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Payload and sail loading dependence study of design sensitivity function and characteristic acceleration of solar sail

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Abstract: In this paper, we have investigated the dependence of characteristic acceleration and design sensitivity function of solar sail on mass and area of solar sail by solving the dynamics of solar sails using electromagnetic treatment of Maxwell's and quantum mechanics of Einstein's theories. It is found that the solar sail with large area A, fewer payloads mass m_p and sail loading σ would be best for distribution in space to meet the new avenues of space science. It has also been observed that higher relative characteristic acceleration procured by using sail of large area with low density sail film as much as possible, which is our requirement for mission of solar sail.

Keywords: Solar sail; Payload mass; Sail loading

1. Introduction

Solar sails are of notable promise for space exploration affording missions that push the boundaries of the possible. They allow a range novel science technology challenge starting from ultrafast interstellar tour to imaging the poles of the Sun mission which are past the attain of present-day propulsion technology [1–6]. A solar sail is a spacecraft with a large, lightweight mirror connected to it that moves by being driven through light reflecting off of the mirror rather than rockets [5–8]. When the light from the Sun reflects off the surface of the solar sail, the energy and momentum of light particles regarded as "photons" are transferred to the sail [9]. This offers the sail a "push" that quickens it via space. Although the acceleration could be very slight, it is also continuous, allowing the sail to attain very excessive velocity in an enormously short time [10–15]. As each sailor knows, to tack or beat a sailboat is to sail the boat at an angle into the wind. Solar sails can do their own form of tacking through his use of the pressure of sunlight pushing out from the sun to actually move nearer the sun [2–9, 13–16].

The idea of solar sailing and the physics on which it's far primarily based totally may be traced back to the seventeenth century [1–12]. Subsequently, the idea of solar sailing became articulated as an engineering principle in the early twentieth century through numerous authors such as the Father of Astronautics, Konstanty Ciolkowski (1921) together with Fridrikh Tsander) and Herman Oberth (1923) [1–11]. The idea of solar sailing seems to have remained largely dormant for over thirty years. However, because the idea re-emerged in the middle of the twentieth century. In the twenty-first century, a considerable amount of each theoretical and realistic work has been performed, thinking about the astro-dynamics, mission programs and technology requirements of solar sailing [7, 15–20].

Solar sails are composed of flat, easy fabric protected with a reflective coating and supported via way of lightweight structures connected to a central hub. Near-term sails possibly will use aluminized Mylar—a strong, skinny polyester film—or CP-1, a space-rated insulating material. Both are verified materials formerly flown in space. More sturdy sails would possibly use a meshwork of inter-locking carbon fibers [1–6, 8, 12–18]. Solar sail is available in three fundamental designs—Square sail, Heliogyro sail, and Disc sail [7–18]. Solar sail of all types includes a large, filmy sail and a few sorts of payload that holds such component as antennas, computers, solar panels, guidance

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sensors, science instruments, shipment containers and crew cabins [5–18].

In Solar sail technology, the design sensitivity function provide a demonstration of relative importance of each design parameter for a given point in the solar sail design space whereas characteristic acceleration which determines the transfer time to a particular object or even whether a particular class of orbits is possible. The aim of present work is to explore the payload and sail loading effect on sensitivity design function and characteristic acceleration of solar sails acting on the sail reflective surface. In this paper, we have analyzed the dynamics of characteristic acceleration and design sensitivity function of solar sail with the mass and area of solar sail by applying the Maxwell's theories of Electromagnetism and Einstein's theories of quantum mechanics. We have also been studied the effect of solar sail mass, relative area and relative sail loading and relative payload mass on the characteristic acceleration and design sensitivity function of solar sail in details.

2. Theoretical description

The source of motive force for solar sail spacecraft is momentum transported to the sail with the aid of using radiative power from the Sun. But the physics of solar radiation pressure may be explored through two physical description as.

2.1. The Quantum Explanation

Using the quantum description of radiation as packets of energy, photons may be visualized as traveling radially outwards from the Sun and scattering off the sail hence offering momentum.

2.2. The Electromagnetic Explanation

Using the electromagnetic description of radiation, momentum is transported from the Sun through the vacuum of space to sail via Electromagnetic waves. Hence, we can conclude that solar sail mechanism may be understand by above two methodologies as follows:

(1) Quantum description

Using quantum mechanics, radiation pressure may is envisaged as because of momentum transported through photons the quantum packet of energy, of which light is composed.

From **Planck's law,** a photon of frequency ν will transport energy E' as follows:

$$E' = h\nu \tag{1}$$

where h is Planck's constant.

In addition to this, the mass–energy equivalence of special relativity left in total energy E of a moving body is given by:

$$E'^2 = p^2c^2 + m_0^2c^4 \tag{2}$$

where m_0 is the rest mass of the body, p is the momentum of the body, and c is the speed of light

Since a photon has zero rest mass, its energy may be written as follows:

$$E' = pc \tag{3}$$

Therefore, using photon energy defined by Eq. (1) and (3), the momentum transported by a single photon is given by:

$$p = \frac{h\nu}{c} \tag{4}$$

In order to calculate the pressure exerted on a body, the momentum transported by a flux of photons must considered. The energy flux W (the energy crossing unit area in unit time) may be written in terms of Solar luminosity L_s and scaled by the Sun–Earth distance D_E as follows:

$$W = W_E\left(\frac{D_E}{r}\right) \tag{5a}$$

$$W_E = \frac{L_s}{4\pi D_E^2} \tag{5b}$$

where W_E is the energy flux measured at Earth's distance from the Sun.

The energy ΔE transported across a surface of area A normal to incident radiation in time Δt is given as follows:

$$\Delta E = WA\Delta t \tag{6}$$

From Eq. (3) this energy transports a momentum Δp given by:

$$\Delta p = \frac{\Delta E}{c} \tag{7}$$

The pressure P exerted on the surface is then described as momentum transported per unit time, per unit area so that:

$$P = \frac{1}{\mathrm{A}}\left(\frac{\Delta p}{\Delta t}\right) \tag{8}$$

Therefore, using Eq. (6), the pressure exerted on the surface due to momentum transport by photons is given by:

$$P = \frac{\mathrm{W}}{\mathrm{c}} \tag{9}$$

For a perfectly reflecting surface the observed pressure is two times the value provided through Eq. (9) because of the momentum transferred to the surface through the incident photons and the reaction provided by reflected photons. Using Eq. (9), the solar radiation pressure exerted on a solar sail at Earth's distance from the Sun (1 A.U.) may be calculated. Since the orbit of Earth about the Sun is barely elliptical, the energy flux obtained on the Earth varies through about 3.5% throughout the year. However, an accepted mean value is the solar consistent WE of 1386 J s-1 m-2. Therefore, the pressure exerted on a perfectly reflecting solar sail at 1 au is taken to be 9.12 × 10–6 N m-2.

(2) Electromagnetic description

Using the electromagnetic description of light, momentum is transported to the solar sail through electromagnetic waves. Physically, the electric field component of the wave E induces a current j in the sail, as shown in Fig. 1. The magnetic component of the incident wave B then generates a Lorentz force j × B in the direction of propagation of the wave. The induced current generates another electromagnetic wave that is observed as the reflection of the incident wave. For a wave propagating alongside the x axis the force exerted on a current element is then given by:

$$df = j_z B_y dxdydz \tag{10}$$

where j_z is the current density induced in the surface of reflector. The resulting pressure on current element, defined as the force per unit area, can be written as follows:

$$dP = j_z B_y dx \tag{11}$$

From Maxwell's equations of electrodynamics in Eq. (11) the current terms may be changed through field terms and as a result time average pressure is then given by:

$$dP = -\frac{\partial}{\partial x}\left(\frac{1}{2}\varepsilon_0 E_z^2 + \frac{1}{2\mu_0}B_y^2\right)dx \tag{12}$$

The term in parentheses is described as the energy density U for the electric component E and magnetic component B of the incident wave, described as follows:

$$U = \frac{1}{2}\varepsilon_0 E^2 + \frac{1}{2\mu_0}B^2 \tag{13}$$

where ε_0 is permittivity of free space and μ_0 is the permeability of free space. The pressure exerted on a surface of thickness Δl is given as follows:

$$\langle P \rangle = -\int_0^{\Delta l} \frac{\partial U}{\partial x} dx \tag{14}$$

For a perfectly absorbing medium the pressure exerted at the surface is given via the total energy density of the electromagnetic wave, viz,

$$\langle P \rangle = \langle U \rangle \tag{15}$$

Consider two plane waves which are separated by a distance Δx and are incident on a surface of area A, as proven in Fig. 2. The spacing Δx among the waves is equal to c Δt, where Δt is the time travel between the wave fronts. The energy density of the electromagnetic wave is given via way of means of

$$U = \frac{\Delta E}{A(c\Delta t)} \tag{16}$$

where ΔE is the energy contained within the volume element. In addition, the energy flux W throughout the surface may be written as follows:

$$W = \frac{1}{A}\left(\frac{\Delta E}{\Delta t}\right) \tag{17}$$

Therefore, using Eq. (16) it can be seen that:

$$U = \frac{W}{c} \tag{18}$$

This last expression is the same obtained by considering photons. It is consequently concluded that the quantum and electromagnetic description of radiation pressure are

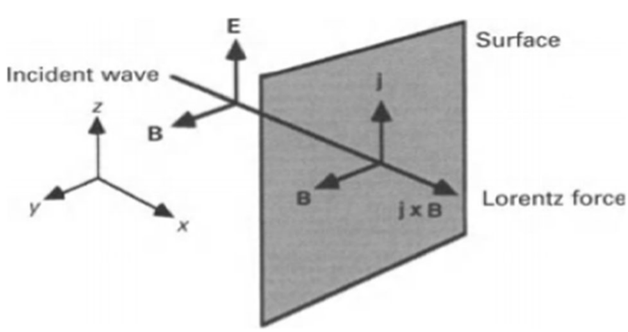

Fig. 1 Electromagnetic description of radiation pressure

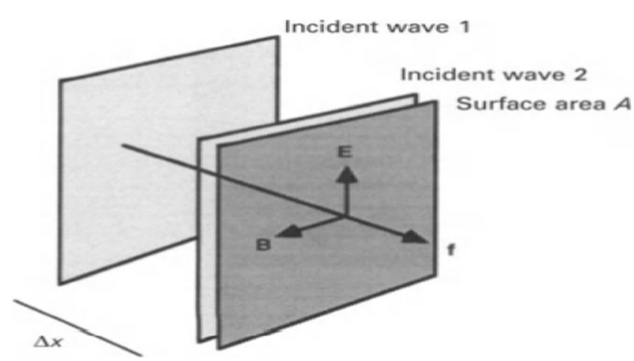

Fig. 2 Energy density of an electromagnetic wave

equivalent. For the electromagnetic wave, as said by Maxwell in 1873 treatise on electricity and magnetism [4–11]. Hence in a medium wherein waves are propagated there is a pressure in the direction normal to the waves and numerically equal to the power in unit volume [8, 18–20].

2.3. Force on a perfectly reflecting solar sail

A solar sail is an orientated surface in order that acceleration experienced by the solar sail is a characteristic of the sail attitude. For a solar sail of area, A with unit vector n, directed normal to sail surface, the force exerted at the sail due to photons incident from the $\boldsymbol{u}_i$ direction is given by:

$$\boldsymbol{f_i} = PA(\boldsymbol{u}_i \cdot \boldsymbol{n})\boldsymbol{u_i} \tag{19a}$$

where A $(\boldsymbol{u}_i \cdot \boldsymbol{n})$ is the projected sail area in the direction $\boldsymbol{u}_i$ as shown in Fig. 3. Similarly, the reflected photons will exert a force of magnitude on the solar sail, however in the specular direction $-\boldsymbol{u}_r$ viz,

$$\boldsymbol{f_r} = -PA(\boldsymbol{u_i} \cdot \boldsymbol{n})\boldsymbol{u_r} \tag{19b}$$

Using the vector identity $\boldsymbol{u_i} - \boldsymbol{u_r} = 2(\boldsymbol{u}_i.\boldsymbol{n})\boldsymbol{n},$ the total force f exerted on the solar sail is therefore given by:

$$\boldsymbol{f} = 2PA(\boldsymbol{u}_i \cdot \boldsymbol{n})^2\boldsymbol{n} \tag{20}$$

Then, using Eq. (5) and Eq. (9) the total force may be written as follows:

$$\boldsymbol{f} = \frac{2AW_E}{c}\left(\frac{R_E}{r}\right)^2(\boldsymbol{u_i} \cdot \boldsymbol{n})^2\boldsymbol{n} \tag{21}$$

where W_E is the solar constant.

The solar sail overall performance can be parameterized by the total spacecraft mass per unit area m/A. This constant may be termed as the sail loading σ and is a key layout parameter. In addition, the sail pitch angle α may be described as the angle between the sail normal and the incident radiation as proven in Fig. 3. Now the solar acceleration can be written as follows:

$$\boldsymbol{a} = \frac{2\mathrm{W_E}}{\mathrm{c}}\frac{1}{\sigma}\left(\frac{\mathbf{R_E}}{\mathbf{r}}\right)^2 cos^2\alpha n \tag{22}$$

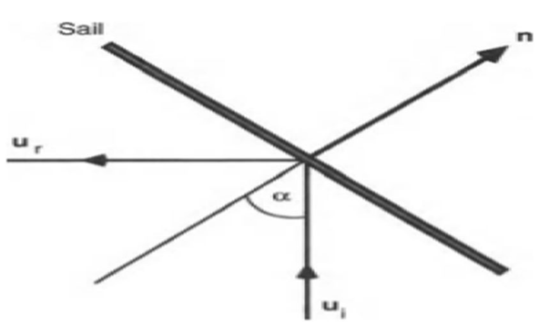

Fig. 3 Perfectly reflecting solar sail

Now the characteristic acceleration of the solar sail is a_0 may be defined as acceleration experienced at 1AU with the sail normal to the Sun α = 0.

For an ideal solar sail, the characteristic acceleration is given by:

$$a_0 = \frac{2\eta A}{mc_0}\frac{L}{4\pi r^2} \tag{23}$$

where r is the distance from Sun to sailcraft. (r = 1AU) and A factor of two are included to account for the ideal sail reflectivity. The characteristic acceleration is an equivalent design parameter to the solar sail loading and may be conveniently written as follows:

$$a_0 = \frac{9.12\eta}{\sigma[\mathrm{g\ m^{-2}}]}\left[\mathrm{mm\ s^{-2}}\right] \tag{24}$$

in which η is some overall efficiency of the solar sail used to account for finite reflectivity of the sail film and sail fluctuations. When changing the reflectivity across the sail film, solar radiation pressure forces and torques can be controlled without changing the attitude of the spacecraft relative to the Sun or using attitude control actuators. The reflectivity can in principle be modified using electrochromic coatings, which are applied here as examples to counteract gravity gradient torques in Earth orbit and to enable specific shape profiles of a flexible sail film [8, 9, 15–18, 20]. Whereas the force changes with solar distance and sail angle, which changes the fluctuation in the sail and deflects some elements of the supporting structure, resulting in changes in the sail force and torque. Sail temperature also changes with solar distance and sail angle, which changes sail dimensions. The radiant heat from the sail changes the temperature of the supporting structure. Both factors affect total force and torque [3, 8–16]. This 'optical reconfiguration' method introduces an adaptive solar sail as a multi-functional platform for novel mission applications. Total solar sail efficiency is of order 0.9. The solar sail acceleration can also be written in terms of the solar gravitational acceleration as follows:

$$\boldsymbol{a} = \beta\frac{GM_s}{r^2}(\boldsymbol{r} \cdot \boldsymbol{n})^2\boldsymbol{n} \tag{25}$$

where M_S is the solar mass and G being the universal gravitational constant. The dimensionless sail loading parameter β is the ratio of the solar radiation pressure acceleration to the solar gravitational acceleration. This parameter is likewise described as lightness number of the sail. Since both the solar radiation pressure acceleration and the solar gravitational acceleration are assumed to have an inverse square variation, the lightness number is independent of the Sun–Sail distance. Using Eq. (22), Eq. (24) and Eq. (5b) the solar sail lightness number may be written as follows:

$$\beta = \frac{\sigma^*}{\sigma} \tag{26a}$$

$$\sigma^* = \frac{L_S}{2\pi G M_S c} \tag{26b}$$

The critical solar sail loading parameter σ^* is found to be 1.53 gm^{-2}. This is a completely unique constant which is a function of the solar mass and the solar luminosity [8, 17, 18].

Now, the fundamental design parameter for solar sail is characteristic acceleration which determines the transfer time to a particular object or even whether a particular class of orbits is possible. The characteristic acceleration is, however, a function of both the efficiency of the solar sail design and the payload mass. As we described the characteristic acceleration as the solar radiation pressure acceleration experienced by a solar sail oriented normal to the Sun line at a heliocentric distance of 1AU unit. At this distance from the Sun the value of the solar radiation pressure P exerted on a perfectly absorbing surface is 4.56×10^{-6} N m^{-2}. Therefore, for a finite sail efficiency η, the characteristic acceleration is given by [19, 20]:

$$a_0 = \frac{2\eta P}{\sigma}, \sigma = \frac{m}{A} \tag{27}$$

where σ is the total solar sail loading, m is the total solar sail mass, and A is the sail area. The sail performance is a function of the optical properties of the sail film and the sail shape. The overall mass of the sail can be partitioned into two components, m_S due to the sail film and structure and m_P the payload mass. Therefore, the characteristic acceleration of the solar sail can be written as follows:

$$a_0 = \frac{2\eta P}{\sigma_S + \left(\frac{m_P}{A}\right)}, \sigma_s = \frac{m_S}{A} \tag{28}$$

where σ_S is the mass per unit of the sail assembly. The σ_S is also called sail assembly loading. This is a key parameter that measure of the performance of the sail film and the efficiency of the solar structural design [20]. For a fixed sail area and efficiency, Eq. (28) becomes a function of two variables: the sail assembly loading σ_S and the payload mass m_P.

"Thus, we have to determine the convenient solar sail design parameter. However, the increase in sail area, lower in payload mass and sail mass is a strong function of the sail design. Such design sensitivities may be determined quantitatively using sensitivity functions 'h'."

2.4. Design Sensitivity Function

Sensitivity function provide a demonstration of relative importance of each design parameter for a given point in the solar sail design space, in general the solar sail design space comprises the sail area, sail assembly loading and the payload mass. For a fixed sail area, the design space is function of only two variables and so may be represented as surface. The sensitivity function provides information at the gradient of this surface at a given design point. For example, the variation in characteristic acceleration (a_0) due to variation in sail assembly loading may be acquired by:

$$\Delta a_0 = \left(\frac{\partial a_0}{\partial \sigma_S}\right)\Delta\sigma_s \tag{29}$$

From using Eq. (28), to calculate the gradient due to variation in the sail assembly loading, it is found that:

$$\frac{\Delta a_0}{a_0} = h_1\left(\frac{\Delta\sigma_s}{\sigma_s}\right), h_1 = \frac{-1}{1+\frac{m_p}{m_s}} \tag{30a}$$

This relation provides a degree of the sensitivity of the solar sail characteristic acceleration to growth in sail assembly loading.

Other design sensitivity functions can also be obtained by using a similar analysis, viz.

$$\frac{\Delta a_0}{a_0} = h_2\left(\frac{\Delta m_p}{m_p}\right), h_2 = \frac{-1}{1+\frac{m_p}{m_s}} \tag{30b}$$

$$\frac{\Delta a_0}{a_0} = h_3\left(\frac{\Delta A}{A}\right), h_3 = \frac{-1}{1+\frac{m_p}{m_s}} \tag{30c}$$

where h_1, h_2, h_3 are the design sensitivity functions.

3. Results and Discussion

The characteristic acceleration a_0 of solar sail in ms^{-2} (Eq. 23) is the function of sail efficiency η, area of the sail A in m^2, Solar luminosity L in Watt and the product of the distance r from the Sun to sailcraft, mass of sailcraft m in kg., the speed of light c_0. The variation in characteristic acceleration a_0 with mass m of the solar sail for different values of A (fixed $\eta = 0.9$, $c_0 = 3 \times 10^8$ ms^{-1}, $L = 3.84 \times 10^{28}$ Watt, $4\pi = 1.256$, and we take r = 1AU) as shown in Fig. 3.

Figure 3 demonstrates that the characteristics acceleration a_0 of solar sail increases with decreasing mass m of sailcraft when A = 1000 m^2. Furthermore, we can also see that acceleration a_0 of solar sail increases more rapidly with decreasing mass of sailcraft when area increases from 1000 m^2 to 3000 m^2. Thus, we can conclude that to achieve higher acceleration a_0 of solar sail, the area must be maximum, so maximum number of photons of sunlight strikes the sail's area so solar sail constantly accelerates through the years and achieves greater velocity. Thus, one can depict that sailcraft attains larger velocity while mass of sailcraft is low as much as possible (Fig. 4). Thus, it is

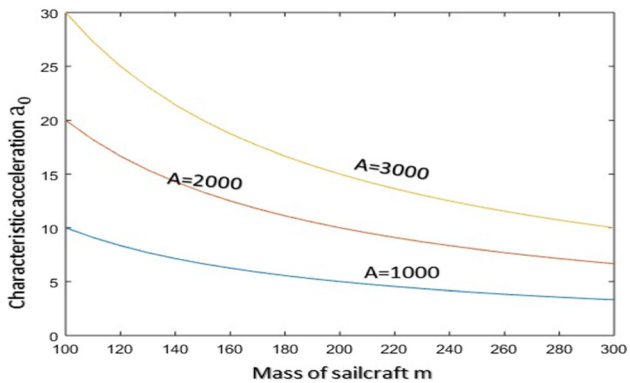

Fig. 4 Dependence of characteristic acceleration a_0 on mass of sailcraft for different area a of sailcraft A

clear that solar sails need to be quite light for generation of high acceleration from the momentum transported through intercepted photons.

Figure 5 shows the variation of characteristic acceleration a_0 of solar sail with mass of sail m for different values of area A (fixed $\eta = 0.9$, $c_0 = 3 \times 10^8$, $L = 3.84 \times 10^{28}$ Watt, $4\pi = 1.256$ and $r = 1$AU) from Eq. (23). Figure 5 depicts that characteristic acceleration of solar sail increases when increment in area of solar sail occurs. This happens due to the fact that it collects as much sunlight as possible, because the larger the area, the greater the force of sunlight. Thus, a sail of bigger area captures more sunlight, gaining more momentum and accelerating more quickly for the same mass. However, it is interesting to note that characteristic acceleration a_0 of solar sail decreases gradually when the increment in mass is rapid. Thus, characteristic acceleration a_0 of solar sail decreases with increasing the mass of the sail because the greater mass results in less acceleration that sunlight imparts to the sail. Thus, one can conclude that characteristic acceleration a_0 of solar sail could be maximize by choosing minimum value for sailcraft's mass m and maximum value for area of sail craft A.

Figure 6 shows the variation in design sensitivity function (h_1) with the relative sail loading $\left(\frac{\Delta\sigma_s}{\sigma_s}\right)$ for different values of relative characteristic acceleration $\left(\frac{\Delta a_0}{a_0}\right)$ of solar sail (Eq. 30a)

From Fig. 6, it is evident that sensitivity design function h_1 increases with increasing relative solar sail loading for fixed value of relative characteristic acceleration of 0.3mms^{-2}.

Thus, one can conclude that solar sail overall performance is insensitive to sail assembly design if the ratio of payload mass to sail mass is large, i.e., for large value of m_p and m_s(Eq. 30a). However, it is interesting to note that sensitivity design function could be minimum for large value of characteristic acceleration; however, the value of relative sail loading remains same. Thus, one can conclude that sensitivity function can be decreased by increasing relative characteristic acceleration of solar sail. But one can maximize the value of characteristic acceleration by choosing low value of m_p and m_s (Eq. 30a) as much as possible. The less payload and sail's mass will then decrease the sail loading and as a result decrease in sensitivity design function will occur. Thereafter, the value of relative characteristic acceleration increases which is our requirement for mission of solar sail.

It can be seen from Fig. 7 that design sensitivity function (h_2) of solar sail is function of relative characteristic acceleration $\left(\frac{\Delta a_0}{a_0}\right)$ and relative payload mass $\left(\frac{\Delta m_p}{m_p}\right)$ of solar sail (Eq. 30b).

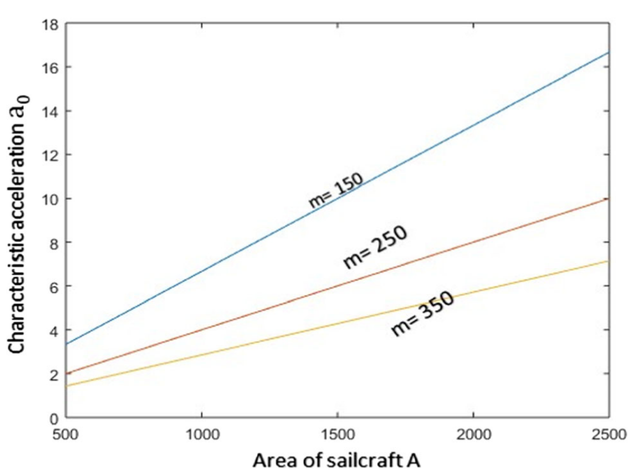

Fig. 5 Characteristic acceleration a_0 versus area of sailcraft A for varying mass of sailcraft m

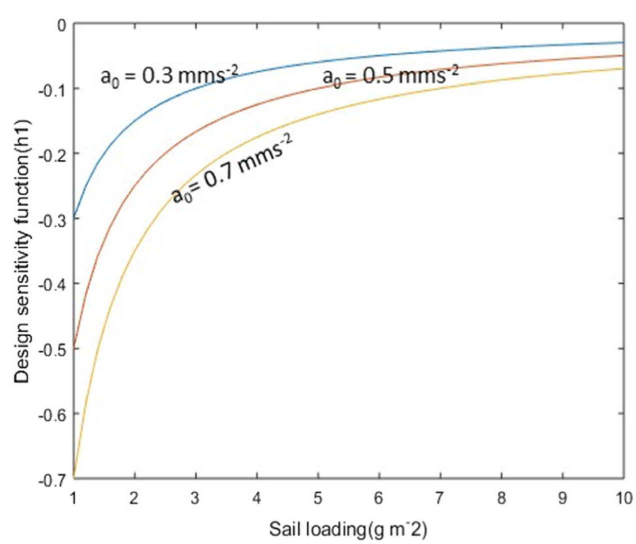

Fig. 6 Variation in design sensitivity function h_1 with relative sail loading for different value of relative characteristic acceleration

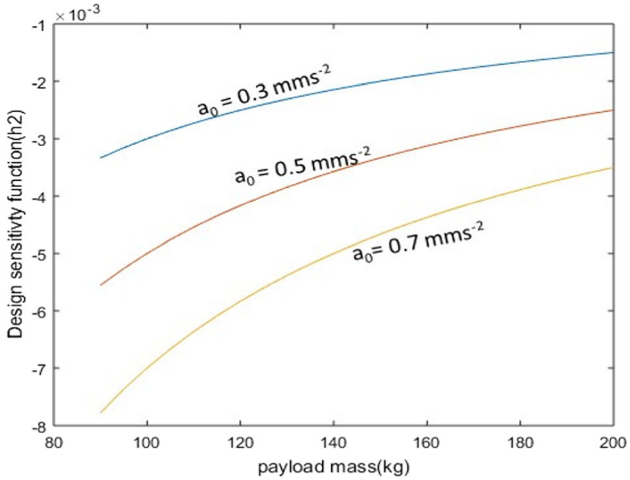

Fig. 7 Design sensitivity function h_2 versus relative payload mass m_p for varying relative characteristic acceleration

From Fig. 7, it is clear that design sensitivity function (h_2) increases with increment in relative payload mass m_p. Thus, one can conclude that sensitivity to payload mass growth increases with the ratio of payload mass to sail mass (Eq. 30b). It is also demonstrated that the value of sensitivity design function (h_2) decreases for large values of characteristic acceleration. But as characteristic acceleration depends on the mass of payload so one must ensure that mass of payload to low as much as possible. Thus, it is clear that for minimum value of payload mass, one can obtain the higher relative characteristic acceleration.

Figure 8 shows the variation in design sensitivity function (h_3) as the function of relative area $\left(\frac{\Delta A}{A}\right)$ for different values of relative characteristic acceleration $\left(\frac{\Delta a_0}{a_0}\right)$ by (Eq. 30c). It is obvious from Fig. 8 that on increasing the area of sail one can depict the decrement in design sensitivity function for fixed value of relative characteristic acceleration 0.3mms^{-2}. But it can also be noticed that for higher value of relative characteristic acceleration the slope of design sensitivity function h_3 is steeper (higher sensitive) than for the lower value of relative characteristic acceleration. This means that design sensitivity function h_3 would be minimum for higher value of relative characteristic acceleration (Fig. 8).

Thus, one can conclude that design sensitivity function could be minimize by maximizing relative characteristic acceleration of solar sail. The latter would be maximum when area of sail will be maximum. Because maximum amount of sunlight could be absorbed by sail of large area, which imparts more momentum to the sail. As a result, by photon absorption higher characteristic acceleration could be imparted to the sail. It is likewise recognized that any increase in sail area, will of course, will increase the whole mass of the solar sail which is ultimately constrained by the selection of launch vehicle. However, the required increase in sail area is a strong function of the solar sail design. But the area can be compensated by dealing with very thin film sail that have good mechanical and thermal properties of low density. Thus, one can conclude that higher relative characteristic acceleration procured by using sail of large area with low density sail film as much as possible.

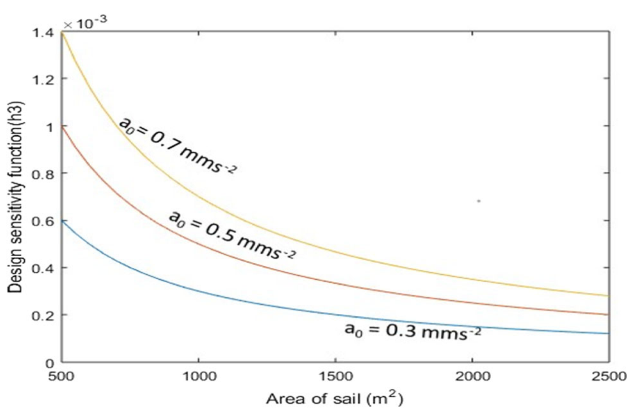

Fig. 8 Dependence of design sensitivity function h_3 on relative area A for different value of relative characteristic acceleration

4. Conclusions

An old common booster rocket requires so much fuel that they cannot push their own weight past the solar system into interstellar space. Space sails, alternatively requires no fuel. This paper deals with the idea of solar sailing for fast, accessible and scalable space exploration past the boundaries of modern propulsion technologies. Without the need to carry onboard propellent, solar sails provide an efficient pathway for space travel. In conclusion, dependence of characteristic acceleration and design sensitivity function of solar sail on mass, area and relative sail loading σ, relative payload mass m_p, relative area A, respectively. It has been found that solar sail of larger area and less mass increases the characteristic acceleration which is our requirement for mission of solar sail. Also, the design sensitivity function commits essential contribution in version of solar sail. It can assist what requirements are needed particularly for model validation so that they may be integrated early into the program to assist in test planning and hardware development. As, if a model has highly sensitive output parameter the corresponding input variable ought to be widely known or appropriately measured. It has been found that for increasing value of relative characteristic acceleration, the design sensitivity function decreases with respect to relative payload mass m_p and relative sail loading σ but converse for relative area A. This means that the value of payload mass m_p and sail loading σ must be low as much as possible so that value of design sensitivity design function is low. Thus, the solar sail with large area A, less payload mass m_p and sail loading σ would be best for deployment in space to meet the new avenues of space science and exploration.

Author Contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by [Dr. M. K. Maurya], and [Dr. Rajkishor Singh Baghel]. The first draft of the manuscript was written by [Dr. Rajkishor Singh Baghel] and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Declarations

Conflict of interest The authors declare that no funds, grants, or other support were received during the preparation of this manuscript. The authors have no competing interests to declare that are relevant to the content of this article. All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript. The authors have no financial or proprietary interests in any material discussed in this article.

Research involving Human Participants and/or Animals The authors declare that none of the any human participants and or animals was involved during the preparation of this manuscript.

Informed consent Since, none of the human participant and or animals was involved during the preparation of this manuscript. So, no need to take the consent from authorities.

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