An estimation method for parachute parameters

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Abstract. As a significant tool of transportation widely used in the logistics field, a well-performed parachute is highly required for this demand, especially for the sake of higher cost performance. The current study aims to investigate the internal relationship amidst various parameters of the parachute, conducting error analysis and accordingly providing an optimal experimental scheme. The objective of this experiment is to determine reference area and the resistance coincident, which are primarily parameters to estimate the weight of the designed parachute. Because the reference area is hard to determine using regular geometry method, a new parameter area ratio is redefined as the ratio of the original area of parachute surface to the reference area so that the reference area can be calculated by solving geometry problem. A simplified assumption that the parachute can be seen as a quasi-rigid body was previously made in order to approach the ideal parachute. Despite several limitations of the experiment, the final results perfectly aligned with the pre-experiment expectation. By following the similar procedures and after several trials, the ratio of the original area of parachute surface to the reference area was determined to be 3.90 and the resistance coincident to fall in the range of 2.00-3.00.

1. Introduction

As an efficient and reliable recovery method, the parachute system has been widely used in manned spacecraft, recoverable satellites, lunar exploration, Mars exploration, and other recoveries or deceleration landing processes. Generally, the parachute is made of flexible materials in the shape of a regular polygon [1], and it is connected to the objects hanging below by ropes with equal length fixed to each corner. During the falling process, the air resistance [2] generated by the parachute surface would act on the object through the rope thus object can fall at a constant velocity in air and guarantee the safety of the landing process.

The weight of external load is determined by air density, falling velocity, reference area, and resistance coefficient [3]. Among the design parameters of the parachute, the resistance parameter is especially essential because it is affected by many factors like the surface area, gliding characteristics, airflow pattern around, shape, the permeability of the fabric, descent velocity and length of ropes [4].
In the following experiment, the resistance coincident is measured using wind tunnel and airdrop. The parameters of the parachute are changed each time until it satisfies the final demand. According to previous literature, most studies optimize parachutes based on motion simulation and mathematical models. For example, some researchers regard parachutes as rigid bluff bodies for 2-D simulations [5, 6]; others make 3-D computations for parachute based on fluid dynamics [7, 8] and structural dynamics [9, 10]. Considering the deployment process and overall changes in the parachute structure, more accurate calculations are required. Some researchers use computational fluid dynamics (CFD) methods to simulate and calculate the parachute movement [11, 12]. Similarly, some researchers regarded the shape of parachutes as a rigid body to study by using CFD [13]. Additionally, many design spacecraft parachutes use computer modeling to simulate the more complex fluid-structure interaction between the canopy of parachute and the air [14].

In this paper, to reduce a large number of complex calculations, the aerodynamic problem, which is based on CFD, is transformed into a geometric problem. The question is whether there is a certain connection between the area of canopy and rope. However, some ideal conditions need to be fulfilled for a simplified experimental way instead of using CFD [15] to find out the internal relationships between the area of parachute and length of rope: 1) First, the canopy and ropes are quasi-rigid bodies during the descent [16], and 2) Second, there is no influence of the transverse wind. This similar approach to design the cruciform parachute has been used [17, 18]. By controlling the length of the rope, the reference area of the parachute was redefined and measured. Furthermore, another parameter was defined as the ratio between the original area and the reference area. When a parachute is fully open, the ratio parameter would be the only function of the length of rope [19]. In the design process, if the original area, falling velocity, and weight of loads were given, resistance coincident would be the only function of the ratio parameter. If a database about the regular pattern of the ratio parameter by pre-experiment can be shown, then the resistance coincident and the length of rope would be easily determined [20]. This study discovered the inner relationship between the parachute parameters and the available range of resistance coincident. The next section provides a clear and precise description of how our experiment was done.

2. Method
Two parachutes were made of polyester fabrics. The surface of one parachute is shaped as a regular hexagon with a circumradius of 20 cm, and that of the other one is a regular octagon with a circumradius of 25 cm, as shown in Figure 1. The rope is fixed at every angle of the parachute surface. The ropes are marked at every 1 cm position. The total weight of the parachute can be expressed as follow:

\[ W_t = \frac{1}{2} \rho v^2 S_0 C_d \]  \hspace{1cm} (1)

where \( W_t \) is weight, \( \rho \) is density of air, \( S_0 \) is reference area, \( v \) is falling velocity, and \( C_d \) is resistance coefficient.

The reference area \( S_0 \) is variable, so \( S_0 \) is defined as the area of the regular polygon formed by the connection between the rope and the parachute surface, shown in Figure 1 below.

Figure 1. The red dotted polygon indicates the reference area \( S_0 \).
Then a parameter area ratio $K$ can be defined as follow:

$$\frac{S}{S_0} = K$$

(2)

where $S$ is the original area of the parachute surface. When the parachute is fully open, for a certain parachute, the relationship between $S$ and $S_0$ is a geometry problem. It is easy to determine that $K$ is the only function of $L$, which is the length of the rope. Then $C_d$ can be calculated as follow:

$$C_d = \frac{2w_L}{\rho v^2 S} K$$

(3)

A simple assumption was made that the parachute could be regarded as a quasi-rigid body when it is entirely open. The acceleration section of falling is neglected, so we focus on the steady section with uniform rope velocity. The experiment was planned to measure the reference area under the condition of different rope lengths. Through this process, the relationship between $K$ and $L$ can be determined and then the general scope of the resistance coefficient can also be determined by doing a falling experiment.

The length of the rope is controlled by applying a crocodile clip on it. The parachute is fixed in front of a fan with substantial power to ensure it will fully open. Every time the length of the rope is changed, a test will be done, and the average side length of $S_0$ will be measured. Therefore, $K$ can be easily calculated by applying equation (3).

In the following experiment, the rope length $L$ is changed by adjusting crocodile clip and weight is altered by changing the number of coins carried by the parachute. A video is taken nearby, and the velocity of the parachute is measured as it falls steadily as Figure 2.

![Figure 2. Drop height (on the left) and the load container attached by ropes (on the right).](image)

From the experiments above, data of $S, K, W$, and $v$ have been collected under different lengths of rope. Then the range of $C_d$ can be calculated.

3. Results
The first experiment is about area measurement. The parachute is shaped as a regular hexagon with a 20 cm circumradius and the curve for function $K$ with parameter $L$ is shown below in Figure 3.

It can be seen from Figure 3 that as rope length grows from a small value, $K$ will decrease. The decrease will slow down, and $K$ becomes a constant of 4 when rope length is longer than 35 cm. The range of rope length is estimated by the parachute surface (from $20 - 10$ cm to $40 + 10$ cm). This result matches up with the pre-experiment expectation.
When the rope length is zero, the reference area should be zero, and $K$ will approach infinity. That is what would happen when the rope length falls on the left side of the experimental data. If the rope length approaches infinity, the force acting on the parachute by the rope should be vertical to the surface. From moment analysis, the parachute that is made of flexible material will only keep a very fragile balance. It will quickly shrink ($S_0 = 0$, $K$ is infinity) and then fall freely with the cargo. So, when rope length falls on the right side of the experimental data, there will be a turning point. When a rope is at this length, the parachute's balance will be broken, and the reference area will reduce to zero very quickly. According to our experiment data, there is always undulation. That is why the stability of a parachute is also vital besides fundamental aerodynamic analysis.

**Figure 3. Relation between $L$ and $K$.**

**Figure 4. Front and top view of the parachute in different states.**

For comparison, the same experiment was repeated and data of another parachute, which is shaped as a regular octagon with a circumradius of 25 cm, was also collected. The curve is shown in Figure 5.

**Figure 5. Relation between $L$ and $K$ of Octagon.**
Due to the relationship between $K$ and $L$ is regarded as a geometric similarity problem, $L$ in the previous set of data is magnified by $25/20=1.25$ times, and in this case, the parachute is shaped as a regular hexagon with a circumradius of 25 cm. All three curves are drawn in the following Figure 6.

![Figure 6](image)

**Figure 6. This figure shows the relationship between the different value of $K$ between $L$**

From Figure 6, it is clear that when the circumradius is the same, for parachute with different regular polygons, the changing trend of $K$ is quite similar. In our experiment, when the rope length and circumradius are the same, $K$ for a regular octagon parachute is smaller than a regular hexagon. Furthermore, when the shape is the same, if their radii are not entirely different, the relationship between $K$ and $L$ can be easily inferred by multiplying the known one.

The relationship between $C_d$ and falling velocity is shown in formula 3. Due to the limitation of our experimental accuracy and the complexity of aerodynamic conditions, we can only provide the broad range of $C_d$. In our case, $C_d$ is about 1.5~3. This result is quite the same as another group working on the parachute, which gets the result of 1.3~2.4 by an independent experiment.

From all the experiments and results above, the regulation of $K$ and the general range of $C_d$ are identified. Imagine that when having a mission of making a parachute, the weight of cargo, the maximum falling speed is given, the first step is to determine the shape and area of the parachute surface. Then assume that $C_d$’s value is 2, from the equation 3 and the value of $K$ can be calculated. Finally, from the relationship of $K$ with $L$ and the similarity theory, the length of rope is determined. So, all the key parameters of the parachute are all known. Though the final project should be determined after real experiment due to the variable of $C_d$, only slight adjustments of relevant parameters will be made.

4. Discussion

According to the results, the relationship between $K$ and $L$ is that they are geometrically similar, and for different regular polygon umbrellas, the change trend of $K$ is very similar. This shows that in the case of determining the rope length and the shape of the parachute surface, a parachute can be quickly designed by using the $K$-$L$ curve. To obtain more accurate data, this experiment needs to be improved. This article treats the parachute as a quasi-rigid body and has not tested it in a wind tunnel or a real airdrop. However, the data and results obtained by simulating the parachute at low speed are in line with expectations. The results indicate that the value of $K$ is close to a constant in a wide range. By analyzing and summarizing the results, the following improvements can be expected.

According to the original equation, the reference area can be used to measure the effective airflow area and could be larger or smaller than the calculated area. However, by defining $K$, the variable area was correspondently changed into a measurable area. This could be considered as a dominating error resource. Given that, the primary improvement could be making a more accurate measurement of the area when the parachute is open. Also, the difference in scale may generate subtle effects on the final results. Aerodynamics results could be different between the small model and the 1:1 model. The
experiment should be well designed based on the similarity theory to deal with these problems, including geometry, movement and dynamic similarity. Finally, when calculating $C_d$, the measurement of $v$ is quite rough, though it seems enough to get a reasonable conclusion. To be more precise, CFD is the feasible way if it’s not tested in real wind tunnel. In the CFD model, a certain velocity should be set and then the total vertical force acting on the parachute also measured so that both $W$ and $v$ can be determined. By doing this, the error will be approximately minimized.

5. Conclusion
The present study's primary purpose is to find the relationship between reference area and the coincident resistance of the parachute by using geometric analysis methods, comparative experiments, and error analysis to create an optimized experimental scheme. In this paper, a parameter $K$ was defined as the original ratio of the parachute surface and the reference area. In this way, the changing trend of $K$ is quite similar for a parachute with different regular polygons when the circumradius is the same. It shows that under conditions of a particular shape and rope length, the $K$ value of the parachute is determined. A more accurate $K$ value can be calculated by accurate measurement experiments or simulation software. As a result, a precise and quick way to design or improve a parachute that meets specific demands can be achieved.

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