Review of Design Aspects and Challenges of Efficient and Quiet Amphibious Aircraft

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Abstract. Apart from the commercial and military aviation sectors, the general aviation (GA) sector is expected to experience a rapid growth, especially in Asia. The increasing economic activities in the region would demand for more efficient and convenient transportation, which would open door to more GA services. This development would require sufficient infrastructure supports, including airports. However, insufficient land area has often imposed limitations in airport development. As such, some areas (e.g., remote islands) are not easily accessible by air. One implication is that travels can only be done via land or water, which might prolong the travel time. This applies to business travels, with the significant increase in business and economic activities, which in turns demands for more efficient and faster mobility. In other cases, this involves some rural areas where the infrastructures are not very well-developed, and where the geographical terrains are too challenging to build a pad for vertical takeoff and landing (VTOL) air vehicles. Under such circumstances, it would be imperative to enable air travels to carry critical logistics such as medical supplies, food, and even sick patients. In this regard, we propose to develop a low-payload, low-altitude amphibious aircraft, which can takeoff and land on both water and land. Aircraft design process is a complex procedure and multidisciplinary in nature, and for amphibious aircraft design we need to consider the two takeoff and landing modes, which imposes further challenges to the design. In this paper we present two preliminary design projects, for two-seater and ten-seater aircraft. To design an efficient and quiet amphibious aircraft, we conduct some experiments on noise shielding mechanisms to reduce the propeller noise. The challenges and resulting designs are briefly discussed in this paper. Amphibious aircraft development will be very relevant to Indonesia, which is the world’s largest archipelago with thousands of islands. More efficient inter-island transportation and mobility would be crucial in the overall economic development in the country.
1. Introduction

The air transportation has experienced a rapid growth, both in military and civil aviation sectors. The civil aviation sector can generally be categorized into two, namely the commercial air transport and general aviation [1]. The commercial air transport involves all operations that transport passengers, cargo, or mail for remuneration or hire. Scheduled services (revenue) are flights scheduled and performed for remuneration according to a published timetable, or recognizably systematic. A charter flight is a non-scheduled operation using a chartered aircraft. Air taxi revenue flights include on-demand, non-scheduled flights on short notice for the carriage by air of passengers, freight or mail, or any combination thereof for remuneration. General aviation, on the other hand, can be classified into instructional, business, and pleasure flying, as well as aerial work. Its activities include air ambulance, crop dusting, traffic monitoring, aerial photography, law enforcement, forest-fire fighting, gliding, etc.

Commercial airlines have been the fastest growing mode of passenger transport. The revenue passenger kilometer (RPK) of international air travel has grown by around 9% annually since 1960 [2, 3, 4, 5]. The passenger traffic in the United States alone has more than tripled since 1970. However, the energy used in air transportation has only increased by 43% [6]. The increase in aircraft efficiency came from several factors, including the introduction to jet engines [7], as well as improvements in avionics, wing design, and materials [8]. The doubling in aircraft efficiency has led to a very rapid decline in air transport price, especially between 1959 and 1972, when jet engines were introduced [8]. This in turn further promotes commercial aviation, and its demand is expected to continue increasing at an average annual rate of 4.8% through 2036 [9].

The general aviation (GA) sector is expected to experience a substantial growth. According to the General Aviation Manufacturers Association (GAMA) [10], the total number of GA aircraft flying worldwide today has reached 362,000 in 2016, ranging from two-seater training aircraft and utility helicopters to intercontinental business jets. Of all these aircraft, 204,000 are based in the United States and 110,000 are based in Europe. In the United States, the GA sector supports $2,219 billion in total economic output and 1.1 million total jobs. The number of GA airports in the United States and Europe has exceeded 5,000, and GA fleet can access over 4,200 airports. In terms of the total number of GA aircraft, Asia-Pacific is still lagging behind, with only 25,000 GA aircraft in operation.

One important aspect of the GA sector is the amphibious aircraft, i.e., air vehicles that can takeoff and land from both ground and water. Amphibious planes have been around since the early age of aviation history. Numerous models of amphibious aircraft or seaplanes were developed for general aviation, military and rescue. Amphibious aircraft have often been used for exploration purposes, due to the versatility in their landing mechanism. In particular, they are favorable in exploring rural areas with rough terrain or with limited areas for proper runways. At present, amphibious aircraft found their applications in leisure, military, and rescue/emergency purposes. With the continued growth of the amphibious aircraft market, we foresee a demand for commercial amphibious aircraft in service for passenger transports.

Needless to say, the dual landing mechanisms and versatility of amphibious aircraft could offer some competitive advantages that conventional, ground-based aircraft could not. These unique characteristics can provide more accessibility. Some of the potential applications for the amphibious aircraft include: (1) short-haul business aviation development to meet the demand for customized high-efficiency travel services, (2) high-end seasonal tourism activities and transport to remote areas, (3) public services, such as search and rescue, fire-fighting, disaster relief, and medical aid, (4) industrial, agricultural, and forestry production activities, (5) sport activities (e.g., diving), and (6) leisure and point-to-point travel between residential properties, resorts, hotels, etc.

The unique characteristics and competitive advantages of amphibious aircraft, however, come with more design challenges than those of conventional aircraft. These challenges will be further discussed in Section 4. This paper presents some preliminary work on designing efficient and quiet amphibious aircraft, as part of students’ final year design project (FYDP). At this preliminary stage, we select three...
primary design challenges to focus on, namely the noise impact, hydrofoil design, and landing gear mechanism.

The remaining of this paper is organized as follows. Section 2 will summarize the market research for amphibious aircraft, focusing on China and Asian region. A brief overview of amphibious aircraft design and current technology, including some popular examples, is then given in Section 3. We then discuss about some challenges on the amphibious aircraft development, including the design challenges (Section 4) and regulations (Section 5). The resulting preliminary designs of two aircraft (two-seater and ten-seater) are then presented in Section 6. This paper is then consolidated with conclusion and some future works in Section 7.

2. Emerging market for amphibious aircraft in Asia

This section summarizes the market research and analysis for our preliminary design projects. Focus is given to the Pearl River Delta region, which covers Hong Kong and some regions in China. The results from this market research are used to determine the mission requirements for the amphibious aircraft considered in this project. The design process and entailing discussion, however, will also be applicable to other uses of amphibious aircraft. Some other potential markets for similar amphibious aircraft designs, e.g., in the Indonesian archipelago, will be discussed briefly at the end of this section.

In the recent years, Asian countries have seen a healthy economic growth. While the US still tops the list in terms of the gross domestic product (GDP), China has been catching up to be the second place, according to the World Bank Data Catalog [11]. At present, the GDP of China is roughly 60% of that of the US. In terms of the GA sector, however, we still observe a stark difference between the two countries, despite the rapid growth observed in the GA market in China in the past decade. This difference can be clearly seen in the summary presented in Table 1.

| Category           | US       | China   |
|--------------------|----------|---------|
| Number of aircraft | 216,000  | 2,250   |
| Number of airport  | 13,513   | approx. 300 |
| Number of flown hours | 23 millions | 0.7 millions |

Table 1. General aviation sector comparison between the US and China.

Despite the recent development in military and commercial passenger aircraft in China, the GA production in the country has not been very active [12]. In 2006, the market share of foreign aircraft in GA industry domestically was 56%. However, the China’s domestic GA manufacturing quantity is currently growing [13]. By the end of 2014, there were only 2,533 licensed pilots to fly GA aircraft [14]. In 2013, the US operated more than 300,000 GA aircraft, with at least 24,000 landing sites. In China, on the other hand, only 1,654 GA aircraft and 399 landing sites were available, according to industry statistics [14]. Moreover, there is still a lack of GA pilots in the region. However, China is expected to see an increase in the number of GA’s pilots in the near future. The Civil Aviation Administration has relaxed standards in theoretical exams, flight tests, and physical conditions set for flight students [14]. With all this development in sight, we can optimistically expect to see further development in GA aircraft, including amphibious aircraft, in the Asian region.

Geographically, Hong Kong is one of the most economically dynamic cities in China. It is located within the Pearl River Delta zone, which allows for a close connection to cities such as Macau, Zhuhai, Guangzhou, and Shenzhen, that are located 65 km, 60 km, 132 km, and 30 km from Hong Kong, respectively. China has a coastline of 18,888 km in length, a total of 1,500 rivers with catchment area of over 1,000 km². There are over 24,800 lakes, where 2,800 of them have water surface areas larger than 1 km². There is a high concentration of middle-class and wealthy populations in the coastal regions such as Beijing-Tianjin-Hebei region, the Yangtze River Delta, and the Pearl River Delta. In these
regions, land is expensive and increasingly sparse. On the other hand, there are a large number of lakes, waterways, rivers, coastal lines, and islands. Moreover, the waterfronts are likely to be adjacent to high-end housing estates. Within this distance range, a light GA aircraft is an ideal means for inter-city transportation. An amphibious configuration that can takeoff and land from water would offer a greater advantage on focusing on the aforementioned potential high-end markets. Amphibious aircraft also offer an advantage superior to other conventional air transportation vehicles in terms of docking space. In general, the water landing mechanism leads to amphibious aircraft requiring a minimum land area compared to that of airport and railway station. Being an island in nature and a harbor in function, Hong Kong could take an advantage of the surrounding sea which constitutes a great source for the development of GA industry. Figure 1 illustrates the areas covered within an 800 km and 1,000 km radius from Hong Kong, which could be the potential coverage of the GA flights from Hong Kong.

Figure 1. The Pearl River Delta area with circles showing regions covered within an 800 km and 1,000 km radius from Hong Kong, respectively.

Though the above discussion is mostly focused in the China region, the amphibious aircraft development will be crucial and beneficial in other countries and regions. Indonesia, in particular, would benefit significantly with it being the world’s largest archipelago. The reported total number of islands in Indonesia varies with different sources, ranging from 13,000 to 19,000, due to tidal activities, remoteness, small island sizes, etc. A survey conducted by Indonesian’s National Institute of Aeronautics and Space (LAPAN) in 2002 stated that there are 18,307 islands in Indonesia. Among all these islands, 922 of them are permanently inhabited [15]. However, not all of them are already well-developed and easily accessible. Moreover, they might not have the infrastructure required to build proper airports. Most of those islands would rely on transportation by sea, which could be significantly more time consuming than by air. Needless to say, amphibious aircraft would provide more transportation means between islands, which can further boost economic development, support logistics to more rural and remote areas, improve medical facilities and mobility.

In addition to the amphibious aircraft’s role as the main means of transportation and logistics, it can also further boost the tourism and sport industries. Diving tourism, for instance, often includes several diving sites that are spread around in the region. Indonesia boasts some of the world’s best diving sites,
which are spread around in different islands. Boats or yachts are currently the most common means to transport divers from one site to another, which might be a bit slow and limits the number of sites that can be visited in one day. An amphibious aircraft will offer an excellent solution in this situation.

3. Amphibious Aircraft Overview and Current Technology

An amphibious aircraft is an aircraft that can takeoff and land on water and on land. It typically features a hull-type fuselage that can assist in the water operation and retractable landing gear to enable landing on land [16].

Some of the earlier generations of amphibious aircraft from the 1950’s and 1960’s include de Havilland Canada DHC-3 Otter, Viking Air DHC-6 Series 400, and Viking Air DHC-6 Series 400S Seaplane. The Dornier Seastar was introduced in 1984, which is a turboprop-powered amphibious aircraft. Composite materials form the bulk of its structures. There have been some recently developed amphibious aircraft designs in the market, such as the ICON A5, MVP Model 3, and LISA Akoya. All three of them are designed to carry two passengers. These three promising designs are shown in Figure 2. The design for each aircraft is described briefly below.

![Figure 2. Some existing amphibious aircraft in the market.](image)

ICON A5 is a high-wing monoplane with its wing and fuselage made up of carbon-fibre material. It is powered by a single 100hp Rotax 912IS engine driving three-bladed push propeller. Its Dornier-style sponsons provide hydrodynamic stability and acts as a step for the crew (for access and egress). One main advantage of ICON A5 is that its wings can be folded for ground transport and storage purposes. MVP Model 3 looks very similar to ICON A5 but it is designed to operate on snow and ice, in addition to water. It has a high-wing structure with foldable wings, made up of carbon fibre and is powered by 115hp Rotax 914 engine driving three-bladed push propeller. One unique feature of the MVP Model 3 is that its floor panels can be rearranged to accommodate fishing or camping. LISA Akoya looks different from the previous two designs. Its unique features include: the wing that can be folded almost 90°, the single engine (100hp Rotax 912 ULS) mounted high on the tail, and its carbon-fibre-reinforced polymer composites body and wing structures. It has a very high aspect ratio of 18, which is uncommon for a powered aircraft, and uses unique trailing edge extensions rather than the conventional hinged flaps.

4. Design and technical challenges for amphibious aircraft

Since an amphibious aircraft need to perform both on water and in the air, there are some operational issues that need to be carefully considered in the design process. It often requires some tradeoffs between the aerodynamics and hydrodynamics performances. For instance, the fuselage now needs to be designed as a hull, to be able to operate on water. This shape, however, is not aerodynamically efficient [16]. The higher drag in turns reduces the rate-of-climb and cruise speed of amphibious aircraft, when using the same power as a conventional aircraft. The relatively low operational altitude of amphibious aircraft makes noise impact a more important consideration in the design compared to that of
conventional aircraft. Therefore, any noise shielding or mitigation procedures need to be considered in the design.

The harsher operating environment also imposes some challenges to amphibious aircraft. For instance, its constant contact with seawater requires a more rigorous corrosion protection and maintenance, including the special selection of the materials and coatings used for the aircraft components. The hull is also more susceptible to damage as it slams into waves or floating debris, or when sliding up on a beach. This requires a strong and sturdy hull and as a consequence, an amphibious aircraft is typically heavier than a conventional aircraft for the same mission requirements. As an alternative to the hull design, some amphibious aircraft use hydrofoils, e.g., LISA Akoya. The hydrofoils can help reduce drag, and thus allows for higher rate-of-climb and cruise speed. Hydrofoils are also adopted in one of our designs, which will be further discussed Section 6.2.

In addition, there are some basic requirements of amphibious aircraft that do not exist in conventional aircraft. The aircraft needs to be watertight, especially for doors, windows, and any panels that give access to dry components. The lower aerodynamic efficiency might call for additional features to control the aircraft when there are not enough aerodynamic forces. The aircraft stability needs to be ensured both during flight and when it is on water, and the aircraft must be controllable in water at all speeds. Hydrostatic stability refers to the tendency of the aircraft to return to its at-rest position, upon application of any external forces that tilt it to one side. For this consideration, we need to look into the buoyancy, which is not required when designing a conventional aircraft. Some additional features, that are not typically used in a conventional aircraft, become necessary when designing an amphibious aircraft. For instance, a keel can help guide the aircraft to move in a straight line, a chine can help direct the water spray away from the hull in addition to increasing the hydrodynamic lift, and spray rails can help reduce the water spray on the propulsive system, since it could be destructive to the propeller.

Pilots need special training before they can operate and fly amphibious aircraft. First, they need to be familiar with some nautical terms used that are not common in any conventional aircraft. For instance, port and starboard are used instead of left and right, windward and leeward to refer to the upwind and downwind, bow and stern to refer to the nose and the bottom of the empennage, respectively. Landing on different water conditions (e.g., a normal rippled water, glassy or mirror-like water, and rough water) also need different techniques and procedures that the pilots need to be familiar with. Moreover, the cockpit design should provide a good visibility for pilots, especially to judge the altitude above water.

5. Challenges in Amphibious Aircraft Development

In addition to the technical challenges, there are three main challenges on the development of the amphibious aircraft industry. They include the regulatory restrictions, restrictive airspace, and weak support/insufficient supplies of equipment. Focus will be given to the China region, but these impeding factors are common for GA sectors in many countries. Each of them will be described briefly below:

1. Regulatory restriction

China’s shortcoming of coordinated regulations and policies across all shareholders made regulators overly cautious in the GA industry. Moreover, China lacks an efficient regulatory framework that encourages the GA development and ensures necessary safety and security [12]. The approval process of GA activities is lengthy, time consuming, and costly. Things have slowly improved since GA is included as one of the key areas of development in the five-year plan of China [17]. The country has attempted to improve the regulatory framework, as well as organize conferences and exhibitions specialized in the development of GA that involve foreign experts and manufacturers [18].
2. Restricted airspace
The airspace in China is divided into classes A, B, C, and D which are tightly controlled and thus restrict the GA aircraft operations. This limited access to airspace and insufficient air traffic management have curtailed GA growth [12]. However, China is gradually moving towards the liberalization of airspace. In November 2010, the State Council and Central Military Commission of China issued “Considerations on the deepening of reform in control mode of airspace at low altitudes” [19], which presented a plan to open the airspace below 4,000 m for amphibious aircraft. Since 2011, China reduced the time needed to obtain flight permissions and in 2014, China took a significant step towards liberalizing airspace below 1,000 m (3,280 ft above mean sea level) upon a joint approval from the State Council, the Air Traffic Control Commission and Central Military Commission [20]. This regulation provides classifications such as (1) those under control and requiring prior permission, (2) areas that do not require prior permission but remain under surveillance, and (3) areas where aircraft can fly freely after filing flight plans [20].

3. Weak support and insufficient supplies of equipment
China still lacks the domestic after-sale support in the GA industry. As such, aircraft owners need to rely heavily on foreign overhaul and supports. To address this problem, China has been trying to establish joint ventures with a majority of the world’s leading manufacturers of GA equipment in the past ten years. In 2007, China's first GA aircraft shop and service center “4S” opened in Hangzhou [12]. Clearly, more companies will be required to support the expected growth of the GA industry development. Moreover, in order to create more favorable conditions for the operators and private owners of GA aircraft, the Civil Aviation Administration of China (CAAC) needs to continue to help reduce operating costs. MacCorkle and Wong stated that CAAC planned to reduce the import duties and value added tax (VAT) for GA aircraft and parts [13]. In fact, the import duties on GA aircraft were reduced from 23% to 5% in 2010, but the VAT still remains at a high 17% [12].

6. Preliminary Designs for Amphibious Aircraft
We have started the preliminary design projects for two amphibious aircraft at the Hong Kong University of Science and Technology (HKUST). The two designs have different basic payload requirement: one is for a two-seater aircraft and the other for a ten-seater aircraft. These design projects are designed to suit Final Year Design Project (FDYP) scopes and requirements for undergraduate students. Each design will be described briefly below. Due to the different payload requirement, the resulting designs are vastly different from each other, as can be observed in the following. Considering the limited time (less than a year) and that the projects were done mainly by undergraduate students, the designs are still at a very preliminary stage and there are still a lot to be done for completed designs.

6.1 Two-seater amphibious aircraft design
The proposed design for the two-seater amphibious aircraft is shown in Figure 6. This configuration features sponsons and an H-tail with two vertical stabilizers. The propeller is located at the back of the tail. This placement would shift the aircraft center of gravity (CG) rearward, which will affect the stability of the aircraft where the aircraft might tip over backwards in water. To counter this rearward CG shifting, we need to adjust the size and positions of the floats. The vertical alignment of the main wings, horizontal stabilizers, and the propeller would affect the aerodynamic performance, due to the interaction of wake produced by the wing during flight. The wing wake is a narrow band of reduced dynamic pressure resulting from the interaction between the upper and lower boundary layers. If the wing wake impinges the stabilizer or the propeller, the overall aerodynamic efficiency will be reduced, and the flight stability will be adversely affected as well. This issue is resolved by shifting the propeller upward. This design change comes with a tradeoff between the aerodynamic efficiency and total gross
weight, by means of the additional structure to attach the propeller to the empennage. Table 2 summarizes the key design parameters and performance of the proposed two-seater amphibious aircraft. 

The Rotax 912ULS engine is used, which has previously been implemented in LISA Akoya aircraft.

![Figure 3. Proposed design for the two-seater amphibious aircraft.](image)

One of the key design elements in the proposed two-seater amphibious aircraft is the noise shielding, to reduce the noise impact to people on the ground. Aircraft noise (acoustics) is an inherent problem in any aircraft operations, with airframe and aircraft engines being the two major noise sources. This problem is even more prominent during takeoff and landing, when the aircraft is still at a relatively low altitude.

In this project, we conduct experiments to test different noise shielding configurations, including the vertical shield and circular shield. The experiments also include the unshielded propeller configuration for comparison purposes. Several sizes for the noise shields (both circular and vertical) are tested, as shown in Table 3. This table summarizes the detailed experimental setup and apparatus. The configurations for the vertical and circular shields are illustrated in Figure 5. For the experimental setup, we use scaled models of propellers and shields. Acrylic is used as the noise shielding materials. The experimental setup is shown in Figure 4. Four microphones are placed at various locations, all with the same height. Microphone 1 is located directly intersecting the propeller axis of rotation, microphone 4 is located within the plane of propeller rotation, whereas microphones 2 and 3 are located at equal angular distances between microphones 1 and 4. To measure the far field noise level of the propeller, a distance between the microphone and propeller is set to be 1.5 m. The motor and microphones are connected to a data acquisition system using the LabVIEW System Design Software.

The experiment results suggest that the proposed method of reducing propeller noise by using the vertical stabilizer as noise shields is ineffective, and could even potentially increase the noise level. On the other hand, the circular cover shield result in reduced noise levels by as much as 9 dB. To further improve the effectiveness of the noise shielding, we can further explore the modifications of the propeller geometry and material selection. Selecting a suitable material for the shield would be quite challenging. The selected material needs to be water-resistant as the amphibious aircraft would consistently be exposed to water. The material also needs to be smooth so as not to increase the aerodynamic drag, which could in turn affect the aerodynamic efficiency of the aircraft. Another critical material property would be the strength of the material, as the shield would be experiencing constant force from the aerodynamic drag. Identifying and integrating an appropriate noise absorbing material would greatly enhance the noise reducing property of the shield.
### Table 2. Summary of the design parameters and performance for the two-seater amphibious aircraft.

| Design Factors       | Design Values                                                                 |
|----------------------|-------------------------------------------------------------------------------|
| **Certification**    | Certification type: FAA Light-Sport Aircraft Airworthiness Certification      |
| **Propulsion system**| Engine: Rotax 912ULS, Propeller: Constant speed 6-blade propeller, \( D = 1.7\text{m} \), Fuel tank capacity: 30gal MOGAS (80.63kg) |
| **Wing**             | Area: 11.7 \(\text{m}^2\), Span: 10.515 m, Aspect ratio: 9.45, Sweep: No sweep, Taper ratio: 0.5 – 1.0, Airfoil shape: NASA LANGLEY LS(1)-0417 (GA(W)-1), Angle of incidence: 2.34° |
| **Tail**             | Horizontal tail area: 2.99 \(\text{m}^2\), Horizontal tail span: 3.458 m, Horizontal tail mean chord: 0.865 m, Vertical tail area: 0.78 \(\text{m}^2\), Vertical tail span: 1.249 m, Vertical tail mean chord: 0.625 m, Airfoil shape: NASA LANGLEY LS(1)-0417 (GA(W)-1), Horizontal tail angle of incidence: -5°, Horizontal tail aspect ratio: 4, Vertical tail aspect ratio: 2, Taper ratio: 0.5 – 1.0, Sweep: 0 - 20° |
| **Material selection** | Fuselage: Carbon-fibre composite, Wing and tail surface: Alclad alloys, Wing and tail internal structures: A1 7475-T7361 |
| **Aircraft performance** | Payload weight: 180 kg, Gross weight: 643 kg, Empty weight: 397 kg, Range: 1,015.6 km, Engine endurance: 7.6 hours, Takeoff distance (on land): 315.53 m, Takeoff distance (on water): 410.19 m, Cruise stall speed: 22.37 m/s |
Figure 4. Noise shielding experimental setup.

Table 3. Apparatus setup for the noise shielding experiments.

| Apparatus               | Specification/model                                      | Amount |
|-------------------------|---------------------------------------------------------|--------|
| Motor                   | E305 2312E (960 kV, CCW)                                | 1      |
| 2-blade propeller       | Diameter: 250 mm                                        | 1      |
| 3-blade propeller       | Diameter: 250 mm                                        | 1      |
| Microphones             | -                                                       | 4 sets |
| DC power supply         | GPC3030DN                                               | 1      |
| Anechoic chamber        | AVIC Advanced Noise Technology Center                    | -      |
| Data acquisition system | LabView System Design Software                           | -      |
| Circular shield         | Diameter: 260 mm, 270 mm, 280 mm                        | 1 each |
| Vertical stabilizer shield | Height: 250 mm, 270 mm, 290 mm, 310 mm                  | 1 set each |
6.2 Ten-seater amphibious aircraft design
The second student project focuses more on designing a ten-seater amphibious aircraft, with eight passengers and two crews. The resulting design is notably different from the two-seater one, which shows that an aircraft design is significantly driven by the mission requirements. Table 4 summarizes the mission requirements for this ten-seater amphibious aircraft. These requirements were decided after performing a market research, to suit the regional needs where we focused on the Pearl River Delta’s region.

| Mission requirement          | Value                        |
|------------------------------|------------------------------|
| Maximum range                | 1,000 km                     |
| Number of passengers         | 8                            |
| Number of crews              | 2                            |
| Baggage allowance            | 20 kg baggage per passenger  |
|                              | 10 kg baggage per crew       |
| Total payload                | 950 kg                       |
| Cruising speed               | 170 knots (approx. 314 km/h) |
| Maximum cruising altitude    | 3,048 m (10,000 ft)          |
Figure 6. Proposed design for the ten-seater amphibious aircraft.

Figure 6 shows the final proposed design for the ten-seater amphibious aircraft, and the selected design parameters are tabulated in Table 5. This configuration is a high-wing, T-tail, twin-engine aircraft with hydrofoil mounted at the bottom of the fuselage. The landing gear mechanism is also specially designed, though not shown in the figure, but will be briefly described shortly. This design is decided upon performing some empirical and numerical analyses on aerodynamic, structures, and aircraft stability. We mainly use OpenVSP [21] as the main aircraft conceptual design software tool. OpenVSP is an open-source software developed by a group of NASA engineers led by J. R. Gloudemans. Using this software, users can construct preliminary geometry models of aircraft, and perform aerodynamic analysis on the model using the vortex lattice method or panel method with an embedded aerodynamic solver, VSPAero.

Table 5. Design parameters for the ten-seater amphibious aircraft.

| Design parameter         | Value                                      |
|--------------------------|--------------------------------------------|
| Total length             | 16.5 m                                     |
| Span                     | 20.8 m                                     |
| Height                   | 7.07 m                                     |
| Maximum takeoff weight   | 5,740 m                                    |
| Powerplant               | 2 Trace OE600 radial engine, 600 hp each   |
| Aspect ratio             | 9.08                                       |
| Taper ratio              | 0.4                                        |
| Wing skin material       | Carbon-fibre reinforced epoxy              |
| Wing internal structure  | A1 6061                                     |

The aircraft structure, including the internal structures, are modeled in Solidworks which enables the estimation of the aircraft mass, center of gravity, and center of buoyancy (for the hydrostatic stability analysis). The landing gear mechanism design and the aircraft structural integrity are analyzed via the finite element method (FEM) performed in ANSYS. The inverted-T variable sweep hydrofoil is designed using Xfoil and Solidworks. The aircraft stability and control were analyzed in MATLAB. To analyze the aircraft dynamic stability, we look into five modes of dynamic responses. They include the longitudinal stability (short and phugoid modes), and lateral stability (roll, Dutch roll, and spiral modes).

As mentioned, we need to design our own landing gear. This is due to the hydrofoil placement under the fuselage, which requires more ground clearance than other standard-sized landing gears. In designing the landing gear mechanism, it is important to make sure that it would not impair the streamline geometry, so as not to sacrifice the aerodynamic performance. We decide on the common tricycle landing gear design with oleo shock absorbers for good ground stability, relatively light in weight, and its efficiency in energy absorption. Figures 7 and 8 show the main and nose landing gear mechanisms, respectively. The landing gear positioning, which is illustrated in Figure 9, is determined upon analyzing the ground stability (tip-back angle) and the aircraft operation and movement during takeoff and landing, to ensure enough clearance and safety. Load analysis is performed to size the wheels and shock-absorber, to ensure that they can withstand the aircraft weight and loads.

An amphibious aircraft needs to be able to takeoff and land from water. Hydrofoil, which is similar to airfoil but works underwater, can provide extra lift and reduce drag during the water takeoff. A hydrofoil is a lift-generating device mounted at the bottom of the fuselage. The hydrofoil can get the hull out of the water, allowing for a faster takeoff with a shorter distance. By lifting the hull out of the water, the aircraft needs to only overcome the drag on the foils instead of all the drag on the hull. There
are two major considerations for designing hydrofoil of an amphibious aircraft. The first one is to prevent cavitation, which occurs when the water pressure drops to the point where the water starts to boil. When cavitation occurs, the foil no longer generates enough lift, which might risk the aircraft crashing down onto the water. Just like airfoil, when a hydrofoil encounters a free-stream velocity, the pressure on the upper surface drops. With the acceleration of the aircraft, this pressure might drop below the vapor pressure of the working liquid such that cavities form. As pressure of downstream of upper surface increases, the bubbles collapse when pressure rises above the vapor pressure. After the bubbles collapse, high density of energy (the latent heat of condensation) is released so that the local pressure and temperature also increase. As cavities form and implode in a very short duration continuously, the phenomenon negatively affects the structural integrity of airfoil and increases the hydrodynamic drag. Therefore, preventing cavitation is the primary consideration in designing the hydrofoil system.

Figure 7. Main landing gear mechanism design for the ten-seater amphibious aircraft
Figure 8. Nose landing gear mechanism design for the ten-seater amphibious aircraft.

Figure 9. Main landing gear mechanism design for the ten-seater amphibious aircraft.
The second one is the lift transfer from hydrofoil to airfoil. Before takeoff, hydrofoil and airfoil both provide lift to the aircraft. However, upon reaching the takeoff speed, the airfoil needs to provide all the required lift as the hydrofoil leaves the water and therefore does not provide lift anymore. This phenomenon would lead to the porpoising of the vehicle before it actually takes off. Therefore, a gradual transfer of lift from the hydrofoil to the airfoil becomes another important design requirement for the hydrofoil system.

To accommodate these two design considerations, an innovative variable sweep hydrofoil design is proposed. Figure 10 shows that changing the sweep angle of the hydrofoils can help increase the pressure acting on them, thus preventing cavitation. This figure shows that when the hydrofoil is unswept, its upper surface is covered by low-pressure region, which corresponds to cavitation. However, when the hydrofoil is swept, the surface pressure dramatically increases and thus prevents cavitation. At the same time, lift is transferred to airfoil.

**Figure 10.** The pressure differences with variable sweep hydrofoils, measured at a water flow rate of 25 m/s.

7. **Conclusion**

In this paper we have discussed the prospect of developing amphibious aircraft, focusing more on the Asian region. The initial market research has revealed its vast potentials, spanning from business, logistics, safe and rescue, and tourism industry. The unique takeoff and landing mechanisms of amphibious aircraft would solve the problem of limited airport infrastructure in some areas, since they can takeoff and land from both water and land. Moreover, amphibious aircraft fly at a lower altitude than the typical commercial passenger and cargo aircraft, and thus their introduction would not further add to the air traffic congestion.

Aircraft design process is a complex procedure, since we need to take into account the different disciplines and their interrelations (i.e., how changing one parameter in one discipline would affect other disciplines). Some disciplines include aerodynamics, structures, stability and control, energy and
propulsive system, and aeroacoustics, to name a few. Each discipline is complex on its own, and taking into account the interdisciplinary relations between them could make the aircraft design problem intractable. An aircraft design process is primarily driven by the specified mission requirements, e.g., payload (passenger, cargo, or both), mission range, cruise speed and altitude, etc.

We discuss some of the design challenges, both the technical and non-technical (e.g., regulatory and certification), and present two preliminary design projects. Most of the mission requirements for these two designs are similar, which were derived based on the market research, with the mission ranges aimed to cater for the Pearl River Delta region. The two amphibious aircraft, however, are designed to cater for different payload requirements. In particular, two-seater and ten-seater aircraft are designed and analyzed. From these design examples we can clearly see how one mission requirement can result in very different designs, and not just in term of size difference. Despite the different requirements, both design projects follow the similar aircraft design procedure.

For the two-seater amphibious aircraft, we look more deeply into the aeroacoustics aspect, i.e., to reduce aircraft noise. While there are multiple sources of aircraft noise (e.g., from airframe and engine), in this work we only focus on reducing the noise impact from the engine propeller. A series of experiments are setup and performed, from which we observe that the circular noise shielding has the potential for the propeller noise reduction. For the ten-seater aircraft, we focus more on the hydrofoil design, landing gear mechanism, and the stability and control analyses. We come up with the variable sweep hydrofoil mechanism to ensure that the aircraft has enough lift upon leaving the water during takeoff. The hydrofoil placement under the fuselage requires a special landing gear mechanism design. The stability and control analyses look into five dynamic response modes, including those in lateral and longitudinal directions.

While still at a preliminary stage, the work and discussion presented in this paper provide reviews on design aspects and challenges of quiet and efficient amphibious aircraft. Due to the complexity of an aircraft system, there are still a lot to be done to produce the final, integrated designs. To design a truly efficient amphibious aircraft, we need to solve other inherent problems of amphibious aircraft, namely higher drag, heavier aircraft, and to obtain the right balance between aerodynamic and hydrodynamic performance. These have been some of the bottleneck problems in designing an amphibious aircraft. In order to revolutionize amphibious aircraft in general, more research efforts need to be invested to overcome the aforementioned challenges.

As mentioned before, the amphibious aircraft development would not only be beneficial to the China region (where most of the background study for this project is based on), but to other countries and regions in Asia as well. Indonesia, in particular, would benefit a lot with the thousands of islands scattered around in the vast archipelago. We strongly believe that stronger collaboration among different institutions in Asia can help propel this project into a greater success.

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