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P5 1 It's Not Possible ... No, It's Necessary

L.Brereton, D.Majithia, S.Biss, H.S.R. Thompson

Department of Physics and Astronomy, University of Leicester, Leicester, LE1 7RH

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Abstract

In this paper we analyse the docking scene in Interstellar where Cooper utilises the retro thrusters on one of the Landers to stop the spin of the Endurance after a catastrophic explosion. Calculations of the moment of inertia and required torque are performed, resulting in a required torque of the order of 300 MNm. This would require a total of 1.7×10^5 of the retro-thrusters used in the Orion mission.

Introduction

Throughout the film Interstellar, Cooper performs numerous feats using different spacecraft. One such is where he uses a Lander to stop the spin of the main hub spacecraft 'the Endurance' after Dr Mann improperly docks and causes an explosion. In the film, he accomplishes this in roughly thirty seconds using only two retro thrusters. By approximating the Endurance to be a hoop and calculating the torque required to reduce the angular momentum of such an object to zero, we estimate the force required per retro thruster. This is then compared to the thrusters used in NASA's Orion mission to see if this is accomplishable with current modern systems.

Method

The total torque to accelerate an object into a spin is given by:

$$\tau = I\alpha, \tag{1}$$

where τ is the total torque, I is the moment of inertia of the body and α is the angular acceleration. The moment of inertia can be found by approximating the Endurance as a hoop with uniform mass density throughout the ring with the equation taken from Tipler [1]. The central mass is omitted since it is aligned with the symmetry axis of the hoop and the rotational axis so does not contribute meaningfully to the moment of inertia.

$$I = \int r^2 dm. \tag{2}$$

Since r is a constant, this integral reduces to,

$$I = MR^2, \tag{3}$$

where M is the mass of the Endurance (taken as the ISS mass of 4×10^5 kg [2] as there is no mass given in the film) and R is the radius, taken through the measurements of a $\frac{1}{15}$ scale model built in the production notes [3] as 57 meters. The mass used here is likely to be an underestimate as the ISS does not carry near to the same fuel capacity nor propulsion systems as the Endurance, however this gives a lower bound for the force required to stop the Endurance's spin. From this, the moment of inertia of the Endurance is found to be 1.3×10^9 kg m^2. The torque applied to the Endurance during the deceleration period is split into two parts, a con-

stant torque from the retro thrusters τ_T and a variable torque from air resistance τ_D. The drag force experienced by the Endurance is taken as [4]:

$$F_D = \frac{1}{2}\rho A C_D v^2, \tag{4}$$

where ρ is the density of air, A is the incident cross sectional area, C_D is the drag coefficient, and v is the velocity perpendicular to air flow. This equation will be dominated by v, and the drag coefficient is close to one for most hoop-like objects. The thickness of the Endurance's outer ring is taken to be approximately a ten meter square as it needs to be tall enough for the astronauts to move around in with other equipment taking up space, giving a cross section of 100 m^2. The density of air is assumed to be the same as for the top of the stratosphere on Earth, found using formulas from a NASA Earth atmosphere model [5] to be 0.017 kg m^{-3}. The torque from aerodynamical drag is now given by:

$$\tau_D = F_D R = \frac{1}{2}\rho A C_D R v^2. \tag{5}$$

Now summing the torques and substituting into equation (1), changing α for $\frac{d\omega}{dt}$ gives:

$$I\frac{d\omega}{dt} = -(\tau_T + \frac{1}{2}\rho A C_D R v^2). \tag{6}$$

Substituting ωR for v and combining the constants in the drag torque into a variable σ gives:

$$dt = -\frac{I}{\tau_T + \sigma\omega^2} d\omega. \tag{7}$$

Integrating from the initial angular frequency to the final and incorporating the negative sign into the limits gives:

$$t = I\int_{w_f}^{w_i} \frac{1}{\tau_T + \sigma\omega^2} d\omega. \tag{8}$$

Applying the limits of the initial angular frequency being 68rpm (and converting to radians per second), and the final being zero:

$$t = \frac{I}{\sqrt{\tau_T \sigma}} \arctan \omega_i \sqrt{\frac{\sigma}{\tau_T}}. \tag{9}$$

Equation (9) does not have an analytical solution so numerical methods must be used to find an approximation for τ_T. The Newton-Raphson method [6] is implemented, using the following iterative formula:

$$x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)}. \tag{10}$$

Where:

$$f(\tau_T) = \frac{I}{\sqrt{\tau_T \sigma}} \arctan \omega_i \sqrt{\frac{\sigma}{\tau_T}} - 30. \tag{11}$$

$f(\tau_T)$ is obtained by substituting $t = 30$ into equation 9 and rearranging to set equal to 0 in order to find the roots. The Newton-Raphson method is suitable to apply to this problem since a good estimate for τ_T can be made as it should be close to the total torque required to stop the spacecraft since air resistance falls off quickly with velocity. This gives a convergent value for τ_T of roughly 3×10^8 Nm. Since the retro thrusters are located roughly 10.6 meters away from the pivot point, this requires each to output a force of roughly 1.9×10^7 N.

Conclusion

In conclusion the required force from each retro-thruster is extremely large, far exceeding modern capabilities. NASA's Orion mission uses 24 retro thrusters [7] each capable of producing 220 N. Using these thrusters, if they were located at the same place on the Lander as the ones in the film are, a staggering 1.7×10^5 retro thrusters would be required to produce the force needed to stop the Endurance's spin. Since the air density is so low at the top of the stratosphere, the atmospheric drag is almost negligible, although without more information on the atmosphere of Dr Mann's planet, it is not possible to say with certainty that the drag experienced in the film is not far greater than that calculated here. A detailed analysis of the atmosphere and further explorations on the drag could explain the disproportionate force required from the retro thrusters.

References

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