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P1_6 Paper Planes - Long-Haul Flight

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Abstract

This article analyses the key factors in the design of a paper aeroplane and its flight dynamics that result in a world record flight time of 27.6 seconds. The launch velocity in the world record flight is found to be 27 ms^{-1} (60 mph) and the lift coefficient is estimated as 0.06 s^{2}m^{-1}. The key design factors for extended flight are maximum wing area and minimum paper weight.

Introduction

It is thought that paper planes were used as early as the 1930s to explore aerodynamics, in order to design the first winged aeroplanes [1]. The current record for the longest flight time for a paper plane is held by Ken Blackburn, keeping his plane aloft for 27.6 seconds [1]. This paper will consider aspects of his design that allow for large flight time and also the dynamics involved in such paper plane flights.

Design of the Plane

The first important point to consider is the design that should be used to maximise the time of flight of the paper plane. When making a paper plane the classic "dart" design is most often used, but simple analysis of the lift force on a paper plane suggest other designs might be more appropriate.

Consider an aerofoil, when travelling through the air, the fluid moves over and under the aerofoil in streamlines. Along the streamlines, the fluid obeys Bernoulli's theorem [2].

$$B = \frac{P}{\rho} + \frac{v^2}{2} + gh. \quad (1)$$

In Equation 1, P is the pressure of the fluid, ρ is its density, v is the speed at which the aerofoil is travelling and gh, the product of acceleration due to gravity and the height of the aerofoil, describes the potential energy. Equation 1 is constant along all streamlines, thus the expressions for below the aerofoil (subscript 1) and above the aerofoil (subscript 2) are equal. Assuming potential energy is equal in each case leads to:

$$\frac{P_1}{\rho} + \frac{v^2}{2} = \frac{P_2}{\rho} + \frac{m^2 v^2}{2}. \quad (2)$$

Due to the curvature of the aerofoil, the streamline above travels further than the streamline below; this causes the pressure difference responsible for lift. The dimensionless parameter m is dependent on the shape of the aerofoil and accounts for this extra distance. The lift force F_L is the product of the wing area A and pressure difference $P_1 - P_2$, so Equation 2 can be manipulated to get:

$$F_L = A\frac{m^2 - 1}{2}\rho v^2. \quad (3)$$

From Equation 3 it can clearly be seen that the lift force generated is dependent on three main factors: the area of the wing, the curvature of the wing and the plane's velocity. Of these the easiest way to increase the lift force is to maximise the area of the wings. Figure 1 shows the paper plane design that set the record – clearly the wing area has been maximised on this design.

Figure 1: Photograph of the paper plane design used to set the world record. [3]

One of key things to look at is the aspect ratio of the wings, this is the ratio of the wing span to the distance from the front of the wing to the back [1]. The classic "dart" design has low aspect ratio of 0.58, whereas the design used in Figure 1 has an aspect ratio of 0.9. For planes travelling at less than 500 mph, high aspect ratio wings are more efficient [1], so although the dart design looks fast, high aspect ratio designs, such as that shown in Figure 1, will achieve longer and faster flights.

Lift off

The world record flight can be divided into two distinct stages, the ascent and the descent. Blackburn describes the best method for launching the paper plane as launching within 10° of the vertical [1] in order to convert the maximum amount of the kinetic energy the plane is launched with, into potential energy, or height gained.

Blackburn estimates that during the ascent phase 50% of the kinetic energy obtained during the launch is converted to potential energy, with the other 50% used to overcome drag [1]. By setting half the kinetic energy $\frac{1}{4}mv^2$ equal to the potential energy mgh, (in both cases m is the mass of the plane) and rearranging for v, an expression for the launch speed is obtained:

$$v = \sqrt{4gh}. \quad (4)$$

During the world record attempt it was estimated that the plane reached a height of 18 m (60 feet), so Equation 4 can be used to estimate the launch velocity required to achieve this height. Taking g as 9.18 ms^{-2}, the launch velocity was found to be 27 ms^{-1}, or 60 mph. This is consistent with the velocity of Blackburn's baseball pitch, which has been measured as 65 mph [1]; taking into account that it is more difficult to throw straight up than close to horizontal (as is the case with a baseball pitch). In fact baseball players have been able to pitch a ball at speeds of over 100 mph (45 ms^{-1}) [4], so this launch velocity is not unreasonable, in terms of human capability.

Descent

After reaching the peak of its flight the paper plane then enters the descent phase of gliding flight. The aim of gliding flight is to descend with the minimum vertical velocity possible (minimum sink rate). This happens when the rate of change of potential energy is a minimum, which is the same as the minimum of the product of drag force and the plane's velocity (in the direction of travel). The minimum sink rate can be obtained formally by finding this minimum power, but the main factor that affects the minimum sink rate is the lift coefficient C_l [1], which is given by:

$$C_l = \frac{2m}{\rho v^2 A}. \quad (5)$$

Here m is the mass of the plane, ρ is the density of air, and v is the velocity of the plane in its direction of travel. The power term described above is a function of C_l^2, so again maximising the area of the wings A is the key to reducing the lift coefficient. The minimum value for C_l is estimated as 0.06 s^2m^{-1}, based on using value printer paper of 80 gsm, ρ is 1.293 kgm^{-3} , v is about 2 ms^{-1} [1] and the wing area is about 54% of the area of the initial piece of paper.

Conclusion

By analysing the design of the paper plane used in the world record attempt, this paper has found that maximising the wing area is the key factor in achieving long flight times. In the launch phase it is necessary to have a high launch velocity in order to gain height. The launch velocity in the world record flight was estimated as 27 ms^{-1} (60 mph). Then in the descent phase a low lift coefficient must be achieved. For low quality 80 gsm paper the lift coefficient was estimated as 0.06 s^2m^{-1}. The issue is whether 80 gsm paper is a strong enough to maintain the structural integrity of the plane during such high launch speeds; a trade off between paper strength and flight time may be necessary.

References

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