to its potential danger in sea surface proximity. Kumar, Irodov, Staufenbiel and Hall conducted studies on the stability of WIG [9].

A new configuration of the compound wing was developed in UTM by Jamei et al. [10]. Based on this study it was found that the stability of the compound wing was higher than a common rectangular wing. In addition, the study shows the height static stability of the designed compound wing was strongly affected with ground clearance. It had slight reduction then fluctuated when Reynolds number was increased [11]. Aerodynamic characteristics of the WIG model with new wing configuration that was constructed in UTM was experimentally investigated by Mobassher et al. [12]. The study shows the WIG model is statically.

There are very few researches that deal with WIG's dynamic stability during takeoff. In order to investigate WIG craft's stability both the static stability and dynamic stability should be studied. Static stability considers only the moment balance by neglecting the inertia and time dependent terms, on the other hand the inertia and time dependent terms are included in the study of the dynamic stability. Time domain analysis is important for studying dynamic stability of WIG craft during take-off as time dependent terms has major effect. In this paper the dynamic stability during cruise and mathematical model for time domain analysis during take-off are discussed.

2. Design Parameters of UTM WIG craft

UTM trimaran single seated WIG was designed for construction. Maxsurf, Hydromax were used to design and to calculate hydrodynamic properties. Weight distribution was estimated through Workshop Maxsurf. The initial design of model and its principal dimension are shown in Table 1 and Figure 1. Figure 2 shows the lines plan.

Table 1 Principle dimension of WIG Trimaran

Length over all (LOA)	7.22 m	
Breadth over all (BOA)	5 m	
Hull breadth (B)	0.8 m	
Wing Span (b)	Ram Wing	2.5 m
	Dihedral Wing	1.25 m x2
Chord length (c)	Ram Wing	4 m
	Dihedral Wing	4 m

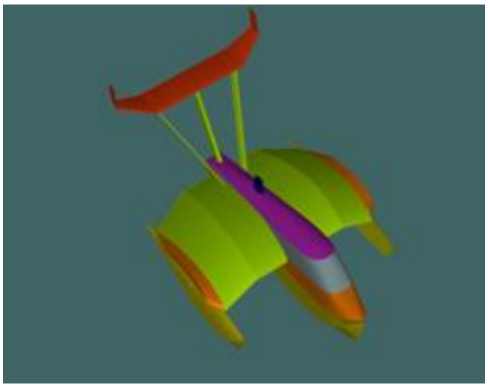


Fig. 1 - WIG Trimaran Design

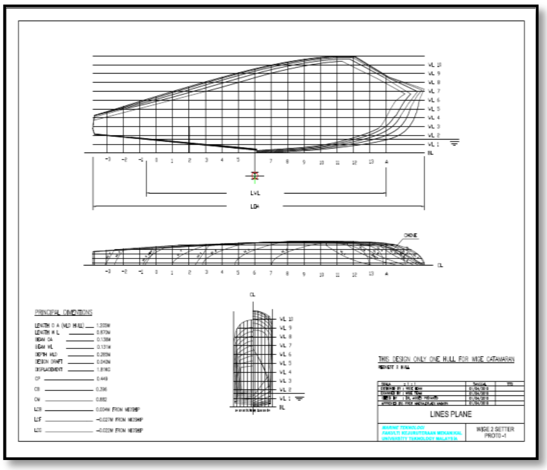


Fig. 2: Lines Plane

3. Static stability of WIG craft

For acceptable stability of WIG craft, the centre of gravity should be close to the height of aerodynamic centre (X_h), and it also should be between the height aerodynamic centre and pitch aerodynamic centre (X_α). Irodov [9] recommended a height static stability criterion as follows:

$$HS=CM_\alpha/CL_\alpha-CM_z/CL_z<0$$

where CM_α, CL_α, CM_z and CL_z are derivatives of lift and moment coefficient with respect to pitching angle and height. In a stable WIG craft, these derivatives usually are $CL_z>0$, $CM_\alpha<0$, $CL_\alpha>0$ and $CM_z>0$ [12]. Aerodynamic coefficients were obtained by conducting model tests at wind tunnel [12].

Fig. 3 - Wind tunnel test for WIG craft model [12]

4. Time Domain Analysis during takeoff

The WIG motion response during takeoff considers 3 DOF, the rotation in the vertical plane of a body-fixed coordinate frame about an earth-fixed reference frame. The origin of the body-fixed coordinate frame is the center of gravity of the body and the body is assumed to be rigid. The body-fixed and earth coordinate showed in the following figure 4.

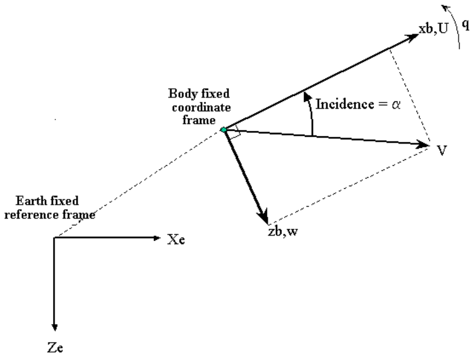


Fig. 4: Coordinate system

The equations of motion of the craft consider the effect of underwater hull forces and moment as follows;

$$(m+m')\ddot{x}_1 + m\dot{x}_5\dot{x}_3 + mgsinx_5 + R(u) = F_x \tag{1}$$

$$(m+m')\ddot{x}_3 - m\dot{x}_5\dot{x}_1 - mgcosx_5 + b_3\dot{x}_3 + c_3x_3 = F_z \tag{2}$$

$$\left(I_{yy} + I'_{yy}\right)\ddot{x}_5 + b_5\dot{x}_5 + c_5x_5 = M_y \tag{3}$$

$$F_x = F_d^w + F_d^t + T^p(u,n,z_e)cos\alpha \tag{4}$$

$$F_z = F_l^w + F_l^t + T^p(u,n,z_e)sin\alpha \tag{5}$$

$$M_y = M_y^w + M_y^t + M_y^p \tag{6}$$

Where index 1,3,5 are surge, heave and pitch respectively. The symbol *w*, *t*, and *p* are wing, tail, and propeller respectively, α is angle of propeller thrust line. The force and moment that affect added mass, added inertial moment, damping, and stiffness were calculated when the underwater hull still existing and as well the force and moment by the hydrodynamic effect are zero when the whole hull above the water. In order to consider the dynamic motion during takeoff, the water forces and moment acting to the underwater hull are considered which are static and dynamic. The static pressure and dynamic forces obtained using panel method where dynamic force obtained using potential flow method. The total force and moment can be obtained by integrating the forces and moments over the surface of the body.

$$F_i = -\int_S pn_i dS \tag{7}$$

$$M_i = -\int_S x_j pn_j dS \tag{8}$$

Where *p* is the pressure, *nk is* normal unit vector component in *k* direction, *xj is* distance from the reference point, and S is the panel's area. Total force and moment are integrated for the whole panels.

Since the hull of the craft assume run in stream flow of water, the panel method can be applied to calculate the pressure on hull surface. This method meshed the hull in quadrilateral panel with collocation point of the panel as the center of acting forces as shown below.

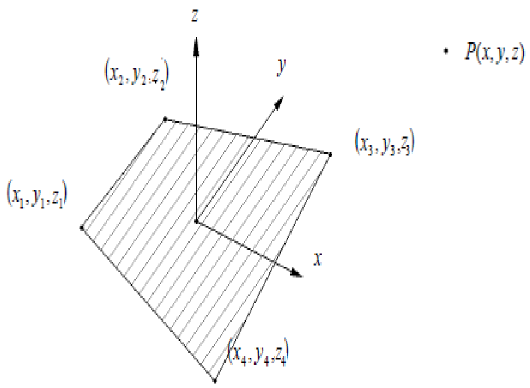


Fig. 5: Panel method

Calculation of collocation point **c** is done by mean values of the panel vortex coordinates:

$$c_x = \frac{(x_1+x_2+x_3+x_4)}{4} \tag{9.a}$$

$$c_y = \frac{(y_1+y_2+y_3+y_4)}{4} \tag{9.b}$$

$$c_z = \frac{(z_1+z_2+z_3+z_4)}{4} \tag{9.c}$$

In 3D panel method the potential of a source and dipole on a point at x,y,z as follows;

$$\Phi(x,y,z) = \frac{-\sigma S}{4\pi\sqrt{x^2+y^2+z^2}} \tag{10.a}$$

$$\Phi(x,y,z) = \frac{-\mu S}{4\pi z[x^2+y^2+z^2]^{-3/2}} \tag{10.b}$$

Where *S* is panel surface.

In the equations, the strength of the source σ and dipole μ are shown. Since these values in those equations are the wanted values, they are set to 1 for calculating the influence coefficients.

In order to make the solution uniquely defined, right combination of sources and dipoles must be selected. Setting up sources to:

$$\sigma_i = n_i . V_\infty \tag{11}$$

where $\mathbf{V}_\infty$ is vector of free stream velocity, will result in the value of the dipole μ as unknowns.

Assembling matrix of influence coefficients and "right hand side" vector in which is included boundary condition enables solving system of equations whose solution is precisely strengths of dipoles. System of equations looks like:

$$\begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1m} \\ a_{21} & a_{22} & \cdots & a_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mm} \end{bmatrix} \begin{bmatrix} \mu_1 \\ \mu_2 \\ \vdots \\ \mu_m \end{bmatrix} =$$

$$\begin{bmatrix} b_{11} & b_{12} & \cdots & b_{1m} \\ b_{21} & b_{22} & \cdots & b_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ b_{m1} & b_{m2} & \cdots & b_{mm} \end{bmatrix} \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \vdots \\ \sigma_m \end{bmatrix} \tag{12}$$

Where m is number of panels, ***A*** matrix of dipole influence coefficients, ***B*** matrix of source influence coefficients. Since the right side equation is known values from the equation (11), they can be multiplied into vector which is called $\mathbf{c}_{\mathbf{RHC}}$ (right hand side), than equation (12) simplified as follows;

$$\mu = A^{-1} . c_{RHS}$$

Velocity components are calculated by;

$$q_u = -\frac{\partial \mu}{\partial u} \qquad or \quad q_u = \frac{\mu_{i-1} - \mu_{i+1}}{\Delta u}$$

It indicated that induced velocity in direction **u** is equal to the difference between the strengths of dipole in front of and behind the observed panel divided by the distance of collocation points.

Induced velocities and free stream velocity are added to get the total velocity by;

$$\begin{bmatrix} v_x \\ v_y \\ v_z \end{bmatrix} = \begin{bmatrix} u_x & o_x \\ u_y & o_y \\ u_z & o_z \end{bmatrix} \begin{bmatrix} (g_u - q_u) \\ (g_o - q_o) \end{bmatrix}$$

Where g_u and g_o are velocity component of free stream in local coordinate system, **u** and **o** are longitudinal and perpendicular unit vectors of observed panel. The pressure field is calculated by;

$$c_p = 1 - \frac{V^2}{V_\infty^2}$$

Equation (7) and (8) are simplified as follow;

$$F_i = -\sum_{k=1}^{m} c_{pk} S_k n_{ik} q$$
$$M_i = -\sum_{k=1}^{m} c_{pk} S_k n_{ik} q \, . \, d_{ik}$$

Where q is dynamic pressure and d_{ik} is panel distance respect to the fixed center of body motion, instead of center of gravity.

The static force of the underwater hull obtained by;

$$F_z = \sum_{k=1}^{m} \rho g h_k$$
$$M = \sum_{k=1}^{m} [0 \quad 0 \quad \mathrm{F_{zk}}] \ (CG - C_c)$$

Where h is vertical distance of water level as the reference point to the panel's collocation point (C_c) and k is panel index.

The dynamic force and moment of wing and tail were calculated by;

$$F_x = 0.5\,\rho C_D S\,U^2 \qquad F_z = 0.5\,\rho C_L S\,U^2$$

$$F^{w,t} = [F_x \quad 0 \quad F_z]$$

$$M^{w,t} = F^{w,t}\ [CG - CP]$$

Where *i* is the index coefficient for drag and lift. CG and CP are center gravity and pressure points. In this paper, coefficients of lift and drag obtained from experiment. The model of thrust propeller developed from empirical data. The thrust value obtained as follows;

$$T = F_{max} R_t(throtle, mach, altitude)$$

$$F_x^p = T\,cos\alpha_p \qquad F_z^p = T\,sin\alpha_p$$

$$F^p = [F_x \quad 0 \quad F_z]$$

$$M^p = F[CG - C_{prop}]$$

Where F_{max} is the maximum force resulted in by propeller, R_t is non-dimensional ratio represents throttle and speed in mach, and δ represents the ratio of the air stream pressure at a chosen reference station relative to sea level standard atmospheric conditions. The model of atmospheric conditions uses COESA 1976, U.S. standard atmosphere. α_p is angle of propeller shaft.

6. Results and Discussion

As discussed earlier, static stability depends on the rate of change of moment and lift coefficient with respect to angle of attack and ground clearance. The height of static stability (HS) of the WIG craft model for both with and without endplates were found to be negative with respect to ground clearance (Figure 6), that makes the craft statically stable for both cases. Figures 7 and 8 illustrate the time domain motions of the WIG craft during take-off such as surge, heave and pitch for two different wing angle of attack, initially zero and one respectively. It should be noted that the angle of attack of the WIG craft is the summation of the angle of attack wing angle of attack (fixed) and pitch angle of the body at any given time. The takeoff is defined in the code when the wetted surface area and the hydrodynamic force become zero. Both figures depict the motion until takeoff. For one degree wing angle of attack, the WIG takes little more time than that of zero wing angle of attack, which occurs due to the difference of pitch motion. When the wing angle is zero the total angle of attack remains a little higher on average. More simulation results are needed to study WIG's performance in detail.

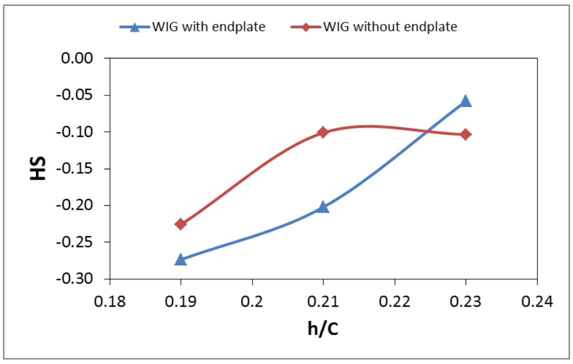
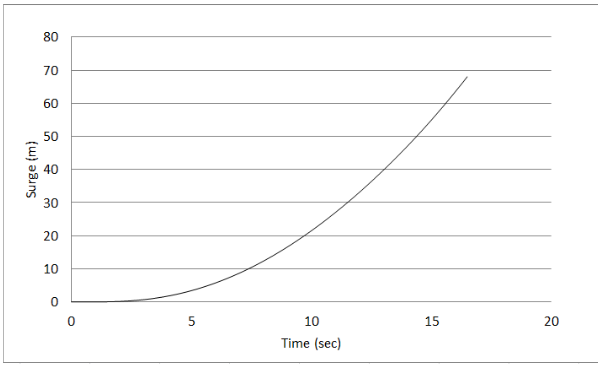


Fig.6: Height of static stability (HS) of WIG craft model with and without endplates versus ground clearance (h/c) at angle of attack of 4°[12].



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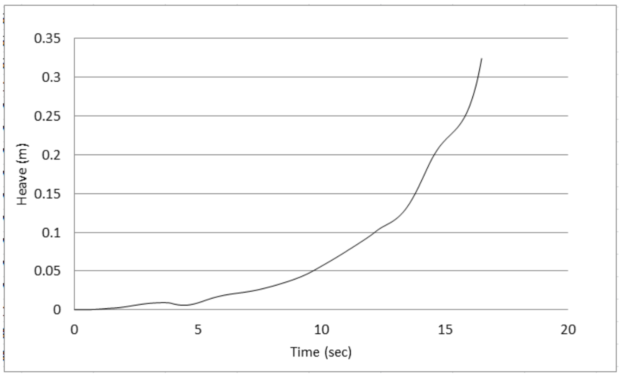

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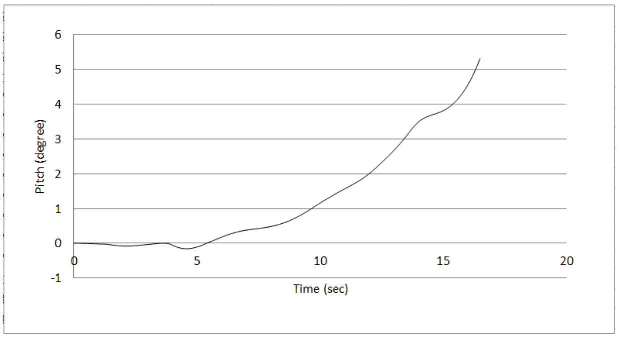

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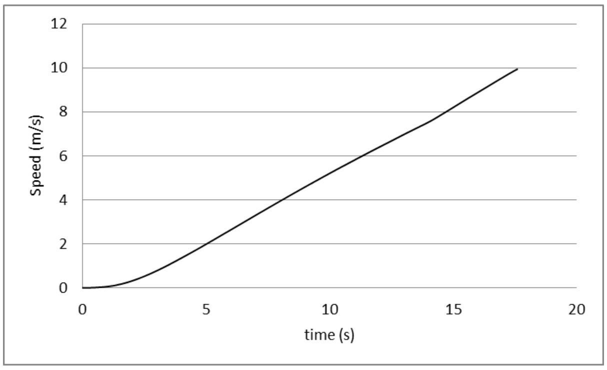
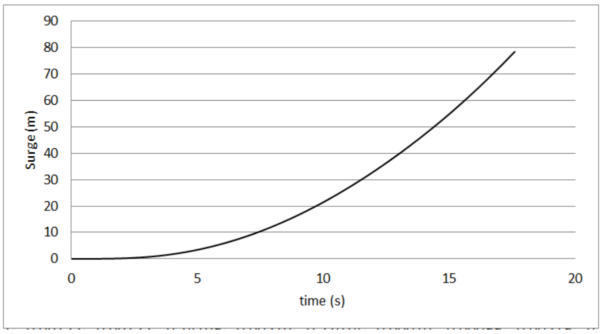


(d)

Fig. 7: WIG's motion during takeoff with initial zero degree wing angle of attack



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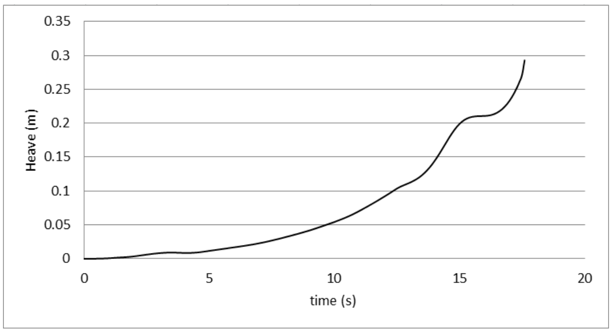

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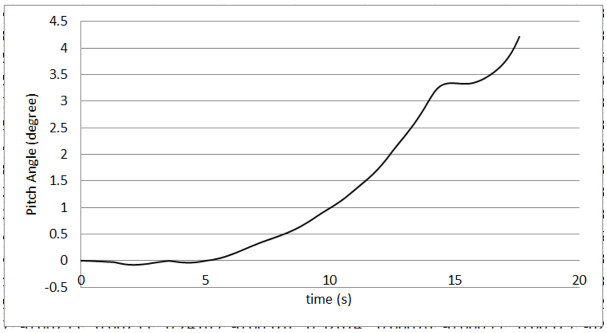

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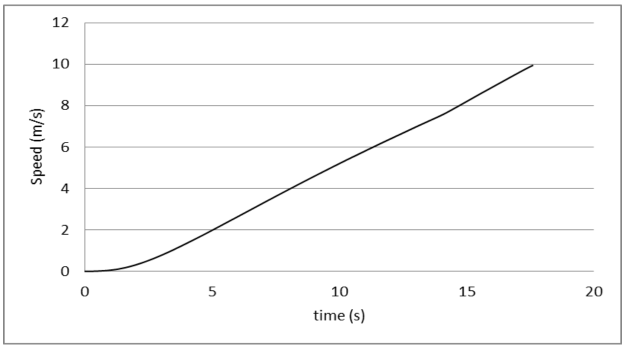

(d)

Fig. 8: WIG's motion during takeoff for with initial one degree wing angle of attack

7. Conclusions

Following conclusions can be drawn from this study;

1) Static stability during cruise was analyzed by conducting Model tests at wind tunnel. It was found that the designed WIG craft is statically stable.
2) A mathematical model is presented to study WIG craft's motion during takeoff that can be used for dynamic stability analysis.
3) Wing angle has an effect on takeoff time requirement, it is not necessary that for higher wing angle take off time will be lesser as we found from initial results that wing angle can have a significant effect on pitch thus on WIG's effective angle of attack.

A complete simulation results with different variable design parameters will be presented in near future.

Acknowledgments

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