Journal of Physics Special Topics

P3_11 Space Aerofoils

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20 November 2013

Abstract

There are many different types spacecraft propulsion, ranging from powerful rockets to far less powerful solar sails. This paper investigates whether an aerofoil could be used to provide propulsion to a spacecraft. It was found that to get a reasonable force (comparable to a solar sail) the aerofoil would need to be 1200m^2 and the orbit would have to be within 0.01AU from the centre of the sun.

Introduction

Solar sails are a means of interplanetary travel that makes use of the radiation pressure to provide a force for propulsion. This paper investigates whether the pressure exerted by solar plasma onto an aerofoil could provide comparable propulsion. This paper will consider two different orientations of a space aerofoil: one where the foil points in the direction of orbit, and one where the foil points towards the sun.

Theory

It is assumed that the aerofoil is attached to a spacecraft in solar orbit. The two most prominent forces that the spacecraft will exhibit are the lift on the aerofoil and the drag force from the large top surface area of the aerofoil. Drag forces from other sources will not be included within this paper as they are assumed to be negligible. The lift force, F_L on an aerofoil [1] is given by

$$F_L = \frac{\rho v^2 A}{2}(m^2 - 1), \tag{1}$$

where ρ is the density of the medium that the aerofoil is moving through, v is the velocity of the medium over the aerofoil, A is the surface area of the aerofoil, and m is that length factor between each surface of the aerofoil. The density of space is incredibly low, but can be given by the density of plasma released from the sun [2], this is

$$\rho = n_{AU} m_p \left(\frac{1}{R_{AU}}\right)^2, \tag{2}$$

where n_{AU} is the plasma density at 1AU, m_p is the average mass of a particle in the plasma (it is assumed that this is equal to the mass of a proton), and R_{AU} is the spacecraft distance from the sun in astronomical units. The force of drag [3], F_D, is given by

$$F_D = \frac{\rho}{2} v^2 A C_d, \tag{3}$$

where C_D is the coefficient of drag. The final equation that is required is the orbital velocity of the spacecraft [4], this is

$$v_s = \sqrt{\frac{GM}{R}} \tag{4}$$

where G is the gravitational constant, M is the mass of the object being orbited (i.e. the Sun), and R is the radius of the orbit.

Sun Orientated Aerofoil

In the orientation depicted in figure (1), the two forces will be in opposite directions, through a combination of equations (1), (2), and (3) the total force, F_{T1}, in the direction of the spacecraft's orbit will be

$$F_{T1} = A m_p n_{AU} \left(\frac{1}{R_{AU}}\right)^2 \left[\frac{v_p^2}{2}(m^2 - 1) - \frac{v_s^2}{2} C_d\right]. \tag{5}$$

This overall force will provide an acceleration in the spacecraft's orbital direction and provide a delta-V.

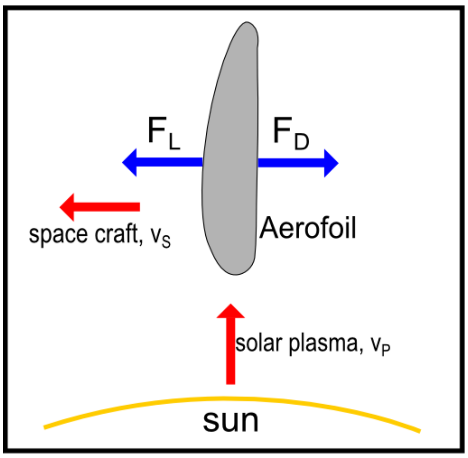

Fig. 1: Orientation of spacecraft's aerofoil when pointing towards the sun. The lift force will be due to the velocity of the solar plasma, v_P, and the drag force will be due to the velocity of the spacecraft's orbit, v_S.

Orbital Direction Orientated Aerofoil

In the orientation depicted in figure (2), the two forces will act in the same direction, accelerating the spacecraft away from the sun. For this orientation, the total force, F_{T2}, in the direction away from the sun will be

$$F_{T2} = Am_p n_{AU} \left(\frac{1}{R_{AU}}\right)^2 \left[\frac{v_s^2}{2}(m^2-1) + \frac{v_p^2}{2}C_d\right] \quad (6)$$

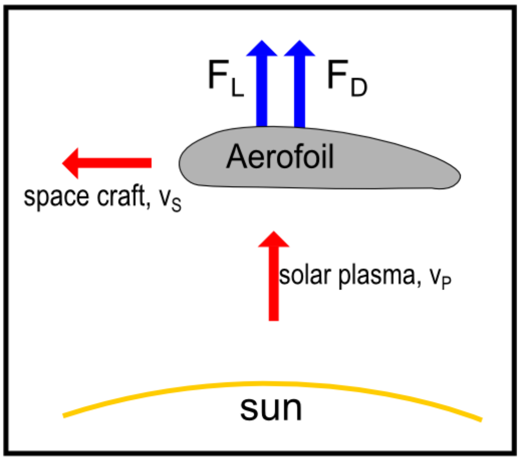

Fig. 2: Orientation of spacecraft's aerofoil when aligned with the direction of orbit. The lift force will be due to the velocity of the spacecraft and the and the drag force is due to the velocity of the solar plasma, both forces will act in the same direction.

Discussion

Some of the variables in equations (5) and (6) have undefined values and as such assumptions will have to be made. It is assumed that the top of the aerofoil is a similar shape to a semicircle and hence C_d is equal 0.42 [3]. The m ratio depends on the design of the aerofoil, but a typical value of 1.1 will be assumed. Values of R_{AU} and A are varied when inputting results. The value of m_p is 1.67×10^{-27}kg, the velocity of the solar plasma is 500kms^{-1}, n_{AU} is 5×10^6m^{-3}, $\sqrt{GM}$ is equal to 1.15×10^{10}m$^{3/2}$s^{-1}.

The area of the aerofoil, A, was set between 1 and 1200m^2. This maximum value was chosen as it is the same size as the largest solar sail that is currently planned for launch [5]. R_{AU} was set to be between 0.005 and 100AU; these limits where chosen as the Sun's radius is around 0.004AU and the heliopause is around 100AU.

The results are summarised in the following table.

Distance	Foil size	$F_1(N)$	$F_2(N)$
0.005 AU	1 m^2	-3.6$\times 10^{-6}$	2.38$\times 10^{-5}$
	1200 m^2	-0.004	0.029
0.01 AU	1 m^2	6.4$\times 10^{-7}$	5.2$\times 10^{-6}$
	1200 m^2	7.6$\times 10^{-4}$	6.2$\times 10^{-3}$
1 AU	1 m^2	2.1$\times 10^{-10}$	4.4$\times 10^{-10}$
	1200 m^2	2.6$\times 10^{-7}$	5.2$\times 10^{-7}$
100 AU	1 m^2	2.19$\times 10^{-14}$	4.93$\times 10^{-14}$
	1200 m^2	2.6$\times 10^{-11}$	5.2$\times 10^{-11}$

For comparison, it is worth noting that the solar sail IKAROS exhibits a force on the magnitude of mN [6].

From the data in the table it is clear that the magnitude of the total force is larger as the spacecrafts orbit decreases. Also, the force is much larger when the aerofoil size is larger. As the radius of orbit decreases, the spacecrafts velocity increases. As the velocity increases the drag force also increases (proportional to v^2) and becomes larger than the lift force, generating an overall negative force. This force could be used to reduce the orbit. However, the spacecraft is almost at the edge of the Sun, if it's orbit is decreased it will burn up into the sun.

In the orbital direction orientated aerofoil, some the forces are much larger and comparable to a solar sail. However, these comparable forces are when the orbit is below 0.01AU with a 1200m^2 foil. This force would help to increase the orbit of such a spacecraft. As such this mission would be futile; in order to increase the orbit, it must first be reduced (assuming it it launched from Earth).

Conclusion

From the values given it is apparent that the force received from an aerofoil is space is negligible compared to other forms of propulsion; and such missions would be futile. Although space is not a perfect vacuum, it's density is low enough that it makes the force from an aerofoil negligible at any reasonable distance from the sun.

References

[1] `http://www.grc.nasa.gov/WWW/k-12/airplane/lifteq.html` (20-11-13)

[2] M.G. Kivelson and C.T. Russell, *Introduction to Space Physics* (1997), 1st Edition, P.100

[3] `http://www.engineeringtoolbox.com/drag-coefficient-d_627.html` (29-11-13)

[4] P.A. Tipler and G. Mosca, *Physics for Scientists and Engineers* (2008), 6th Edition, P.372

[5] `http://www.nasa.gov/mission_pages/tdm/solarsail/solarsail_overview.html` (20-11-13)

[6] `http://www.jaxa.jp/press/2010/07/20100709_ikaros_j.html` (20-11-13)