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Development of the Conceptual Design Algorithm for Tactical Aerostats

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Abstract

In this paper, an algorithm for the conceptual design of the aerostat is developed. This tactical aerostat is an intermediate step for stratospheric high altitude platforms. In the presented algorithm, the design and operational parameters of the aerostat such as geometry and dimension of the aerostat hull, shape and configuration of the tails, the mass budget of the balloon components, ballonet percentage, fabrics materials, stress of hull fabric, tether tension at the winch, static margin, angle of attack, blow by, tether length, tether profile, the confluence point position, etc. are determined via 4 distinguished loops. In addition, an aerostat is designed for the special given requirements using this algorithm, and the results are prepared in the paper. Furthermore, to optimize the tail sizing, the Taguchi orthogonal array L16 (45) is used. 16 different tails are designed and the static stability of the aerostat is analyzed using these tails and the final optimum geometry of the tail is introduced. Finally, the influence of the wind velocity, payload mass, payload position, and the operational height above mean sea level on the operational parameters of the aerostat are explored.

Keywords: Tactical Aerostat, Aerostat Design, Tethered Balloon, Design algorithm, Aerodynamic coefficient.

1. Introduction

In recent decades, to establish telecommunications and remote sensing, many types of research have been conducted on high-altitude platforms. These platforms are deployed in the stratosphere at a height of 20 km from the earth's surface and include airships, balloons, and airplanes [1]. Stratospheric platforms have advantages such as low air traffic, low energy consumption, wide field of view, and mild atmospheric currents compared to airplanes that are close to the ground. These platforms are much cheaper compared to satellites and do not have the problems caused by the lack of atmosphere [2].

Investment and research in the field of aerostatic systems is essential for the country to reach new heights. As an intermediate step, aerostat systems can be considered. Aerostat systems are streamlined balloons that are tethered to a ground platform. They use helium or hydrogen gas to provide buoyancy and are lighter than air [3]. Based on their dimensions, payload capacity, altitude, and flight endurance, these systems are divided into three categories: strategic, operational, and tactical systems.

Previous research in open literature has shown that existing design algorithms for tethered balloons do not comprehensively consider all important design parameters and have serious flaws. This article aims to address these gaps by developing a new design algorithm that can determine the dimensions of the body and tails of the balloon, as well as the appropriate confluence point, to ensure suitable static stability in different design conditions. The article presents a new design algorithm that considers all important parameters and outlines the various steps involved in the algorithm. The design process for the balloon was demonstrated, and various design parameters were determined. The optimal tail for the balloon is obtained using Taguchi's method. Finally, the article investigates the effect of different operating parameters on balloon performance.

2. Aerostat design algorithm

This section presents the design algorithm for the aerostat, which is aimed at conceptual design and determining the shape and dimensions of the body. Figure 1 depicts this algorithm.

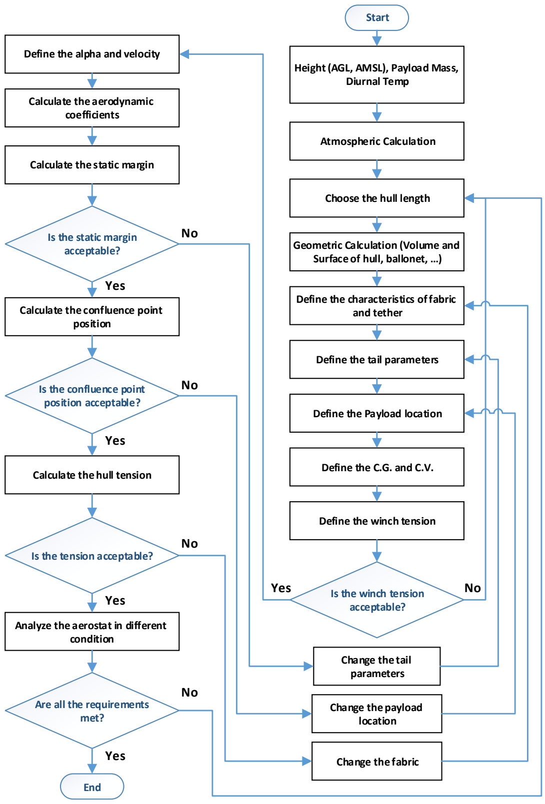

Figure 1. Design Algorithm in conceptual phase

Generally, the aerostat tether is connected to the balloon using several side ropes to prevent tension concentration. The correct location of this connection point is crucial to maintain the balance of the balloon. To determine the location of this point, the torque balance equation is used by considering the forces acting on the balloon around this point. The free body diagram of the balloon is illustrated in Figure 2.

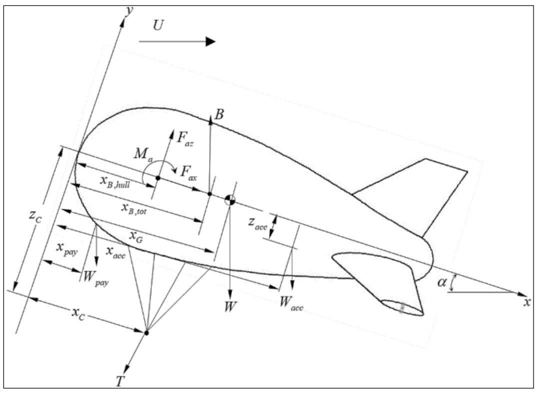

Figure 2. Free body diagram of the aerostat

The operational requirements of the aerostat are presented in the following table:

Table 2. Aerostat requirements

Parameter	dimension	value
Height (AMSL)	m	1200
Height (AGL)	m	200
Payload Mass	kg	40
Operational wind velocity	m/s	10
Diurnal temperature	ºC	20

After completing the design process by using the explained cycle and solving the balance equations, finally, the characteristics of the balloon are obtained as follows:

Table 2. Designed aerostat characteristics

Parameter	dimension	value
Winch tension at 10m/s	kgf	50.3
Gross weight	kg	126.8
Blow-by	m	87.7
Tether length	m	221.8
Tether weight	kg	67.8
Static margin	---	-0.13

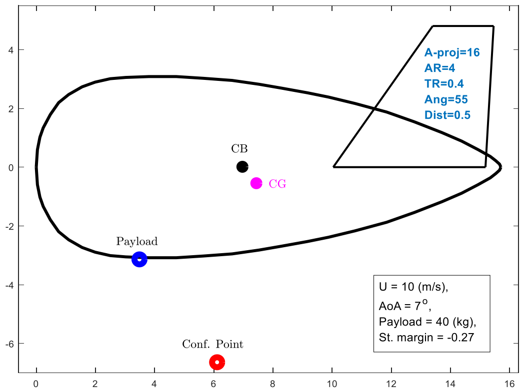

Figure 3. Schematic geometry of the designed aerostat

3. Tail Optimization

In this research, the Taguchi method was used to optimize the tail design, with four levels considered for each of the design parameters. As a result, 1024 modes were created for the tail. To narrow down the search, the L_{16} orthogonal array matrix (4^5) was applied, given that five parameters with four levels were studied. This matrix allowed for the examination of only 16 states out of the 1024 possible states, leading to the identification of the optimal state. Table 4 presents the optimized parameters, the number of levels, and the corresponding values for each tail parameter. Details on how the different parameters were determined for each of the 16 tests in the L_{16} array (4^5) can be found in [4].

Table3. Taguchi parameters and the Levels for each parameter

Value				Level Number	Paremeter
13	14	15	16	4	Tail projected Area
3.5	3.7	4	4.3	4	Aspect Ratio
0.3	0.37	0.42	0.5	4	Taper Ratio
40	45	50	55	4	Sweep Angle
0.5	0.8	1.2	1.5	4	Tail Distance

Using the data obtained from the 16 studied cases and Taguchi method, the optimal tail mode can be extracted. Figure 3 shows the optimal tail and the parameters related to it. By determining these parameters, the value of the stability margin is -0.27.

4. Results and Discussion

The design of an aerostat is based on certain conditions, such as wind speed, payload mass, and height above sea level. However, during operation, these conditions may vary, and the balloon's performance may be affected as a result. For instance, the wind speed and payload mass may differ between operations, or the balloon may be deployed in an area with a different elevation than what was considered in the design. Therefore, it is important to investigate the impact of these parameters on the balloon's behavior.

The most significant parameters that can affect the performance of the balloon are operational wind speed, payload mass, payload installation location, operational height above sea level, and balloon height above ground level. Each parameter is examined individually while keeping the other parameters constant. The design outputs used to assess the balloon's performance are the tether tension at the winch, angle of attack of the balloon, static margin, and tether profile. In this study, we will focus on the parameters that have the most significant effect.

Figure 4 illustrates the effect of operational wind speed on the angle of attack of the balloon, the tension in the tether at the winch, and the static stability margin. As shown in the figure, increasing wind speed from zero to 25 meters per second significantly increases the tension of the tether in the winch. Additionally, the angle of attack of the balloon slightly decreases with increasing wind speed. Meanwhile, the absolute value of the stability margin parameter also decreases, indicating reduced stability of the balloon at higher wind speeds. However, the reduction in stability caused by the change in speed from zero to 25 m/s is only six percent.

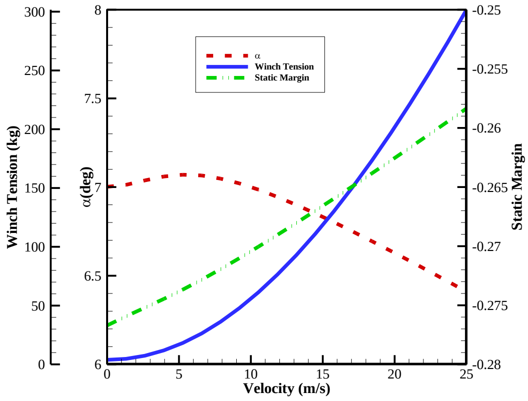

Figure 4. The variation of winch tension, angle of attack and static margin with respect to wind velocity

Figure 5 displays the changes in the tether profile at different flow speeds, with the tether length always assumed constant at 200 meters. As the flow speed increases, the amount of balloon blow-by also increases, resulting in a visible decrease in the height of the balloon, as shown in the figure.

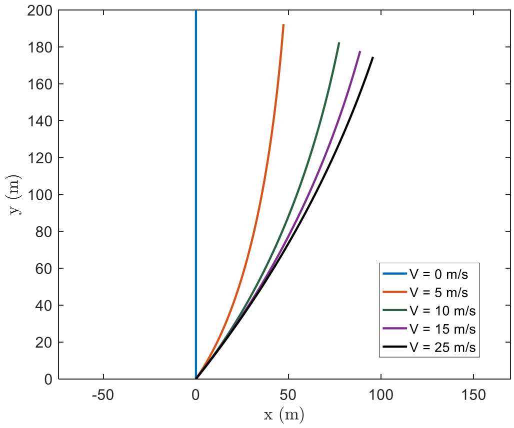

Figure 5. Tether profile with the variation of wind velocity

Figure 6 illustrates the changes in the angle of attack of the balloon as the payload mass varies. The figure clearly shows that an increase in mass leads to a decrease in the angle of attack, due to the moment effect of the payload weight around the balloon's confluence point. Furthermore, as expected, the winch tension decreases with an increase in payload weight. Additionally, increasing the payload weight reduces the static stability of the balloon. However, compared to the previous case, the changes in the balloon's stability are less significant, as seen in the figure

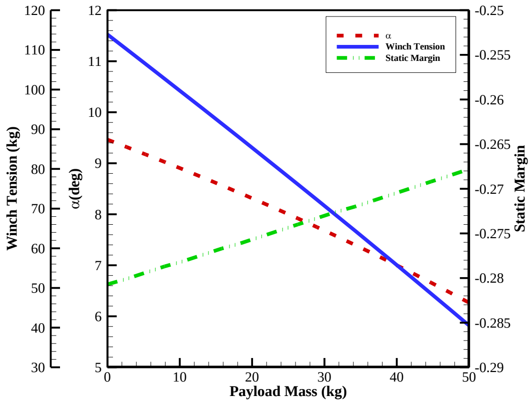

Figure 6. The variation of winch tension, angle of attack and static margin with respect to payload mass

Figure 7 shows the effect of the location of the payload on the behavior of the balloon. As shown in the figure, changing the location of the payload from m = 3.5x (relative to the tip of the balloon) to almost the middle of the balloon at m = 7.5, causes a significant change in the angle of attack, increasing from 7 degrees to 11 degrees. This increase in angle of attack leads to an increase in the aerodynamic force on the balloon, resulting in an increase in the tension of the tether at the winch. Moreover, this change in the location of the payload increases the static stability of the system.

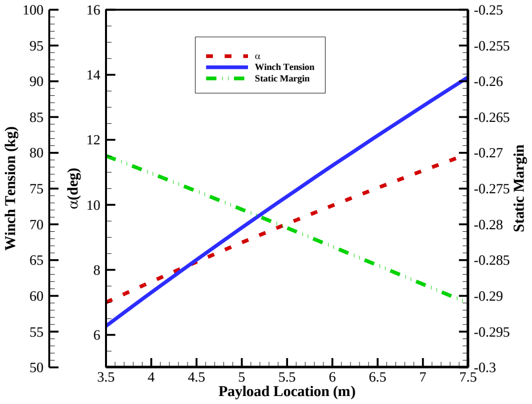

Figure 7. The variation of winch tension, angle of attack and static margin with respect to payload location

5. Conclusions

This article presents the development of a aerostat design algorithm in the conceptual phase, which consists of four separate cycles that determine various parameters including the dimensions of the balloon, the shape and configuration of the tail, the installation location of the payload, the profile of the tether, the amount of winch tension, the amount of stress on the shell, the amount of balloon blow-by, the weight budgeting of balloon components, and aerodynamic coefficients. The system also considers the percentage of the ballonet, the amount of static stability margin, the location of the balloon confluence point, and many other parameters.

The algorithm allows for changes to be made to the tail shape and quickly observe its effect on the static stability of the balloon, using a combination of analytical relations and CFD solutions to determine the aerodynamic coefficient of the entire system. After presenting the algorithm, a design algorithm for a body profile with specific operational requirements was implemented, and the results related to the design were presented. To optimize the designed tail, the Taguchi method was used to check different factors of tail design and present the optimal tail for the designed balloon.

In the final step, the article examines the effect of various design parameters, such as operating wind speed, payload mass, payload installation location, and the height of the operation location relative to sea level, on the balloon angle of attack, the static stability of the balloon, and the amount of winch tension.

6. References

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