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Design of Small Three Seat Flying Boat by using Air Cushion: Stability and Control

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Abstract: Nowadays, the need for nautical transportation by using high speed vehicles is increasing. Wing in ground effect craft *(*WIG) is one of the vehicles that can meet this demand well. However, WIGs mostly have a large size, not suitable for Vietnam's terrain. Therefore, the aircraft design team concentrated on researching to design a small-sized WIG so that can be applied to Vietnam environment, especially for transferring between Truong Sa islands. This paper presents preliminarily the design points, basic configuration of a small-sized WIG. The research focuses on flight stability and automatic control for the three-seat WIG. Flight stability and automatic control have a significant meaning, helping WIG to operate smoothly. Flight stability includes two sub-sections: dynamic stability and static stability. After investigating the flight stability, we could able to find out basic parameters that make the WIG work effectively while operating on water and flying out of water. These parameters help us predicting its responses and make use thoroughly of the wing in ground effect.Dynamic stability and static stability are investigated by using analytical methods. Longitudinal, directional and rolling stabilities were considered carefully in static modes. And then, short-period, long-period modes were investigated for longitudinal direction in case of dynamic stability analysis. Moreover, spiral mode, roll mode and dutch-roll mode were also analysed for responses of WIG in lateral direction. We also examine the stability of the designed WIG when it stays on the water surface. The results show that all criteria for verifying the stability modes of the designed WIG are in acceptable ranges.

Keywords: *Dynamic Stability, Static Stability, Spiral Mode, Roll Mode, Wing in Ground Effect Vehicle, Dutch-Roll Mode.*

Introduction:

Taking off from water by ground effect craft requires so much power than cruising in ground effect. The difference in the power requirement creates inefficiency in the engine. To reduce the power difference, Mr. Hanno Fischer sponsored by the German Ministry for R&D (BMB+F) invented the hover-wing technology. The idea is to have air cushion underneath the craft as shown in the presentation below. At about to take-off, a pylon door opens to channel some of propeller stream for inflating the air cushion. The air cushion provides extra lift and reduces water drag. Consequently, the power required for take-off reduces substantially. Once the craft is cruising and not in touch with the water, the pylon door closes and the air channel retracted. The propeller stream that is used to inflate the air channel is directed backward to provide additional thrust.

- ***Principle of the flying boat by using air cushion***

Initially, static flying boat is fully submerged to build up hydrostatic lift. A huge wetted area will lead to a high drag when moving. After starting the engine, the pylon flap is opened; the airflow is guided to the tunnel below hull. The bag skirt is blown up by the airflow to seal the cushion to the aft. The airflow continues to move forward and open the finger skirts at front, which stops the airflow in the cushion and therefore, the pressure rises. Now, the static air cushion can build up, and press the water level in between the two catamarans and the skirts at front and aft down to reduce the wetted area. When the air cushion is fully build up, and the hydrostatic lift is replaced by 80% with aerostatic lift. At this point, the wetted area is highly reduced and the craft in take-off run condition.

When reaching take-off speed, the aerodynamic lift increases and the aerostatic lift decreases. The increased speed allows the free air steam to balance with the static cushion pressure. At take-off speed, the air cushion static pressure diminishes, and the free air stream deflects the finger skirts into cruise position. The pylon flap is closed and the bag sealing is deflected also into cruise position. The craft now is in clean configuration for ground effect cruise. With the pylon flap closed, full thrust is available for cruise.

For a soft and smooth landing without water impact, the power is reduced slightly below cruise power, and the pylon flap is open in order to inflate the bag seal at the aft, and to build up airflow through the tunnel. At the very first touch of the water surface, the airflow under the hull immediate deflects the front skirts, and seals the static air cushion again, and the cushion pressure is built up. The pressure in the cushion is easily adjusted by the captain. The captain can control a soft landing with higher power setting. The higher the power setting is, the higher the air cushion pressure and the smoother the landing is. Or the captain can choose to close the pylon flap only, or even stop the engine to shorten the landing distance, if necessary. By closing the pylon flap, the craft will use the drag of the water to make an extremely short lading due to low displacement of the catamaran hull. After landing, the craft will safely maneuver due to its stable and capsize proof design, even with wings folded up to match the requirements in harbors. In displacement, the craft will maneuver with main engine or auxiliary drives.

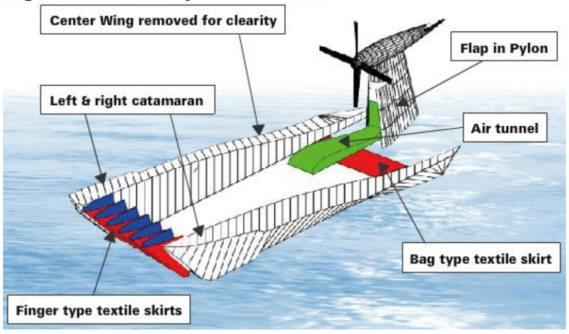

Figure 1: Model flying boat

Preliminary sizing of flying boat:

Estimating flying boat weight

$$W_{TO} = W_E + W_{PL} + W_F \quad (1)$$

Take-off gross weight, W_{TO}

Empty weight, W_E

Mission fuel weight, W_F

Payload weight, W_{PL}

Mass	
W_{PL}	210 kg
W_E	500 kg
W_F	70 kg
W_{TO}	780 kg

Estimating wing area, S, take-off power, P_{TO} and maximum lift coefficient, C_{Lmax}: clean, take-off and landing

In this section, methods will be presented which allow the rapid estimation of those flying boat design parameters which have a major impact on the performance categories (stall speed, take-off distance, cruise speed, …). The methods will result in the determination of range of values of wing loading, W/S, power loading, W/P, and maximum lift coefficient, C_{Lmax}, within which certain performance requirements are met. Since W_{TO} was already determined, it is clear that now S and P_{TO} can also be determined.

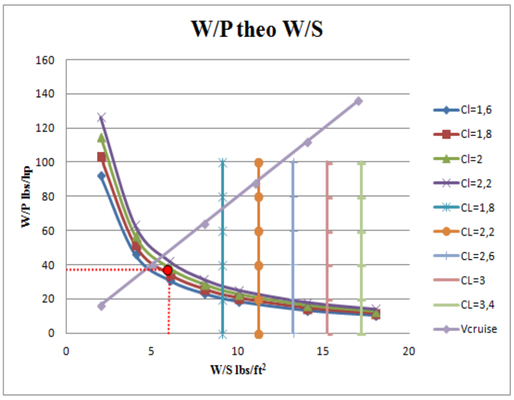

Figure 2: Matching result for sizing of flying boat

We chose a satisfactory match point (W/S, W/P) = (7, 38). We obtained the wing area $(S_w = 23\ m^2)$, required power $(P_{req} = 45\ HP)$.

Stability and control:

Static stability

Stability is a property of an equilibrium state. Static stability is the initial tendency of the vehicle to return to its equilibrium state after a disturbance. If we are to have a stable equilibrium point, the vehicle must develop a restoring force or moment to bring it back to the equilibrium condition.

3.1.1. Longitudinal static stability

Let us consider two airplanes and their respective pitching moment curves shown in Figure 3. In Figure 3, both airplanes are flying at the trim point denoted by B; that is, $C_{m_{cg}} = 0$. Suppose the airplanes suddenly encounter an upward gust such that the angle of attack is increased to point C. At the angle of attack denoted by α, airplane 1 would develop a negative (nose – down) pitching moment that would tend to rotate the airplane back toward its equilibrium point. If we were to encounter a disturbance that reduced the angle of attack, say, to point A, we would find that airplane 1 would develop a nose-up moment that would rotate the aircraft back toward the equilibrium point. On the other hand, airplane 2 would develop a nose-down moment that would rotate the aircraft away from the equilibrium point.

In this case, the requirement for static stability would as follows: $C_{m\alpha} < 0$ and $C_{mo} > 0$.

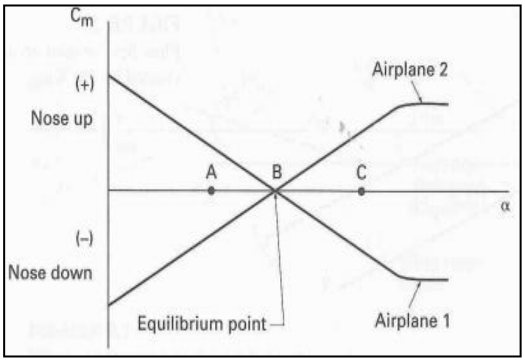

Figure 3: Pitching moment coefficient versus angle of attack

The following equation for the elevator angle to trim:

$$(\delta_e)_{trim} = -\frac{C_{mo}C_{L\alpha} + C_{m\alpha}C_{Ltrim}}{C_{m\delta e}C_{L\alpha} - C_{m\alpha}C_{L\delta e}} \qquad (2)$$

3.1.2. Directional stability

Directional, or weathercock, stability is concerned with the static stability of the airplane about the z axis. Just as in the case of longitudinal static stability, it is desirable that the airplane should tend to return to an equilibrium condition when subjected to some form of yawing disturbance. Figure 4 shows the yawing moment coefficient versus sideslip angle β for two airplane configurations. Examining these curves, we see that to have static directional stability the slope of yawing moment curve must positive: $C_{n\beta} > 0$.

The yawing moment coefficient is:

$$C_{n\beta} = \frac{N}{qSb} = C_{n\beta_{w,f}} + C_{n\beta_v} \qquad (3)$$

For a positive rudder deflection, a positive side force is created on the vertical tail. A positive side force will produce a negative yawing moment:

$$C_{n_{\delta r}} = -\eta_v V_v C_{L\alpha v}\tau_v \qquad (4)$$

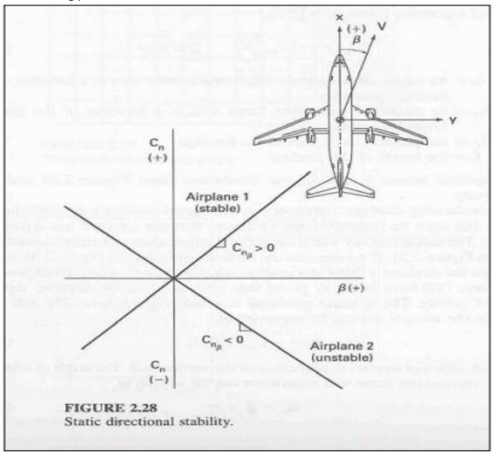

Figure 4: Static directional stability

Roll stability

An airplane possesses static roll stability if a restoring moment is developed when it is disturbed from a wings- level attitude. The restoring rolling moment can be shown to be a function of the sideslip angle β as illustrated in Figure 5.

$$C_{l\beta} = \frac{L}{qSb} = C_{l,wing} + C_{l,fuse} + C_{l,vertical} \qquad (5)$$

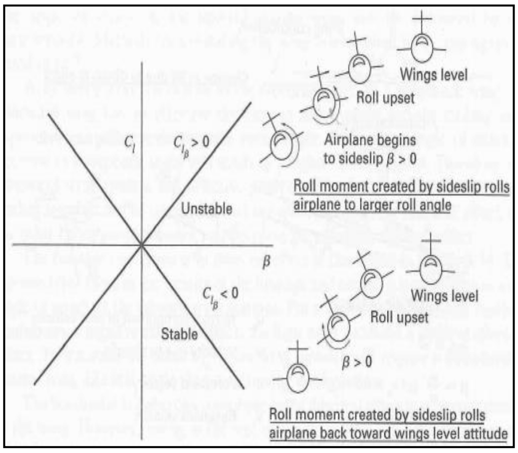

Figure 5: Static roll stability

The requirement for stability is that $C_{l\beta} < 0$. The roll moment created on an airplane when it starts to sideslip depends on the wing dihedral, wing sweep, position of wing on the fuselage and vertical tail. The major contributor to $C_{l\beta}$ is the wing dihedral angle Γ.

Dynamic stability

3.2.1. Longitudinal stability

The matrices A and B are given by

$$A = \begin{bmatrix} X_u & X_w & 0 & -g \\ Z_u & Z_w & u_o & 0 \\ M_u + M_{\dot{w}}Z_u & M_w + M_{\dot{w}}Z_w & M_q + M_{\dot{w}}u_o & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} X_{\delta e} & X_{\delta T} \\ Z_{\delta e} & Z_{\delta T} \\ M_{\delta e} + M_{\dot{w}}Z_{\delta e} & M_{\delta T} + M_{\dot{w}}Z_{\delta T} \\ 0 & 0 \end{bmatrix}$$

We will determine four eigenvalues for the particular characteristic equation. The eigenvalues are complex and the real part of the root is negative. This means that the system is dynamically stable.

- *Long-period:* The long-period or phugoid mode as a gradual interchange of potential and kinetic energy about the equilibrium altitude and airspeed. The long-period mode is characterized by changes in pitch attitude, altitude and velocity at a nearly constant angle of attack. The long-period mode can be obtained by neglecting the pitching moment equation and assuming that the change in angle of attack is 0.

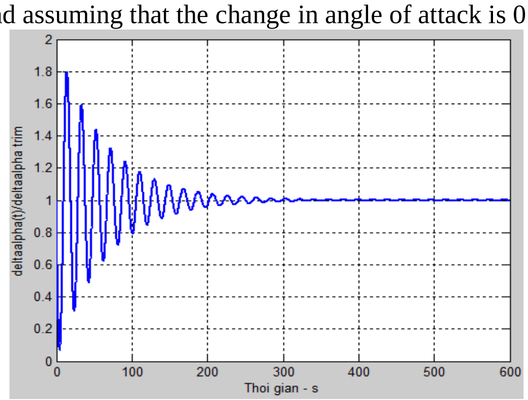

Figure 6: The long-period motion

- *Short-period:* Short-period will last on a few seconds. Short-period mode of motion can be obtained by assuming $\Delta u = 0$ and dropping the X-force equation.

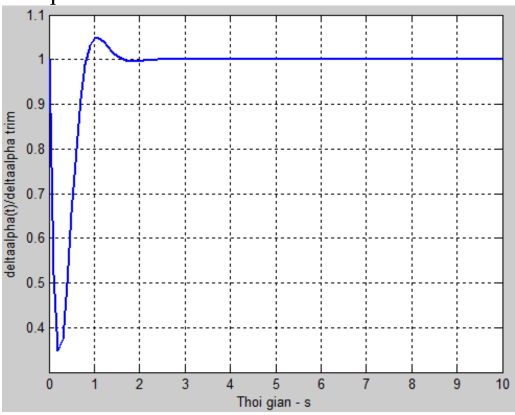

Figure 7: The short-period motion

3.2.2. Lateral stability

The matrices A and B are given by

$$A = \begin{bmatrix} \frac{Y_\beta}{u_o} & \frac{Y_p}{u_o} & 0 & \frac{g\cos\theta_0}{u_o} \\ L_\beta & L_p & L_r & 0 \\ N_\beta & N_p & N_r & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \quad B = \begin{bmatrix} 0 & \frac{Y_{\delta r}}{u_o} \\ L_{\delta a} & L_{\delta r} \\ N_{\delta a} & N_{\delta r} \\ 0 & 0 \end{bmatrix}$$

In general, we will find the roots to the lateral-directional characteristic equation to be composed of two real roots and a pair of complex roots. The roots will be such that the airplane response can be characterized by the following motions:

- *Spiral mode:* A slowly convergent or divergent motion, called the spiral mode. An unstable spiral mode results in a turning flight trajectory. The airplane's bank angle increases slowly and it flies in an ever-tightening spiral dive.

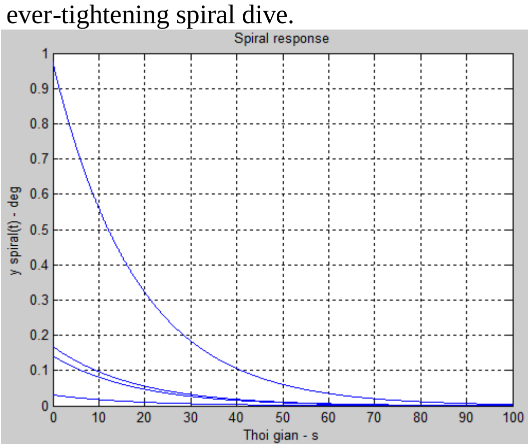

Figure 8: The spiral motion

- *Roll mode:* A highly convergent motion, called the rolling mode. The rolling motion usually is highly damped and will reach a steady state in a very short time.

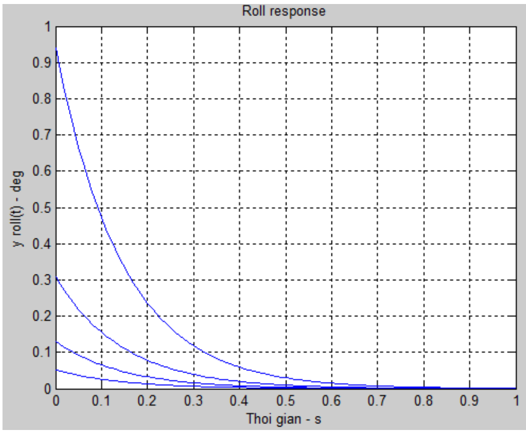

Figure 9: The roll motion

- *Dutch-roll mode:* A lightly damped oscillatory motion having a low frequency, called the Dutch-roll mode. It combines the yawing, rolling oscillations.

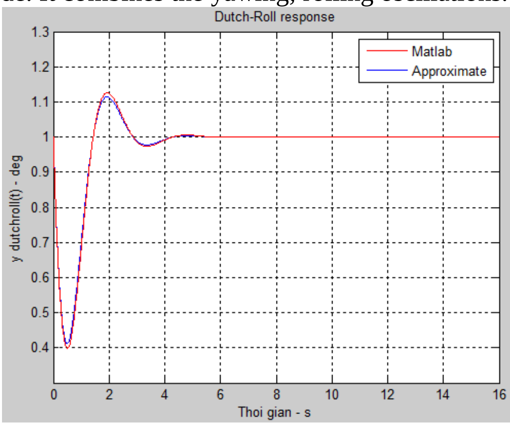

Figure 10: The Dutch roll motion

Response to flying control

Suppose that when the flying boat is under a small disturbance, all aerodynamic forces immediately have to have an appropriate value toward the stable stream condition and at a specific angle of incidence. If the flying boat is under a disturbance following the angle of incidence's component, incident velocity,… How all the disturbance components be change? Will they stop following time or destabilizing the flying boat?

Steps to calculate the response to flying control:

- Consider each disturbance component following the elevator angle δ_e.
- From the equation of longitudinal motion, change the inverse Laplace, then find the transfer function.
- Draw the response of the transfer functions with steps or the elevator angle δ_e.

→ Similar to the longitudinal motion, calculate the lateral motion.

Flying boat's stability on the water surface:

This section will calculate and determine the metacentric height for the case that the flying boat is on the water surface when are not moving, and through this, determine the static stability on the water of the flying boat with payload and no payload.

Floating ability of the flying boat:

When is on the water surface, the flying boat will be affected by two contrary forces concurrently. Gravitation includes empty mass of the flying boat, passenger's and luggage's weight. Water's floating force has opposite direction with the Gravitation.

Floating force (F): According to the law of Archimedes, floating force equal to water mass that was occupied by the flying boat's fuselage, affect with the upward direction. Floating force has the centre of force at B, floating centre of the flying boat. At the position where all forces are balanced, the floating force depending on water's effect equal to the flying boat's weight. Centre of force B has to be on the line which is perpendicular to the waterline area and goes through the center G of flying boat.

Force balance: W=F (6)

Moment balance: W x L – F x L = 0 (7)

(L is the distance between vector W and vector F)

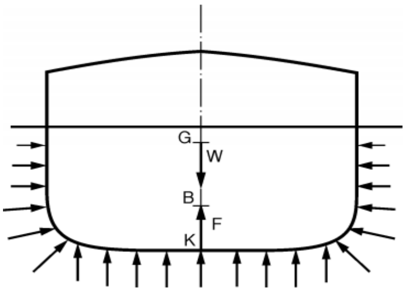

Figure 11: Gravity and floating force

Initial lateral stability

First stage: suppose that the volume of the sinking part is constant V, at a small tilt angle. M is the intersection point between the lines containing the instant floating centre B' and symmetric centre crossing the fuselage.

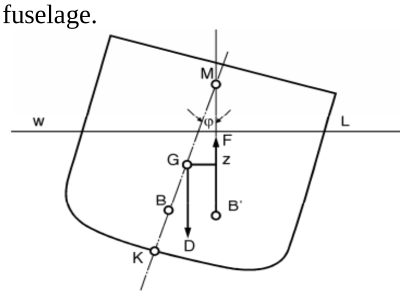

Figure 12: Lateral metacentric height

Which:

M is the metacentric height (stable lateral centre)

$R = BM_L = \frac{I_t}{V}$ is the radius of the metacentric height

KG is the central height compared to the standard plane trough the bottom of the flying boat.

When tilt angle is small, floating center B move on an arc, which has the radius r = BM, the centre is at M.

We have:

$$GZ = GM.\sin\phi \qquad (8)$$

ϕ is the fuselage's tilt angle compare to the waterplane area in static status.

GZ is the stable lever of the craft's stable moment.

Stable moment:

$$M = D.GZ \qquad (9)$$

$D = \gamma V$ is the amount of water that the fuselage occupy [N]

$\gamma = \rho g$ is the specific gravity of water [N/m^3]

ρ is the density of water [kg/m^3]

Recovery moment (M_{ph}):

$$M_{ph} = D*DM*\sin\phi \qquad (10)$$

Some formulas are given by

$$KB = \frac{T}{3}\left(\frac{5}{2} - \frac{CB}{CW}\right) \text{ hay } KB = \frac{1}{3}\left(\frac{5T}{2} - \frac{V}{AW}\right) \qquad (11)$$

When flying boat gets out of initial stable range, the moving process of point M and B are fairly complicated. With big GM, moment recoveries fast. This moment can quickly catch up and surpass the tilt moment value, against the fuselage's tilt and easily put flying boat back to its initial position after tilt moment stop its effect. In contrast, with a small GM value, the ability against external force is not much.

However, the bigger the GM value, the shorter the longitudinal shake period. Therefore, the flying boat will vibrate a lot. That huge acceleration could move the fixtures and damage the frame. For this reason, stability requirement do not allow a large value for the GM.

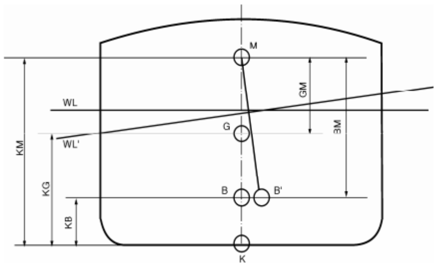

Figure 13: Model calculation

Initial longitudinal stability

The height of initial longitudinal stability's centre can be calculated as the lateral stability, switch the BM value for longitudinal stability with the BM value for lateral stability.

The height of initial longitudinal stability's centre:

$$GM_L = KB + BM_L – KG \qquad (12)$$

Recovery moment's lever GZ_L in lateral tilt:

$$GZ_L = GM_L.\sin\Psi \qquad (13)$$

$R = BM_L = \frac{I_L}{V}$ is the radius of lateral stability's center

Recovery moment of static stability:

$$M_{ph} = D.GZ_L = D.GM_L.\sin\Psi \qquad (14)$$

- ***Condition of static stability***

Under external effect, the flying always has the appropriate reaction. Suppose the craft is under the effect of a tilt moment with different intensities I, II, III. Under the effect of moment I, the flying boat tilts when $M_{ng} > M_{ph}$. After Φ_1, $M_{ph} > M_{ng}$ therefore the craft goes back to Φ_1. In this case, Φ_1 is considered as a static angle. On the other hand, also under the effect

of moment I, the craft reaches Φ_2. In this position, $M_{ph} = M_{ng}$. After Φ_2, $M_{ng} > M_{ph}$ which causes the flying boat to capsize. Although at Φ_1 and Φ_2, $M_{ph} = M_{ng}$, but Φ_2 is not considered to be a static angle.
As a result, the condition of static stability: $M_{ng} = M_{ph}$
Tilt moment II is limited moment. If tilt moment is bigger than II, reaches III, the flying boat will be unstable on the water surface.

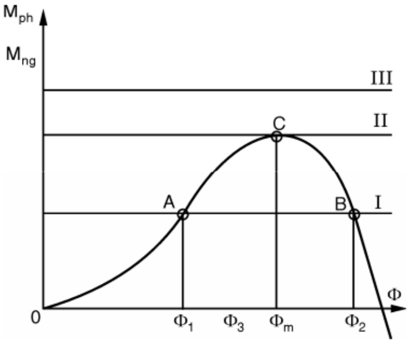

Figure 14: Static stability graph

Results and discussion:
The calculating process given in the previous sections provide the basic parameters, and stability is the premise for designing the flying boat model. This section will total up and discuss the achieved result to apply for the final design.

- Wing characteristics

Parameter	*Value*
Wing surface area (S_w)	23 m²
Wing span (b_w)	9 m
Wing chord (c_w)	2,56 m
Sweep angle ($\Lambda_{w,c/4}$)	7 deg
Dihedral angle (Γ_w)	-3 deg
Wing airfoil section	NACA 4412

- Horizontal tail characteristics

Parameter	*Value*
Tail surface area (S_h)	4,7 m²
Tail span (b_h)	4,1 m
Tail chord (c_h)	1,14 m
Airfoil section	NACA 0015

- Vertical tail characteristics

Parameter	*Value*
Vertical surface area (S_v)	2,5 m²
Vertical tail span (b_v)	1,8 m
Vertical tail chord (c_v)	0,7 m
Airfoil section	NACA 0012

- Fuselage characteristics

Parameter	*Value*
Fuselage width (w_f)	1,8 m
Fuselage length (l_f)	7,9 m
Maximum diameter (d_f)	1,32 m

- Static stability and control characteristics

Parameter	*Value*
Pitching moment (C_{mCG})	0,043-0,506α
Elevator angle to trim (δ_{etrim})	0,234 deg
Yawing moment coefficient ($C_{n\beta}$)	0,148 rad^{-1}
Rudder angle ($C_{n\delta r}$)	-0,06 rad^{-1}
Rolling moment coefficient ($C_{l\beta}$)	-0,078 rad^{-1}

- Dynamic stability and control characteristics

Parameter	*Value*
Short mode	$\lambda_{1,2} = -3,1596 \pm 2,1572i$
Long mode	$\lambda_{3,4} = -0,0156 \pm 0,2014i$
Spiral mode	$\lambda_s = -0,0554$
Roll mode	$\lambda_r = -6,862$
Dutch-roll mode	$\lambda_{DR} = -1,403 \pm 2,1543$

Conclusion:
This research has given the preliminary model of a small three seat flying boat. Through the calculating process, the specific size is determined, and this result can be used to manufacture the product. The first task was to propose a method to calculate the stability and control. In the section of calculating the stability, I considered all the components that affect the flying boat's stability.
Aside from calculating the calculating and control when the flying boat operating, I was also regarded the static stability when the flying boat standing still on the water surface. Thereby, the stability on the water of the flying boat when has no load and when is fully loaded can be clearly observed.
There are some disadvantages in this research:
- The deviation when calculating and measuring is inevitable. This can affect the stability and control in practice.
- Poorly design software, can only calculating the eigenvalues of the matrix on MATLAB therefore causes the deviation in practice.
The thesis's theme could be improved to increase the operation of the flying boat, make full use of the ground effect. The roll control can be added to make the flying boat more stable. Research in improving the manufactured materials is necessary to decrease the weight of structure and to increase the passenger's weight for the highest economic efficiency.
Viet Nam has a dense river system, thus it is very favourable for applying the flying boat into the tourism industry, transportation. With a developing country like Viet Nam, this subject should be strongly invested to open a bright future for Viet Nam's aviation due to the advanced function of the flying boat in various fields such as tourist activity, search and rescue, patrol…

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