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Preliminary Investigation into the design of a Mathematical Control Model for Flying Airboat Concept within Ground Effect

H. Y. Akuma[1] and M. Arifin[2]

[1]Faculty of Engineering & Life Sciences, Universiti Selangor, Jalan Timur Tambahan, 45600 Bestari Jaya, Selangor
yhellstrome@yahoo.com
[2]Faculty of Engineering & Life Sciences, Universiti Selangor, Jalan Timur Tambahan, 45600 Bestari Jaya, Selangor
irmuhidin@unisel.edu.my

Abstract: Despite the rapid evolution of technology in both the mechanical and aviation fields, one area that remains unexplored is the ground effect (GE) and its potential implication on land, sea and air vehicles of the future. In this regard, the development and implementation of Wing-in-Ground (WIG) crafts have particularly been lagging behind. WIG crafts are essentially vessels which are operated within the GE, whereby, an improved lift-to-drag (L/D) ratio is considered as a major enabling factor for aerodynamics improvement. Because of the unique properties within the GE, WIG crafts are inherently energy-efficient and performance-oriented vessels. Their versatility also makes them ideal for a wide range of applications encompassing both military and civilian use. The flying airboat (FA) concept is an example of a WIG craft that utilizes these characteristics, with a design that seeks to add the benefit of vertical take-off and landing (VTOL). In this study, the approach adopted for designing a mathematical control model of the concept is explored. The analysis findings indicate that the controllability of a WIG craft, such as the FA, is mostly reliant upon the fundamental equations of motion. Incorporation of span dominated GE (SDGE) into the control model substantially improves the lift-to-drag ratio and therefore, the overall performance of the WIG. The investigation concludes that implementing a manoeuvrability control model for the FA is viable with minor changes to the presented physical design.

Keywords: aerodynamics, flying airboat, lift-to-drag ratio, motion, performance-oriented, versatility, wig crafts

1. Introduction

Ground Effect (GE) is a phenomenon experienced when a mobile object is in close proximity within the earth surface either over the sea or land. This effect of the earth surface plane changes the airflow patterns and influences various aerodynamic characteristics during the process (Ghafoor et al., 2015). The result of GE is that there is enhanced body motion due to an increase of lift forces, and an enhanced power-to-weight ratio that increases overall performance. GE Vehicles (GEVs) or Wing-in-Ground Crafts (WIGs) are especially developed and designed to travel within the GE. In the modern transportation design, GEVs and WIG crafts continue to be implemented in various forms including Air Cushion Vehicles (ACVs), commonly known as hovercrafts, that employ the use of inflated skirts to travel over both sea and difficult land surface terrains. It is, however, worth noting that the majority of GEVs and WIG crafts currently being tested have a relatively high cruise speed which requires prolonged contact with the ground surface during the initial (take-off) and last (landing) stages of their flights (Dakhrabadi & Seif, 2018). This can significantly limit the scope of their runway and manoeuvre operations. Current limitations of Integrating Vertical Take-Off and Landing (VTOL) manoeuvres into WIG crafts and the relevant GE can be improved. The combination of the VTOL properties with GE creates a more manoeuvrable craft. VTOL properties are therefore evidently necessary in creating more versatile and practical crafts. A brief examination of the existing technology within this context suffices as a precursor to establishing the need for a hybrid model, such as the FA concept.

1.1. WIG Crafts (GE Vehicles)

WIG crafts are capable of travelling at relatively high speeds close to the ground surface (primarily the sea. This means that WIG crafts have the convenience of high-speed boats while avoiding limitations of turbulent or stormy sea conditions since they are not in contact with the sea (Dakhrabadi & Seif, 2018). However, to gain lift, WIG crafts like conventional aircrafts need to instigate airflow over the winged surface, which is primarily achieved by powered forward motion (Lee & Lee, 2013). WIG crafts therefore also need varying amounts of distance to gain speed and momentum for the creation of lift.. Additionally, WIG crafts need a relatively extended braking distance during landing due to the decreased coefficient of friction on water surfaces (Seif & Dakhrabadi, 2016). This can prove inconvenient in applications such as search and rescue missions that require, among other things, hovering capabilities, vertical landings and takeoff, as well as abrupt manoeuvre and precision.

1.2. Air Cushion Vehicles (ACVs)

ACVs, or hovercrafts as they are commonly referred to, are similar in operation to WIG crafts in that they are also vessels that operate within the GE, and like WIG crafts, not necessarily in contact with any ground surface. However, to achieve sustained motion, ACVs are equipped with pressurized tubing within their hull, facilitating differentiation of air pressure between the bottom of the vessel and the atmosphere above (Eremeyev et al., 2017). This pressure difference facilitates the creation of lift. The mode of propulsion for this type of vessels is typically high-powered ducted fans that facilitate forward and aft movement, as well as the pressure differentiation in the hull necessary for lift. The presence of a hull and skirts means that they can travel over various land terrains and water, hence their amphibious characteristics (Eremeyev et al., 2017). ACVs, however, also need horizontal distances to gain momentum and the speeds necessary for the creation of lift within the GE.

1.3. Vertical Take-off and Landing Crafts

VTOL crafts encompass any vehicle that is capable of creating and sustaining vertical lift as well as land vertically in relation to the earth surface. Conventionally, VTOL crafts mainly employ rotary wings as a means of creating vertical lift. The most fundamental disadvantage of aircraft with VTOL capabilities is their limited horizontal speeds, as a result of their power-thrust orientation in relation to the crafts' flight attitude (Eremeyev et al., 2017). To solve this, significant in-roads have been made into the implementation of tilt-rotor setups that significantly improve the horizontal speeds which the aircrafts can achieve during cruising (Nonami et al., 2010). The Bell V-22 Osprey, developed by Boeing, is an example of this configuration. There has also been the development of thrust vectoring aircrafts such as the F-35, with tilt jet tubes (Wang & Cai, 2015). A major drawback of this configuration, however, is that the tilt tubes potentially cause destruction to the ground environment and/or inflicting injuries to persons on the ground. On the other hand, VTOL crafts that employ tilt-rotor mechanisms have complex mechanisms that can be difficult and expensive to maintain (Wang & Cai, 2015). Tilt rotors also have exposed rotor blades with high tip vortices, which leads to tip losses and significantly reduces the efficiencies of the rotor blades.

1.4. Discrepancies

Based on the above brief analogies, there are a few discrepancies that are worth consideration:

I. WIG crafts and ACVs have notable limitations in relation to horizontal distances required to achieve lift within the GE, as compared to VTOL crafts.

II. ACVs rely on a combination of on-board engines and pressurized skirts for lift creation, whereas WIG crafts primarily rely on winged surfaces for this purpose.

III. VTOL crafts are significantly more precise in their ability to stop within short distances as compared to WIG crafts and ACVs.

IV. The ability to achieve Vertical Take-Off, hovering and landing capabilities for most VTOL crafts also greatly limits their maximum cruising speeds.

Based on the above considerations, the proposed concept should meet the following minimum thresholds:

I. Operate within the GE for optimum performance and efficiency

II. Have the ability to achieve Vertical Take-off, hovering and landing characteristics

III. Achieve cruising speeds that are close to or better than those of current WIG crafts.

IV. Have well-defined design characteristics that facilitate enhanced manoeuvrability characteristics synonymous with VTOL crafts.

The FA is an example of a WIG craft that seeks to integrate VTOL into its manoeuvre. This is achievable by implementing a design that uses twin ducted fans to provide thrust in combination with a tubing system underneath the craft that creates pressure differentiation to provide vertical lift. This paper thus examines the preliminary control design framework for the FA concept with regard to the various concepts that are necessary for the achievement of such manoeuvrability.

2. Methodology

Based on the above parameters and the favourable characteristics of the considered WIG, ACV and VTOL crafts, a configuration that incorporates variable area ducts and/or thrust vectoring method is ideal for achieving VTOL properties as well as sustained hovering. The FA is a type of WIG craft that utilizes twin ducted fans powered by a diesel engine to produce vertical lift. To achieve this, the pressurized air from the ducted fans is fed into a tubing system underneath the hull with eight outlets; four on the ports and four on the starboard. The outlets are responsible for creating an area of pressure differentiation underneath the flying boat's hull, which creates and sustains vertical lift. Its engine configuration is similar to that of ACVs and encompasses ducted fans to minimize blade tip losses and maximize power output and efficiency. The FA configuration also encompasses a winged surface that enhances its lateral stability to prevent unnecessary rolling moments and a rudder system for directional manoeuvrability (Oo et al., 2017). An iteration of the flying boat is presented as follows:

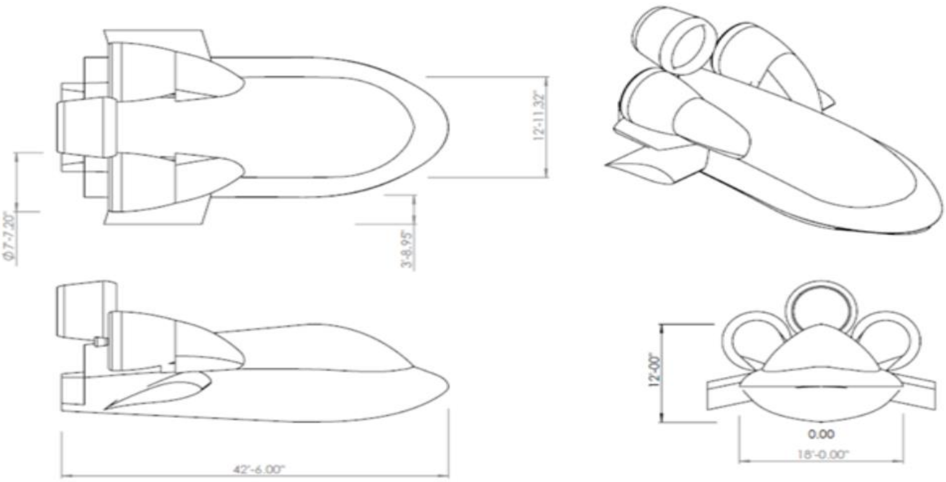

Fig 1. Sketches showing various elevations of the FA's conceptual design (Mohd Zaid, 2015)

2.1. Frames of Reference

The vital frames of reference for the purpose of this investigation are as follows (Duke et al., 1988):

A. Inertial (Earth Fixed) frame (EFF) - it is assumed that the inertial and earth fixed frame are the same since the FA travels within the GE, relatively close to the earth surface. In this frame, the origin O is the center of the earth, Z is directed downwards in the same direction as gravity, X axis is towards the geographical north, and the Y axis is eastwards.

B. Navigation (Vehicle Carried) frame - This frame has its origin at the center of gravity of the FA. The Z direction is collinear with the gravitational axis and points downwards towards the earth. The X and Y axes are similar to EFF and are directed northwards and eastwards, respectively.

C. Body Frame – The Center of Gravity (CG) of the body is the origin O. The X axis is along the longitudinal axis and points towards the nose; Y axis is along the lateral axis and points to the right (starboard) side; Z axis is along the vertical axis and points towards the earth. The figure below illustrates various denotations of the body frame (Wieselsberger, 1921).

The relationship between the identified reference frames above can be summarized using key transformations as follows:

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i. The transformation from Earth Fixed Frame (EFF) to body Frame (BF) with gravitational force as the major underlying factor
ii. Relationship between the wind frame and the body frame as a definition of the body's aerodynamics

In a relationship (i) above, the transformation from EFF to BF is facilitated by a transformation matrix that is defined as follows:

$$X_B = T_{B \to E} X_E \tag{1}$$

In this investigation, the approach adopted involves designing the mathematical control model for the FA's manoeuvrability based on preconceived parameters and operational objectives as demonstrated above. There are several theories applied to come up with the ideal control design framework for the concept, including aerodynamic theory, GE theory and Feedback control theory.

2.2. Aerodynamic Theory

The aerodynamic theory is one of the frameworks for the control design of the FA and involves the concept's reliance upon dynamic pressure and the free air stream for the achievement of motion and lift. The lift, drag, thrust and weight forces acting on the FA are thus mathematically derived as components of the concept's manoeuvrability. The resultant definition of the primary axes of motion and manoeuvrability is similar to that of aerodynamic bodies such as aircraft and is as follows.

X-axis - Longitudinal axis running from the fore to the aft of the craft

Y-axis - Lateral axis running from the left to the right of the craft

Z-axis - Vertical axis running perpendicular to a reference point on the earth's surface.

Wind axes – These axes along which disturbances such as turbulence can be referenced relative to the craft's position and motion.

Forces and moments in relation to the above axes are illustrated below:

$$\begin{bmatrix} X \\ Y \\ Z \\ L \\ M \\ N \end{bmatrix} := \begin{bmatrix} \text{longitudinal force} \\ \text{transverse force} \\ \text{vertical force} \\ \text{roll moment} \\ \text{pitch moment} \\ \text{yaw moment} \end{bmatrix} \tag{2}$$

In relation to the above forces, the expected translational and angular velocities for the craft are defined as follows.

$$v := \begin{bmatrix} U \\ V \\ W \\ P \\ Q \\ R \end{bmatrix} = \begin{bmatrix} \text{longitudinal (forward) velocity} \\ \text{lateral (transverse) velocity} \\ \text{vertical velocity} \\ \text{roll rate} \\ \text{pitch rate} \\ \text{yaw rate} \end{bmatrix} \quad (3)$$

The fundamental angles used as references for the different motions and manoeuvres in relation to the Earth Surface are as follows.

$$\eta := \begin{bmatrix} X_E \\ Y_E \\ Z_E, h \\ \phi \\ \theta \\ \psi \end{bmatrix} = \begin{bmatrix} \text{Earth fixed } x \text{ position} \\ \text{Earth fixed } y \text{ position} \\ \text{Earth fixed } z \text{ position} \\ \text{roll angle} \\ \text{pitch angle} \\ \text{yaw angle} \end{bmatrix} \quad (4)$$

To establish the manoeuvrability control framework for the FA concept, two assumptions are made in relation to their positioning in space as follows.

I. The earth is the inertial reference frame

II. The WiG craft is a rigid body

2.3. GE Theory

The GE theory is a major component of the research since it hypothesizes the FA's projected capabilities to operate within the predetermined conditions and achieve its intended objectives. The theory entails Chord-dominated and Span-dominated GE (CDGE & SDGE). The research concentrates on Span-Dominated GE as a means of reducing drag and necessitating ideal aerodynamic characteristics for flight of the FA close to the ground surface. Within the GE, the aspect ratio of the FA is increased significantly, therefore increasing its lift producing capabilities (Bennett et al., 2007).

2.3.1. Span-Dominated GE (SDGE)

This form of GE is associated with the induced drag, resulting from leakages on a finite wing. As a result of SDGE, a body in motion within the GE appears to have a higher aspect ratio (the effective aspect ratio, AR') in comparison with the actual geometric aspect ratio, AR when the body is in free flight (Wieselsberger, 1922). Because this research focuses on the manoeuvrability of the FA concept comprising a finite wing for the sustenance of lift during motion along the X-direction, SDGE is the main form of GE considered for the design of a mathematical control model. SDGE can be illustrated as follows.

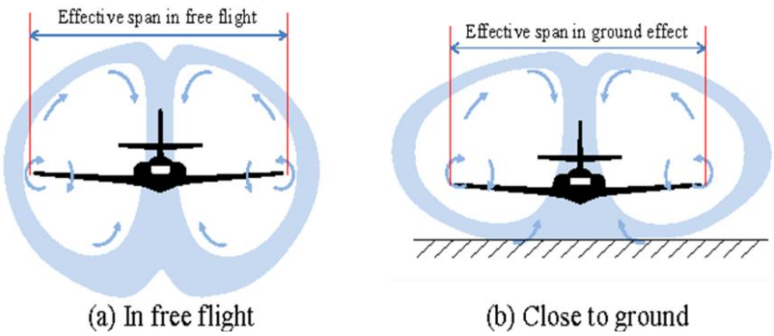

Fig 2. Aspect ratio in free flight vs in GE (Wieselsberger, 1922)

The illustration above demonstrates an enhanced effective span and a subsequent improved aspect ratio within the GE. The GE's parametric influence was first determined by Wetmore and Turner and for the purpose of this investigation, is presented as follows.

$$\sigma_{ge} = e^{-2.48(\frac{2h}{b})^{0.768}} \quad (5)$$

where σ_{ge} is the GE factor of influence, h is the height above the ground surface, and b is the wing span

In the above equation, the ratio of Height to Aspect ratio (h/b) is assumed to be in the range of 1/1.5 to 1/2. The general assumption within the GE is, therefore that H is twice the height of the body in motion from the ground (Wieselsberger, 1921). In a winged body, the induced drag acting on a body travelling within the GE can thus be denoted by the following equation.

$$C_{Di} = \frac{C_L^2}{\pi e AR} \quad (6)$$

where e is the span efficiency, and AR is the resultant aspect ratio

The effective aspect ratio is subsequently derived as follows.

$$AR = AR'/(1 - \sigma_{ge}) \quad (7)$$

3. Results and Discussion

The theories pursued as methodologies can be used to define the manoeuvrability of the FA concept. To do so, forces and moments of the body are defined within the Newton-Euler framework to come up with various equations defining the six degrees of freedom for the body. These equations denoting the flight dynamic system are applied in conjunction with state equations to model the concept's controls.

3.1. Flight Dynamics System

Fundamentally, the airboat is designed to have four (4) degrees of freedom encompassing translation motion about the three primary axes (X, Y, and Z), and a singular rotational motion about the Z axis (yawing). The translational forces in the X, Y and Z directions for a rigid body in space can be summarized by the following relationship between the respective forces (X,Y, and Z), the body mass M and the velocity (U, V and W).

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = M \begin{bmatrix} U \\ V \\ W \end{bmatrix} \qquad \begin{bmatrix} U \\ V \\ W \end{bmatrix} = \begin{bmatrix} a_x + rv - qw - g\sin\theta \\ a_y + pw - ru + g\sin\varphi\cos\theta \\ a_z + qu - pv + g\cos\varphi\cos\theta \end{bmatrix} \tag{8}$$

To determine the inertial acceleration along the defined axes, the body frame (FA) is assumed to be moving in reference to the earth fixed frame. In this regard, the motion of the FA is divided into translational and rotational motions and described in the following sections.

3.1.1. Translational Dynamics

For this investigation, translational dynamics are used to define the change in the vertical position of the FA, entailing the motion of the CG from an initial position to a final position. The fundamental principle applied to this regard is Newton's second law, which is given by the following set of equations:

$$\sum F = ma \tag{9}$$

$$d\vec{F} = \mathrm{m} \cdot d\vec{a} = \mathrm{m} \cdot d\overrightarrow{\left(\frac{d}{dt}(\vec{V})\right)} \tag{10}$$

$$\frac{d}{dt}(\overrightarrow{V_T})_E = (\frac{d}{dt}(\vec{V}_T))_B + \vec{\omega} \cdot \overrightarrow{V_T} \tag{11}$$

In the second set of equations above, the velocity derivative with reference to the EFF is equated to the sum of the total velocity of the body (BF) and the cross product of angular velocity and linear velocity, respectively. The representation of angular and linear velocities on the body frame can be further broken down as follows respectively.

$$\vec{\omega} = \vec{\imath}p + \vec{\jmath}q + \vec{k}r \qquad \overrightarrow{V_T} = \vec{\imath}u + \vec{\jmath}v + \vec{k}w \tag{12}$$

The components of $d\vec{F}$ and $\overrightarrow{V_T}$ in the above equations can further be broken down as follows.

$$F = [\Sigma X \ \Sigma Y \ \Sigma Z]^T \tag{13}$$

$$V = [u\ v\ w]^T \tag{14}$$

$$\frac{d}{dt}(\vec{V}_T) = \frac{1}{m}F - \omega \times \overrightarrow{V_T} \tag{15}$$

To determine the translational acceleration of the airboat in the wind axis system, total velocity V_T along x, y and z axes is denoted in terms of the angle of attack α, and sideslip angle β as follows.

$$\begin{aligned} u &= V_T \cos\alpha \cos\beta \\ v &= V_T \sin\beta \\ w &= V_T \sin\alpha \cos\beta \end{aligned} \tag{16}$$

Where;

$$\begin{aligned} V_T &= |V_T| = (u^2 + v^2 + w^2)^{1/2} \\ \alpha &= \tan^{-1}(\frac{w}{u}) \\ \beta &= \sin^{-1}(\frac{v}{V_T}) \end{aligned} \tag{17}$$

The acceleration terms in the translational dynamics of the wind axes, which are defined above can thus be summarized as follows.

$$[\dot{V}_T\ \dot{\alpha}\ \dot{\beta}] = f_2[x(t), \dot{x}(t), u(t)] \tag{18}$$

Simulation of the above equations on the MATLAB platform shows velocity along the linear axes represented by U, V and W, which denote the translational dynamics of the FA. This is illustrated in Fig. 3 below.

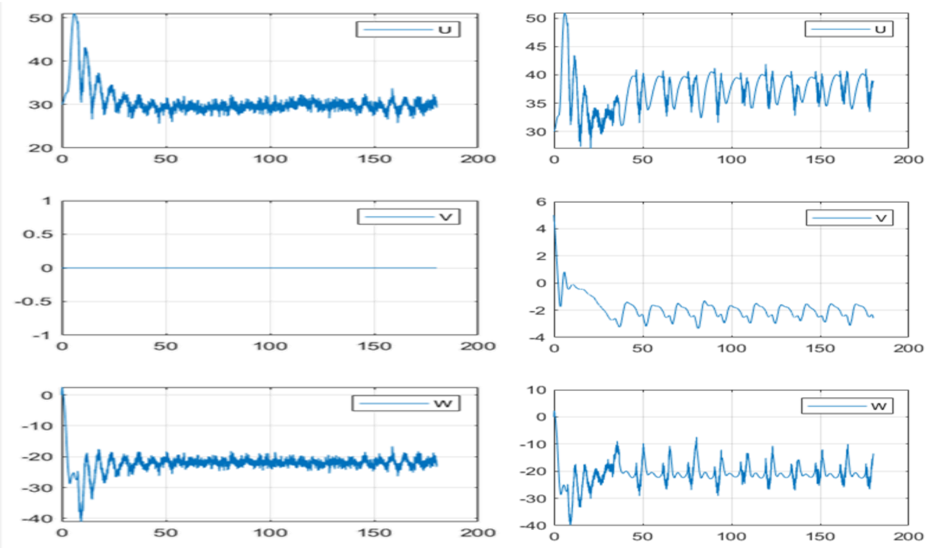

Fig 3. Translational dynamics showing velocities u,v and w

In the first illustration, the control input velocity is set at 30 m/s and a pitch angle of 5 degrees. The results show that the velocity in the x-direction denoted by 'u' initially increases before eventually oscillating around the 30 m/s marks in accordance with equation 16. The illustration also shows that velocity in the y-direction remains unchanged if there is no change in the sideslip angle, as denoted by Eq. 16. Changes are also noted in the velocity along the z-axis denoted by W. This is because, despite an initial state of zero, the pitch angle (θ) of five degrees contributes to the vertical velocity, W.

In the second illustration, an initial velocity in the y-axis is introduced. The input of v is thus set at 5 m/s. The resultant plots show that all the velocities about the primary axes, u, v and w are affected. This is because of the relationship between the v velocity and the total velocity of the body as denoted by Eq. 16 and 17. The results here show that the conceived equations are ideal as a means of determining and showing the concept's translational dynamics.

3.1.2. Rotational Dynamics

The investigation also encompasses the rotational dynamics of the FA concept which involves motion about the center of gravity with relation to the frame axes.

Newton's second law of motion is also applied to determine rotational force or torque, as follows.

$$\vec{M} = \frac{d}{dt}(\vec{H}) \tag{19}$$

Whereby M is torque and H is angular momentum.

The angular momentum of the body H can further be broken down as follows.

$$\vec{H} = I\vec{\omega} \tag{20}$$

Whereby I is the matrix defining inertia on the body and ω is the angular velocity

The inertia matrix is subsequently defined as follows (Zipfel, 2007).

$$I = \begin{bmatrix} I_{xx} & I_{xy} & -I_{xz} \\ I_{yx} & I_{yy} & I_{yZ} \\ -I_{zx} & I_{zy} & I_{zz} \end{bmatrix} \tag{21}$$

The terms of the above matrix can further be derived as follows.

$$\begin{aligned} I_{xx} &= \int_m (y^2 + z^2)dm \\ I_{yy} &= \int_m (x^2 + z^2)dm \\ I_{zz} &= \int_m (x^2 + y^2)dm \end{aligned} \tag{22}$$

The other terms in the inertia matrix, including I_{xy}, I_{yz} and I_{xz} cancel each other and are considered zero because the FA, like many other aerodynamic bodies, is symmetric in the yz plane. A correlation between inertia and the rotational rates can thus be defined as follows.

$$\begin{aligned} \dot{p} &= qr(I_{yy} - I_{zz})/I_{xx} + M_x/I_{xx} \\ \dot{q} &= pr(I_{zz} - I_{xx})/I_{yy} + M_y/I_{yy} \\ \dot{r} &= pq(I_{xx} - I_{yy})/I_{zz} + M_z/I_{zz} \end{aligned} \tag{23}$$

The equations shown above can be incorporated into the MATLAB platform to show their effect on the rotational dynamics of the FA concept. The results are denoted in terms of the rotational velocities, P, Q, and R.

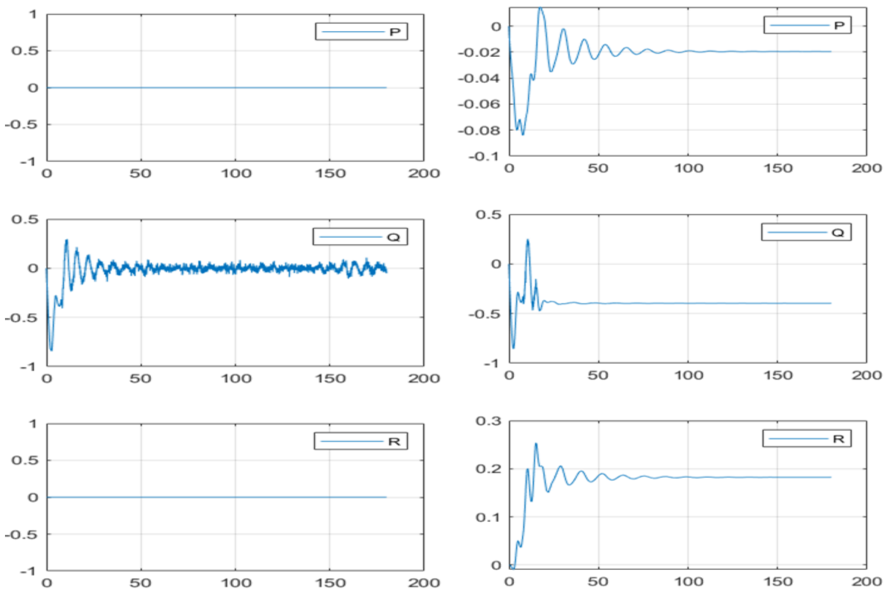

Fig 4. Rotational dynamics showing p, q and r at 5 degrees pitch

In the first illustration, a 5˚ pitch angle causes an initial change in the rotational velocity about the y-axis. However, stability is eventually achieved as the body oscillates around the zero radians/sec mark after approximately 30 seconds. On the other hand, rotational velocities about the x-axis (roll rate) and z-axis (yaw rate), remain unchanged due to the symmetry of the body and the incorporation of the inertia tensor matrix presented in Eq. (21).

In the second illustration, a five-degree change of both the pitch angle and the roll angle are introduced to the model. The results show initial changes in all the rotational velocities, before stability is achieved. The value for p settles at about -0.02 rads, showing the effect of the deflection on the roll rate. The results show thus prove that modeling the rotational dynamics based on Eq. (19) to (23) can be idealized.

3.1.3. Rotational Kinematics

The relationship between rotation about the Earth Fixed frame (EFF) and the Body Frame defines the rotational kinematics of the FA. According to Zipfel et al., this relationship can be realized through the rotational kinematic equations (RKE). These equations provide a relationship between the Euler angular rates and the body-axis angular rater and are presented as follows.

$$\begin{aligned} \theta &= q\cos\varphi - r\sin\varphi \\ \varphi &= p + q\sin\varphi\tan\theta + r\cos\varphi\tan\theta \\ \psi &= q\sin\varphi + r\cos\varphi\sec\theta \end{aligned} \quad (24)$$

The above equations can also be modeled and simulated in MATLAB to demonstrate the dynamic behavior of the concept. The results illustrate changes in φ, θ and ψ as follows.

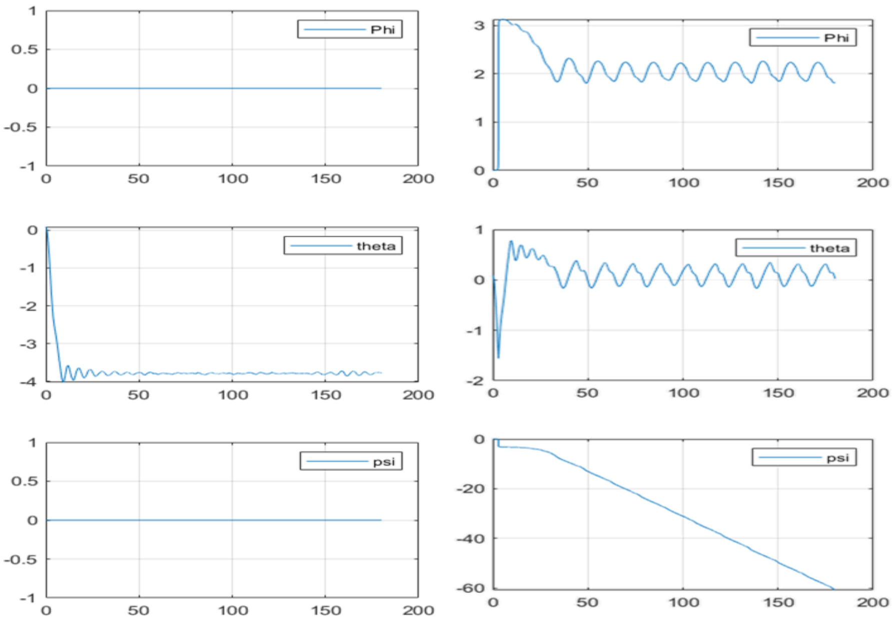

Fig 5. Rotational kinematics showing phi, theta, psi

The illustrations above depict changes in the rotational angles denoted by phi φ, theta θ and psi ψ. In the first illustration, phi and psi are held at a constant state of zero while the elevator angle of the control input is five degrees. The result shows that the other rotational remains constant, whereas the body eventually regains stability for theta. In the second illustration, a deflection of 5 degrees about the Z axis is simulated. The results show that this causes a linearized change in the yaw angle (ψ). The results shown are thus consistent with Eq. (24).

3.2. Summary of the Flight Dynamics System

Based on the various equations inferred in the previous section, a typical body travelling in the atmosphere entails 6 Degrees of Freedom (DOF) with 12 Ordinary Differential Equations (ODEs) that define the body's dynamics. These equations are as follows:

Table 1. Summary of the flight dynamic equations

Equations	**Definition**
$\dot{p} = qr(I_{yy} - I_{zz})/I_{xx} + M_x/I_{xx}$ $\dot{q} = pr(I_{zz} - I_{xx})/I_{yy} + M_y/I_{yy}$	Rotational Velocity

$\dot{r} = pq(I_{xx} - I_{yy})/I_{zz} + M_z/I_{zz}$	
$\dot{u_e} = \frac{X}{m} + rV - qw$ $\dot{v_e} = \frac{Y}{m} - ru + pw$ $\dot{w_e} = \frac{Z}{m} - pv + qu$	Translational Velocity
$\dot{\theta} = q\cos(\phi) - r\sin(\phi)$ $\dot{\phi} = p + q\sin(\phi)\tan(\theta) + r\cos(\phi)\tan(\theta)$ $\dot{\psi} = (q\sin(\phi) + r\cos(\phi))\sec(\theta)$	Airboat attitude
$\dot{x}_E = u\cos\psi\cos\theta + v(\cos\psi\sin\theta\sin\phi - \sin\psi\cos\phi) + w(\cos\psi\sin\theta\cos\phi + \sin\psi\sin\phi$ $\dot{y}_E = u\sin\psi\cos\theta + v(\sin\psi\sin\theta\sin\phi) + w(\sin\psi\sin\theta\cos\phi - \cos\psi\sin\phi)$ $\dot{z}_E = -u\sin\theta + v\cos\theta\sin\phi + w\cos\theta\cos\phi$	Airboat Location

4. Conclusion and Future Works

The results presented above encompass an initial framework for designing and developing a control system for the FA. Based on the analysis presented, the application of aerodynamic properties in conjunction with span-dominated GE has the potential to improve the FA's manoeuvrability with regard to lateral and longitudinal motion. Further, the FA's presented design would be ideal for implementing of a control methodology applicable for vertical take-off and landing operations in future works. This is attributed to the vectoring of engine thrust to tubing underneath the airboat that can be directed along the Z-axis by variable ducts to provide lift in the z-direction.

Among the issues that are realized by conducting this preliminary investigation are as follows.

I. Combining the desirable properties of ACVs and WIGs, two vehicles that use GE has the potential to create a new hybrid system with far more superior characteristics.

II. The FA concept's design embodies a combination of the most desirable properties of ACVs, WIGs and potentially VTOL crafts.

III. The incorporation of aerodynamic theory, GE theory and control theory can be used to establish a framework of control for the FA concept.

IV. Span-dominated GE is idealized for the longitudinal and lateral motion of winged bodies.

V. PID control systems can potentially be applied in conjunction with the dynamic system of the model to develop a control model that provides feedback and minimizes error, hence portraying robust properties.

Based on the above inferences, future work in this study can be defined as follows:

I. The design and development of a feasible non-linear model for the design encompassing established physical parameters
II. The implementation of the identified Newton-Euler equations and incorporation of the physical parameters of the FA concept to simulate motion and control of the FA on the MATLAB platform.
III. The modification of various parameters and design attributes for the FA to improve performance capabilities and stability.
IV. The tuning of the PID controller to determine the most ideal control for the concept.
V. A further examination of secondary control inputs to determine the viability of Vertical Take-off and Landing capabilities with the incorporation of dynamic pressure.

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