Takeoff Performance Analysis of a Light Amphibious Airplane

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Abstract
The performance analysis of a light amphibious airplane during takeoff from the water surface has been presented in this paper. The airplane is one of the light amphibious airplane series built in Thailand with a bi-wing configuration. The conceptual design aims to build a short takeoff and landing (STOL) amphibious airplane. The mathematical model cooperated with several complicated parameters is presented and solved by MATLAB. The water-drag resistance of the airplane is estimated from typical seaplane hull NASA technical information, which enhances the correctness of the model at takeoff configuration. The simulation reveals that the seaplane can successfully takeoff from calm water in 24.5 seconds at the speed of 54 KCAS and an approximate distance of 890 feet with the AOA of 10 degrees.

Keywords: takeoff performance analysis, water-drag resistance, light amphibious airplane

1. Introduction
The "NAX" project initiated by the Royal Thai Navy research team has been started since the year 2002, aiming to design and build a light, versatile amphibious airplane (seaplane) and exploiting several missions such as coastal patrol, search and rescue, fire extinguish including any others mission assigned by military and civilian purposes. The initial version of the airplane, NAX-3, has been designed from the concept of the EDRA Aeronautic Super Pérel, an amphibious pusher configuration biplane. The NAX-3 has demonstrated its satisfaction flying qualities in both performance and safety, but the total weight of the airplane is above 650 kilograms, which is the number classified as a light sport airplane category stated by the Civil Aviation Authorities of Thailand (CAAT).

The new design of the NAX-4 project has started with the concept of modifying an amphibian pusher bi-wing configuration. The main seaplane structure is mostly made from composite, gains benefits in lightweight control, and enhances the strength of structure with aluminum alloy as a structural bone. By the retractable landing gears, the seaplane can takeoff and landing on a short airfield or water runway. A more powerful 115 Hp, Rotax 914 piston engine with three blades constant pitch propeller is installed as a "pusher" bi-wing configuration. The seaplane basic design performance is shown in Table 1.
Since the seaplane can operate from the water surface, its motion is distinguished from conventional land airplanes \cite{1, 2}. When the seaplane left the water surface, it operates like other fixed-wing airplanes but draggier than a landplane due to its hull design and many numbers on posts that support wings and undercarriage \cite{3, 4}. The determination of the airborne performance follows the procedure typically determine the airborne of the landplane. The motions of seaplanes on the water, however, introduce additional complications. The seaplane goes through a transition process from a state of static buoyancy to dynamic planning \cite{5}. The seaplane must be designed to smoothly transferable in four phases, i.e., displacement phase, hump or ploughing phase, planning or on the step phase, and airborne or liftoff flight.

### Table 1. “NAX-4 light amphibious airplane"

| Specifications:       |       |
|-----------------------|-------|
| Crew                  | 1 person |
| Capacity              | 1 person |
| Length                | 19.88 ft |
| Upper Wingspan        | 32.94 ft |
| Upper Wing area       | 97.52 ft² |
| Lower Wingspan        | 18.77 ft |
| Lower Wing area       | 52.96 ft² |
| Cabin width           | 4.12 ft |
| Empty weight          | 880 lbs |
| Max fuel capacity     | 40 gallon |
| Max takeoff weight    | 1,430 lbs |

| Performance:          |       |
|-----------------------|-------|
| Maximum speed         | 179.81 mph |
| Cruise speed          | 141.47 mph |
| Stall speed           | 53.98 mph |
| Endurance             | 5 Hrs |
| Rate of Climb         | 863.75 fpm |
| Take off Distance (Runway) | 650 ft |
| Take off Distance (Water) | 890 ft |
| Landing Distance (Runway) | 600 ft |
| Landing Distance (Water) | 700 ft |

**Figure 1. “NAX-4 amphibious light airplane” general dimension.**
This paper determines the analysis of the NAX-4 amphibious light airplane in takeoff configuration incorporate with essential and imperative parameters that help to understand the characteristics of the seaplane in detail. The results from the modeling analysis will be validated and verified through the actual flight test.

**Abbreviations**

| Symbol | Description                  |
|--------|------------------------------|
| \( F_b \) | Buoyancy force               |
| \( C_{\Delta} = \frac{F_b}{\rho_w g B^3} \) | Buoyancy force coefficient |
| \( C_v = \frac{v}{\sqrt{g B}} \) | Speed coefficient           |
| \( C_R \) | Resistance coefficient       |
| \( \alpha_{trim} \) | Trim angle                   |
| \( R \) | Water resistance             |
| \( R_{Froude} \) | Froude water resistance      |
| \( v \) | Linear velocity of the airplane |
| \( \alpha \) | Incidence angle              |
| \( \alpha_{trim} \) | Trim angle                   |
| \( m \) | Mass                         |
| \( T \) | Thrust                       |
| \( g \) | Gravity                      |

**2. Seaplane Motions in the Water**

When the seaplane is taxying with an idle RPM engine, it is considered as a displacement phase [6]. Normally the taxi speed is about 6-8 knots so that the propeller will not pick up water spray that causes serious erosion problems of the propeller blade. Since the seaplane has no brakes, it is very important to taxying at low speed to avoid any collision in a confined area. When the power is increased significantly above idling, the seaplane will usually become nose-up or ploughing position. For seaplanes that have a high thrust-line will tend to nose down upon applying power, it is imperative that the elevator should be in the full up position. The ploughing position is about the combination of high velocity streamline flows through the elevator and the hydrodynamic force exerts on the immersed part of the hull. However, hydrodynamic or water drag becomes the major part of the force resisting acceleration. This resistance reached its maximum at a speed of about 30 knots, just before the hull is placed into the planing phase. The trim angle needs to be slowly increasing approximately two more degrees helping the hull to ride on the step. The point of the highest resistance is called the "hump." After the hump is passed and the seaplane is traveling on the step, and water resistance \( R \) continue to decrease.

The planning or step position is attained by advancing the throttle to full power, and the elevator is slightly up. As the seaplane accelerates, it will gradually assume a nose-high pitch attitude raising the hull up to the step area. As a result of aerodynamic and hydrodynamic lifting, the seaplane is raised high in the water, allowing the hull to ride on top of the water wave. The airborne is merely transferring lift force from the hull to the wing by applying back elevator pressure resulting in the seaplane lifting off the water and becoming airborne. To avoid a rhythmic pitching motion caused by dynamic instability in forces along the hull, so-called "porpoising" while on the step, it is crucial to maintain the proper pitch angles during the takeoff run. Too much back-elevator pressure during planning will force the aft part of the hull more profound into the water, creating a strong resistance and retarding takeoff. On the contrary, insufficient back elevator pressure will cause the hull to remain in the water, which results in excessive water drag. During the seaplane acceleration, the water is increasing sprayed upward, outward, and rearward from the bow and will be directed into the propeller, causing erosion of the blades as well.
2.1 The Hydrodynamic Force, Resistance, and Drag Force

For the seaplane operating near the water surface, the hydrodynamic force is affected by gravity acting on the wave and by surface tension [7]. By dimensionless analysis, the force acting for the seaplane body can be expressed by:

\[ F_H = k \frac{1}{2} \rho_w v^2 L^2 \frac{\mu}{\nu} \text{Re} \left( \frac{\rho_w L}{\mu} \right) \text{Fr} \left( \frac{v}{\sqrt{gL}} \right) \text{We} \left( \frac{\rho_w^2 L}{\sigma} \right) \]  

(1)

where \( k \) is a constant coefficient, \( \rho_w \) is water density, \( v \) is the seaplane velocity, and \( L \) is the submerged length of the seaplane in the water. Equation (1) illustrates that the hydrodynamic force depends on the function of three characteristic dimensionless ratios, the Reynolds Number, the Froude Number, and the Weber Number lied in order. The Reynolds Number indicates the ratio of dynamic forces to viscous forces, the Froude Number is the ratio of dynamic forces to gravity force, and the Weber Number is the ratio of dynamic forces to surface tension forces. In the model of the seaplane framework, the effects of Weber number are confined to low speeds and are considered constant, which equals to unity.

The total resistance of a seaplane consists of (i) hull form water drag, which includes wave and eddy drag, (ii) parasitic drag, and (iii) induced drag. The hull drag portion of the hydrodynamic force while the seaplane is moving on the water surface can be determined from the resistance coefficient \( C_R \) as:

\[ C_R = \frac{R}{\rho_w B^3} \]  

(2)

where \( R \) is water resistance, and \( B \) is the seaplane cabin width.

The parasitic drag and induced drag can also be determined through a drag coefficient \( C_D \) using a quadratic polynomial as:

\[ C_D = C_{D_{\text{min}}} + \frac{C_L^2}{\pi \text{AR} \delta} \]  

(3)

where \( C_{D_{\text{min}}} \) is the minimum drag coefficient, \( \text{AR} \) is the reference aspect ratio, and \( \delta \) is Oswald efficiency.

These resistances directly affect the takeoff safety and performance of the seaplane and yet are taking into account in the design and production phase.

3. Seaplane Takeoff Estimation

The seaplane takeoff from the water surface is more complicated than conventional airplanes due to the complexity of water resistance and aerodynamic drag. The seaplanes are generally very draggy due to their shape of the hull and associated support structure, generating lots of drag. However, the shape of the seaplane is dictated by hydrodynamic design and operation, and yet it is practically impossible to reduce its drag. Drag can be minimized by other means such as using aerodynamic strut profile, keep landing gear behind a smooth door compartment, or making fuselage and main parts of the seaplane by composite material (to reduce weights and number of rivets), etc.

To be able to lift off from the water surface safely and efficiently, several parameters have to be considered as follow,

Buoyancy force coefficient:

\[ C_\Delta = \frac{F_b}{\rho_w g B^3} = \frac{\Delta}{\rho_w g B^3} \]  

(4)

where, \( F_b = \rho_w g \Delta \) is the Buoyancy force.

the maximum Buoyancy force coefficient (when the seaplane is stationary) is denoted as:

\[ C_{\Delta_0} = \frac{W}{\rho_w g B^3} \]  

(5)

and speed coefficient as a function of the seaplane speed is denoted by:
To estimate the water-resistance of the seaplane more effectively, the water resistance coefficient $C_v$ as a function of speed coefficient $C_R$ can be obtained from the experimental model towed in the water tank [8]. However, NACA TN-2481 [5] provides the graph of $C_R$ and $C_v$ for planing-tail seaplane model and can be the empirical curve fitting of a Gaussian function as:

$$C_v = 0.05789e^{\left(-\frac{(C_R-1.907)^2}{0.7561}\right)^2} + 0.0273e^{\left(-\frac{(C_R-1.347)^2}{0.2536}\right)^2} - 0.3322e^{\left(-\frac{(C_R-23.41)^2}{11.74}\right)^2} + 0.07924e^{\left(-\frac{(C_R-2.227)^2}{1.951}\right)^2}$$

(7)

For reduction of water resistance with loading, the following expression is given:

$$R_{\Delta} = C_{R\Delta} \frac{C_R}{C_{R0}}$$

(8)

and water resistance is given by:

$$R = C_R\rho W g B^3$$

(9)

Also, the trim angle curve can be approximated by the equation:

$$\alpha_{\text{trim}} = \alpha + \left(\frac{a - \alpha_1}{2}\right) * (1 + \tanh(aC_v + b))$$

(10)

where $a = \frac{5.294}{C_{R2} - C_{R1}}$, $b = -(2.647 + AC_v^1)$

Figure 3. Trim angle and water-resistance as a function of speed coefficient.

From Figure 3, the “hump” or the peak of $C_R$, the value indicates the maximum water resistance resulting from the seaplane reaches its hull speed [9]. Practically, it means the seaplane is on the step and ready for the pilot to rotate the seaplane. The trim angle indicates the orientation of the seaplane on the water surface during takeoff. It is very important for takeoff analysis because it directly affects the angle of attack (AOA) of the seaplane. By adding the trim angle to the AOA, the seaplane will merely on the step at a certain $C_v$ value at the planing stage and ready to airborne [10, 11].

The friction resistance of submerged surfaces, while the hull is in the planning stage, by William Froude is introduced by:

$$R_{\text{Froude}} = f \cdot S_W \cdot v^n$$

(11)

where $f$ is the coefficient of friction resistance depends on the hull surface, $S_W$ is the wetted area, $n$ is constant depend on surface quality, usually close to 2.

The thrust of the seaplane as the functions of power and velocity for fixed-pitch propeller can be approximated by a cubic spline method as the form [12, 13]:

$$T(v) = A v^3 + B v^2 + C v + D$$

(12)

when $A, B, C, D$ are constants and can be determined from the following matrix equation
\[
\begin{bmatrix}
0 & 0 & 0 & 1 \\
\frac{v_c^2}{3} & \frac{v_c^2}{2} & v_c & 1 \\
v_H^2 & v_H^2 & 1 & 1
\end{bmatrix}
\begin{bmatrix}
A \\
B \\
C \\
D
\end{bmatrix}
= 
\begin{bmatrix}
T_{\text{static}} \\
T_C \\
-n_P P_{\text{BHP}}/v_c^2 \\
T_H
\end{bmatrix}
\]

where \( n_P \) is the propeller coefficient, \( v_H \) is maximum level airspeed, \( v_C \) is cruise airspeed, \( T_{\text{static}} \) is static thrust at zero airspeeds, \( P_{\text{BHP}} \) is engine brake horsepower, \( T_H \) is thrust at maximum airspeed, \( T_C \) is thrust at cruise airspeed.

Figure 4. Thrust-velocity for fixed-pitch propeller.

Equation of motion for 2-D [14] taking off from water of seaplane in the longitudinal axis is expressed as:

\[ T \cdot r - D - R - R_{\text{Froude}} = ma \]  \hspace{1cm} (13)

where \( r \) is ramp up the factor of a pilot to slowly increase power from takeoff, which is given by the expression:

\[
r = \begin{cases} 
0.1 + 0.9 \left( \frac{t}{10} \right) & \text{if } t < 10 \text{ sec} \\
1 & \text{if } t \geq 10 \text{ sec}
\end{cases}
\]

4. Simulation Results
The necessary information of the NAX-4 light amphibious airplane [15, 16] for 2-D takeoff estimation under the calm water condition is given in Table 2.

| Parameter                          | Value       |
|------------------------------------|-------------|
| Fuselage Beam                     | 4.27 ft     |
| Fuselage Water Length             | 13.55 ft    |
| Wing Span                         | 32.94 ft    |
| Wing Area                         | 152.85 ft²  |
| Wing Aspect Ratio                 | AR 7.1      |
| Wing AOI wrt Keel                 | αw 4 deg    |
| Gross Weight                      | 1430 lbf    |
| Rotax 914 UL Engine Power         | 115 BHP     |
| Propeller Diameter                | 6 ft        |
| Spinner Frontal Area              | A spinner 5 ft² |
| Maximum Speed @5000 ft            | V_{max} 151 KCAS |
| Propeller Efficiency              | η 0.82      |
| Thrust Function @ Max Power       | T 1972.32 lbf |

The simulation shows that the seaplane starts increasing power gradually from idle to full power in 10 seconds. The seaplane starts to pick up the speed, and also the aerodynamic drag, water drag, and lift force start increasing at different rates. However, the water resistance that is the function of the speed starts growing exponentially and reach the top at hull speed in 12 seconds, making the seaplane to be the planning stage and begin to get on the step at this period. Once the seaplane is on the step, the hydrodynamic resistance, \( R_{\text{Froude}} \), starts its value due to the submerged part of the hull while the water
resistance reduces to “zero” at the speed of 36 KCAS. The pilot can rotate the seaplane at this speed but must be aware of the rear shifting of the center of buoyancy (CB) that could make the seaplane enters porpoising if too much rotation. The seaplane will lift off the water when the displacement load becomes “zero” at the speed of 54 KCAS within 24.5 seconds, and the total distance is 893 feet.

![Figure 5. Lift, Drag, Water resistance, Hydroplane resistance, Displacement Load versus Water/Airspeed.](image)

![Figure 6. Displacement Load, Thrust, Total Resistance versus Time.](image)

The takeoff configuration of the seaplane has been analyzed using ANSYS-fluent in VOF module. The 3-D model of NAX-4 is built without engine and propeller to study the seaplane behavior at the planning stage. The FEM mesh is tetrahedrons with 538,282 elements and 104,052 nodes. The multiphase – VOF CDF model is analytically selected along with a realizable k-epsilon model. The couple solution technique is chosen with a flow courant number equal to 0.5, and the surface tension between two media, air and water, is set to be 0.75. The AOA of the seaplane is 10 degrees, and the airspeed is 30 meters/sec.

The simulation shows that the lift coefficient $C_L$ converges to the value of 1.007 while the drag coefficient $C_D$ converges to 0.08, making the aerodynamic lift equal to 1,515 lb at liftoff. One can visualize some turbulence after the upper wing that creates drag to the seaplane and the surface shear (red arrows) along the body surface. This turbulence affects the stabilizer fins and elevator for maintaining the trim angle, which the pilot needs to be aware of while lifting off the seaplane.
Figure 7. NAX-4 FEM mesh model.

Figure 8. NAX-4 while on the planning stage.

Figure 9. NAX-4 two-phases VOF model on the planning stage.

5. Conclusions
A light amphibious airplane takes off modeling and analysis are presented in this paper. The motion of the seaplane on the water surface consists of four different phases as displacement phase, hump or ploughing phase, planning or on the step phase, and airborne or liftoff flight. The water resistance is considered as the most complicated resistance in addition to aerodynamics drag directly involving in the seaplane takeoff configuration. The water resistance coefficient as the function of the speed coefficient and trim angle are two key parameters to determine the successful takeoff performance of the seaplane. For our NAX-4 light amphibious airplane, the 2-D takeoff simulation and the two-phases VOF model in ANSYS-fluent at the planning phase show the corresponding hydrodynamics and aerodynamics parameters. The seaplane can successfully takeoff from calm water in 24.5 seconds at the speed of 54 KCAS and an approximate distance of 890 feet with the AOA of 10 degrees. However, the NAX-4 light amphibious airplane is currently on the maintenance schedule; therefore, all the seaplane takeoff parameters will be verified through an actual water takeoff flight once the NAX-4 is ready to fly in the near future.
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