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Initial Development of LTA-HALE Airship

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Abstract—This present work describes the development and performance analysis of a High-Altitude-Long-Endurance (HALE) hybrid-airship. Hybrid-airship design was chosen because it uses both the Lighter-Than-Air (LTA) and Heavier-Than-Air (HTA) concept to produce lift. LTA concept uses less energy than Heavier-Than-Air (HTA) concept, hence more endurance and flight hours in certain condition. This special characteristic of LTA-HALE concept gives extensive opportunities of development in many areas, such as surveillance, scientific, and technological purposes. The airship was designed to reach the target altitude of 60,000 ft. and the target velocity of 10 m/s. Glass fiber frame are used to maintain its shape and also function as its primary structure. Helium weather balloons are used to produce lift for the airship. A thin layer is placed in the frame as the outer layer of the ship, protecting the balloons. As a basis for the primary structure design, gas behavior such as pressure and volume variation in various altitudes also studied and presented. Computational Fluid Dynamics (CFD) analysis was performed to the airship model on the target altitude and velocity in order to obtain drag of the model. From this data, the power required for propulsion in cruise condition can be calculated. The produced design then compared with existing airships and aircrafts to determine the effectiveness of the design.

Keywords—HALE, LTA, volume variation, scaled model.

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I. INTRODUCTION

HIGH-Altitude Long Endurance Aircraft (HALE) is starting to take the attention of scientific, commercial and military world. The ability to fly in near-space environment for a long duration enables scientist or any other user to conduct observation, research, or surveillance in this environment.

The main challenge of flying in a near-space environment is how to produce lift. The conventional Heavier-Than-Air (HTA) concept, which uses pressure differential in its wings to produce lift, is proved to be inefficient since in this altitude the air density is very low. Aircraft should travel in a higher velocity to compensate this issue, therefore more fuel used and decreasing the fly time of the aircraft.

Other than air density, pressure and temperature also gradually decrease with the increasing altitude. Changes in pressure and temperature cause a variable-volume balloon to expand in higher altitude. This issue also poses some challenges in the design process.

The present work explains the design process of a LTA–HALE Airship. The airship was aimed to fly in 60.000 ft. (18,000 m). For this project, we use a hybrid of the Lighter-Than-Air (LTA) concept and Heavier-Than-Air (HTA) concept as a mean to produce lift. LTA concept uses buoyancy effect to produce lift. Unlike the HTA concept, which needs the aircraft to keep moving to produce lift, the LTA concept enables the aircraft to hover in the same position for a long period of time, hence resulting in more endurance.

Theoretical studies are firstly conducted to determine the most efficient design by using present theories about lift forces, drag forces, and balloon volumetric expansion rate. Comparison between the existing designs then presented.

II. METHODOLOGY

A. *Lift*

Buoyancy force is the resultant force acting to a body when a body is submerged into a fluid. Since pressure increases with depth, the pressure forces acting from below are larger than the pressure acting from above, thus creating a net upward vertical force [1]. This vertical force is the buoyancy force and can be expressed as

$$F_B = \rho_f . V_s . g \qquad (1)$$

where ρ_f is the density of the fluid, V_s is the volume of the submerged body and g is the gravitational acceleration.

To be able to produce lift, the weight of the body must be smaller than the buoyancy force. To achieve this within the same volume, the density of the body must be smaller than the surrounding fluid (ambient air). In case of a balloon, this can be achieved by filling the balloon with low density gasses, lower than of ambient air, for example helium and hydrogen.

Taking consideration of the balloon weight and gas weight, the net amount of lift which a balloon provides can be expressed as [2]:

$$F = \left(\rho_f - \rho_g\right) . V_s . g - W_B \qquad (2)$$

where ρ_g is the density of the gas which fills the balloon and W_B is the net weight of the balloon material.

Lift is the resultant force normal to the upstream velocity as a result of the interaction between the body and the fluid when those body moves through a fluid. This interaction can be described as pressure force and viscous force [1]. Since lift is the resultant normal to the upstream velocity, lift force can be described as

$$dF_Y = (P . dA) . \cos\theta + (\tau_w . dA) . \sin\theta \qquad (3)$$

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where P is the pressure distribution and τ_w is the wall shear force distribution. The first cosine component describes the pressure effect on lift, and the second component describes the shear force effect.

Since the knowledge of body shape, the pressure distribution, and shear force distribution along the surfaces are required, manual calculations are difficult to be conducted. Among available solutions, approximate solutions using Computational Fluid Dynamics (CFD) analysis are used in this paper. This analysis will be used to determine the approximate lift force produced by an airfoil.

Airfoil selection is based on the characteristics of lift coefficient (CL) and drag coefficient (CD) of the airfoil. In order to select the best airfoil, these characteristics are gathered and compared from the airfoil database. For HALE airfoil with the highest CL to CD ratio is selected because it can produce the highest possible lift with minimum drag. The airfoil must also operate efficiently in operating altitude (18,000 m) and in low speed environment. The two latter criteria can be analyzed using Reynolds Number (Re) since different Reynolds Number produce different characteristics of CL/CD ratio. For a flow around airfoil, chord Reynold Number (R) can be defined as [3]:

$$R = \frac{V.c}{v} \tag{4}$$

where V is the flight speed, c is chord length and ν is the fluid kinematic viscosity.

Both buoyancy force from balloon and lift force from airfoil are used to produce lift for the airship. Specifically, buoyancy force is designed to be equal with the total weight of the airship system and acts as the primary lift force of the airship. Lift from airfoil then can be used as positive or negative ballast to increase or decrease the altitude of the airship. Airfoil also can also be used to provide pitch and roll stability in flight.

B. Drag

Other than lift, drag force is also existed as a result of the interaction between body and fluid when a body is moving through a fluid. Drag force is the resultant force in the direction of the upstream velocity and can be described as [1]

$$dF_X = (P.dA).\sin\theta + (\tau_w.dA).\cos\theta \tag{5}$$

Similar to lift calculations, the scarcity of knowledge in body shape, pressure and shear force distribution make the calculations of drag force difficult to be done manually. Thus for this calculation, approximate solution is more preferred using CFD analysis.

Since HALE operates in a long period of time, drag force must be minimized to achieve power efficiency. Drag force obtained from the approximation, and then can be used to decide whether the current airship design met the maximum drag force criteria. This data can also be used to calculate the minimum propulsion force needed in the target operating condition.

C. Balloon Expansion

Properties of an ideal gas whose equation of state is given by $p.v{=}R.T$ will change according to temperature [4]. In case of gasses inside a balloon, this change in temperature will occur as the balloon increases its altitude. Temperature will decrease linearly in the troposphere level (0–11,000 m) with a lapse rate of -6.5 ℃/km. From this altitude the temperature becomes constant with the value of –56.5 ℃ until the altitude of 20,000 m (Tropopause) [5]. Using relationship as described above, temperature in a given altitude can be expressed as [10]

$$\begin{aligned} T &= 288.15 - 0.0065.h \qquad [h \leq 11{,}000\ m] \\ T &= 216.65 \qquad\qquad [h > 11{,}000\ m] \end{aligned} \tag{6}$$

where T is temperature and h is altitude above mean sea level (AMSL).

From all of those properties, temperature and pressure pose a significant role in airship performance. The decreasing pressure causes balloon to expand its volume, thus decreasing its internal pressure to achieve equilibrium with the environmental pressure. This causes the volume of a balloon increases in higher altitude.

To calculate pressure value in a specific altitude, barometric equation can be used [5] as follows:

$$p = p_b.\left[\frac{T_b}{T_b + L_b(h - h_b)}\right]^{\frac{g.M}{R^*.L_b}} \tag{7}$$

where p_b, T_b, L_b, h, h_b, R^*, g, and M are standard static pressure (Pa), standard temperature (K), standard temperature lapse rate (K/m), height above sea level (m), height at bottom of layer b (m), universal gas constant for air, gravitational acceleration, and air molar mass, respectively.

This equation applies in the area with existent temperature lapse rate (stratosphere). The second equation

$$p = p_b.exp\left[\frac{-g.M.(h - h_b)}{R.T_b}\right]^{\frac{g.M}{R.L_b}} \tag{8}$$

can be used in area of no temperature lapse rate. The term b differentiates the standards value that is used in the equation according to value of airship's position above mean sea level. The standard value in each of b can be seen in **Table I**.

Table I Standard value of b

b	AMSL (m)	Static Pressure (Pa)	Standard Temperature (K)	Temperature Lapse rate (K/m)
0	0	101325	288.15	-0.0065
1	11000	22632.1	216.65	0
2	20000	5474.89	216.65	0.001

Ideal gas equation can be expressed and rearranged as [4]

$$P.v = R.T \tag{9}$$

$$P = R.T.\rho \tag{10}$$

where P is pressure, v is the specific volume, R is the universal gas constant, ρ is density, and T is temperature. This equation can be used to obtain the pressure value inside the balloon.

Because the value of ideal gas constant (R) is always constant, the following relationship can be obtained.

$$\frac{P_1.V_1}{T_1} = \frac{P_2.V_2}{T_2} \tag{11}$$

Since variable-pressure balloon is used, the pressure between the inside and outside of a balloon is always equal until the point when the balloon is going to burst [6]. Using the pressure value obtained from Equation (7) or (8) and temperature from Equation (6), Equation (11) can be used to obtain the volume of the balloon at an altitude.

The ultimate balloon diameter in operating altitude is then used as basis for the airship design, primarily the dimension of the airship, so that the airship frame can still contain the balloon in its operating condition.

D. *Power Requirement and Efficiency*

Power needed by the propeller to produce certain thrust in certain velocity can be calculated by

$$P = T.v \tag{12}$$

where T is the thrust produced and v is the velocity that can be produced by the propeller.

To completely negate the effect of drag force, produced thrust must be equal or greater than drag force. Therefore, to calculate the power needed, thrust (T) can be substituted by the drag force (D).

Power efficiency can be analyzed using weight-to-power ratio. It is a measure of how much payload can be moved with a certain amount of power. In term of HALE, a more efficient vehicle must have higher amount of weight-to-power ratio, since it means that for the same amount of energy, it can lift more payload. Weight-to-Power Ratio (WTPR) can be expressed as:

$$WTPR = \frac{m_v}{P_v} \tag{13}$$

where m_v is the mass of the vehicle and P_v is the power required by the vehicle.

III. RESULT AND DISCUSSIONS

A. *Balloon*

1) *Balloon Expansion*

Using Equation (6), (7), (8) and (11) volume of the balloon in various altitudes can be calculated. The diameter of the balloon can then be obtained. This result is compared to the initial diameter to obtain the expansion ratio, which is the ratio of diameter in h and the initial diameter. Result as presented in **Figure 1** shows that the value of expansion ratio in 18,000 m is 2.5.

Using Equation (2) a balloon which has 350 N of lift requires to be inflated to diameter of 90 cm. This ratio means that in the operating condition of 18,000 m, the balloon will expand 2.5 times into a diameter of 225 cm. This value is then used as the design requirement of the airship. The diameter of the airship must be designed to be more than 225 cm to be able to tolerate the expansion of the balloon.

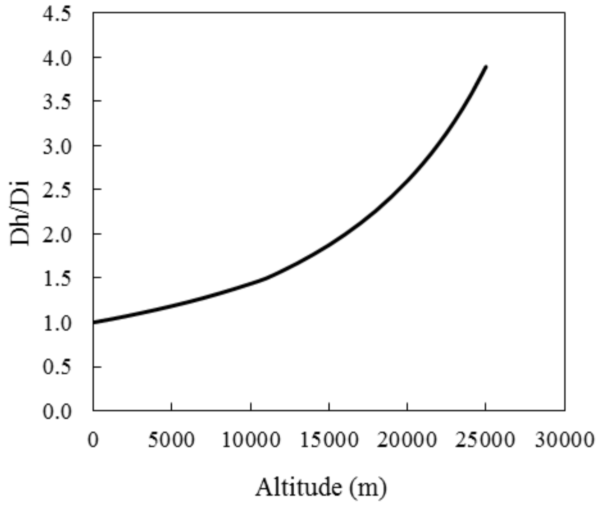

Figure 1 Expansion ratio

2) *Balloon Lift*

Lift force produced from balloon is used to completely negate the weight of the airship system. Therefore, amount of lift produced must be equal with the weight of the airship system to achieve equilibrium condition. The total system weight criterion is chosen to be 1.75 kg.

Equation (2) shows that an increase of lift value can be achieved by increasing volume that is submersed in fluid. For the design we will choose a 50 gram weather balloon and helium to fill the balloon, since helium is safer due to its inert characteristics. Table below show the net lift a single balloon can produce, also the number of balloon needed to meet the 1.75 kg lift criteria.

TABLE II BALLOON LIFT REQUIREMENTS

Balloon Diameter (cm)	Net Lift per Balloon (N)	Balloon Needed (pcs)
50	17.942	98
60	67.403	26
70	136.432	13
80	228.289	8
90	346.236	5
100	493.534	4
110	673.444	3
120	889.227	2

TABLE II shows a 90 cm diameter balloon is a good choice for the design, since it can meet the 1.75 kg lift criteria only with 5 balloons. A 100 cm seems better at first but a bigger dimension means that it will expand more in the operating condition, resulting in a bigger airship dimension, and ultimately a greater drag force.

In higher altitude, the surrounding fluid will have less density. However since the balloon expands in higher altitude, the lift force will generally have the same value in all altitude. The limiting factor of the balloon's performance is its material. As the volume expands, balloon material will stretch, causing stresses in the material. Balloon will keep going up until balloon material gives up and burst.

B. *Airship Model*

With the previous analysis, an airship design can be made. Using the balloon expansion, and balloon lift analysis, the diameter and length of the body frame can be determined. The selected airfoil also installed into the body. Design specifications are presented in **TABLE III** and the design concept are shown in **Figure 2**.

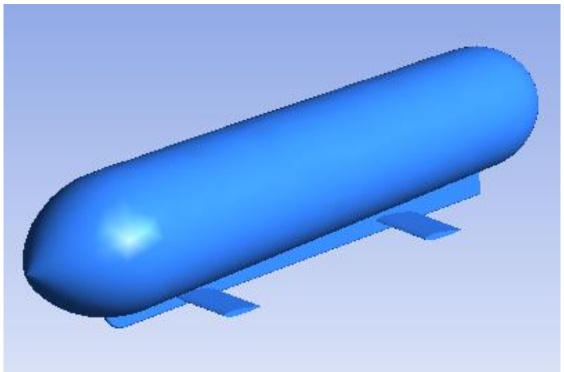

Figure 2 Design concept

TABLE III DESIGN SPECIFICATIONS

Body		
Total Length	14	m
Front Diameter	2.5	m
Rear Diameter	2	m
Wing		
Wing Span	1.5	m
Chord Length	1	m

TABLE IV AIRFOIL COMPARISONS

Airfoil	α (°)	C_L	C_D	C_L/C_D
GOE 411	5.5	0.725	0.024	30.1
J5012 12%	5	0.669	0.023	29
Eppler 521	6.25	0.779	0.026	29.2
Eppler E171	6.25	0.699	0.023	29.2
Eppler E297	5.5	0.652	0.022	29.3
NACA 63012A	5.5	0.626	0.022	28.9

C. *Performance*

1) *Airfoil selection*

Based on the airfoil data, some airfoils that that satisfy the high CL to CD ratio criteria are chosen. The chosen airfoil is symmetrical airfoils because airfoil not only used to increase altitude, but also to decrease the altitude. These CL/CD ratios are met in various angles of attack. The results are shown in **TABLE IV**.

The highest CL/CD ratio is given by GOE 411 Airfoil. Although Eppler 521 airfoil has bigger lift coefficient, it also has bigger drag, making it less efficient for the airship design.

2) *Power Efficiency*

The produced design then analyzed using computational fluid dynamics (CFD) to approximate the drag force on the body of the airship. Since air at different altitude will have different properties, the analysis will be conducted in two conditions. The first analysis will simulate drag force at 18.000 m in variable velocities, ranging from 0 to 15 m/s. The second analysis will simulate drag force at various altitudes, ranging from sea level to 18.000 m with constant velocity of 10 m/s. This velocity is the design velocity of the aircraft. Power required in each condition is also calculated using Equation (12). Pressure contour from the analysis is presented in **Figure 3**. The results are shown in **TABLE V** and **VI**.

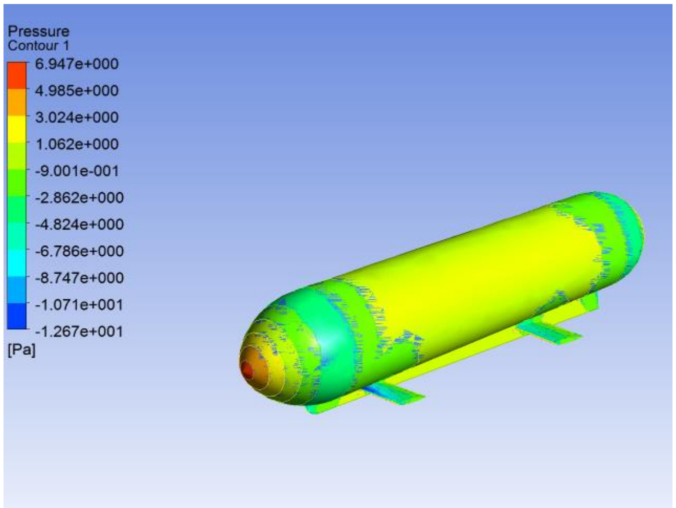

Figure 3 Pressure contour

From drag data shown above, operational power requirement needed by the airship can be calculated. From **TABLE V** and **VI**, it is known that as the airship increases its altitude, power required to drive the airship also decreases.

To achieve operational altitude, the airship must climb from sea level into 18.000 m, thus airship's propeller must be able to oppose drag force occur at sea level where it is at its maximum. However, this doesn't happen for long period of time. Airship can gradually decrease its propeller power until it reaches the most minimum power at operational altitude of 18.000 m. At this altitude the airship will spend most of its flight hours.

Therefore for the minimum design requirement, airship's propeller must have maximum power and can operate most efficiently at power level of 43.4 W. Although at sea level airship can't achieve velocity of 10 m/s, it can still provide lift to the airship and climb until altitude of 18.000 m. From simulation result it is known that with power of 43.4 W the airship can achieve velocity of approximately 4 m/s and 1.3 kg lift at sea level.

TABLE V DRAGS AT ALTITUDE OF 18,000 m

Velocity (m/s)	Drag (N)	Power (W)
2.5	0.296	0.7
5	1.114	5.6
7.5	2.463	18.5
10	4.337	43.4
12.5	6.737	84.2
15	9.671	145.1

TABLE VI DRAGS AT FLIGHT SPEED OF 10 m/s

Altitude (m)	Drag (N)	Power (W)
0	41.515	415.2
5000	25.425	254.3
10000	14.257	142.6
15000	6.426	64.3
20000	2.478	24.8

Based on those power requirements, the airship's Weight-to-Power Ratio (WTPR) can be calculated. Using Equation (13), the airship WTPR is 0.04 kg/W.

D. Comparison

The result from the preceding section with the existing HTA or Hybrid HALE technology to determine the efficiency of the designed airship with respect to another airship can be compared.

WTPR value serves as the base of this comparison, since a higher WTPR value mean more payloads can be lifted with the same amount of power. Data regarding various airship are collected from various literature [10-14] and presented in the table below.

The first three designs including the designed airship are the hybrid airship variant of the HALE UAV, while the last three are the HTA HALE UAV. Based on **TABLE VII** which contain the resulting WTPR from six airship design, the present design has a high WTPR ratio compared to another design, only second to Zephyr 7.

While Zephyr 7 has a higher WTPR ratio, its HTA nature makes the designed airship has some considerable advantages when compared to Zephyr 7. As mentioned before, HTA concept requires the aircraft to continuously move to produce lift. This means the aircraft need to constantly burn fuel to operate. The designed airship however, uses buoyancy lift from the balloon. Therefore, unlike the HTA counterpart the designed airship can still operate without using the engine, resulting in the increase of endurance.

Nonetheless, the designed airship still has some shortcomings in its ability. As shown in **TABLE VII** compared to other airship, the designed airship still has major flaw regarding the total payload available. To solve this problem an increase in balloon volume can be done to increase the buoyancy lift in the airship. A considerable bigger volume that can be seen on the LMH-1 design can be applied to the designed airship.

However, increase in balloon volume also results in bigger structure of the airship. This can lead to an increase in drag force and ultimately power requirement of the airship. Therefore the increase of balloon volume must also consider its effect into power requirement to find the best optimum condition.

TABLE VII AIRSHIP DESIGN COMPARISONS

Airship	Total Mass (kg)	Power (W)	WTPR (kg/W)
Present Design*	1.75	43.4	0.0403
Lockheed Martin LMH1*	23000	900000	0.0256
HAV 304 - Airlander 10*	20000	968000	0.0207
Pathfinder**	191.01	4823.5	0.0396
Helios HP 01**	589.91	18310	0.0322
Zephyr 7**	55.5	900	0.0617

*Hybrid variant of HALE UAV
**HTA variant of HALE UAV

IV. CONCLUSIONS

Various analysis regarding balloon, airfoil, lift and drag has been conducted to design a Hybrid Lighter-Than-Air High-Altitude-Long-Endurance Airship. The airship is able to operate in the altitude of 18,000 m and with the speed of 10 m/s. The payload available for use is 1.75 kg

Airship design is further compared with existing HALE UAV design regarding its Weight-to-Power-Ratio to determine its effectiveness. It is found that among the HALE UAV design selected, the produced design has second highest Weight-to-Power-Ratio of 0.04 kg/W. Further improvement in balloon volume can further increase payload available to use.

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