Space debris turbine: Energy extraction and annihilation of space debris

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Abstract- Engineering is not just solutions to problems but an investigation to turn problems into solution to future problems.

Space debris is a miscellany of objects in space which is a mixture of rocket stages, satellites, and fragments from disintegration, erosions and collisions. Space debris, considered as a danger and nuisance to active spacecrafts and future space missions are a collection of defunct objects orbiting the Earth. The density of this junk around earth increases due to collisions with other objects and with each other. It has been found that increase in their number is much faster than their decrease due to natural processes. This leads to an overall increase of junk with time, leading to the so called Kesseler's Syndrome. Hence the space debris is a serious threat to space missions in the future. In this paper we consider space debris as a useful source of energy for clearing smaller debris using laser techniques.

The present paper proposes a model to extract energy from medium to large size (10cm or more in size) space debris. The methodology involves an array of rotating plates colliding with debris for energy extraction. The strength of materials to withstand such huge impulses is also taken into consideration. Electrostatic repulsion is also mentioned as a technique to extract energy, if avoiding collisions become mandatory. All the analysis is done using simple mathematical relations from classical physics and electrostatics.

This method can be an energy resource in case of large space missions though it may not be very cost effective. We believe that the current new approach can be an implementable solution to the problem of space debris.

Index Terms- Space debris, Kesseler's Syndrome, Impulse, Eletcrostatic repulsion, Large space missions

I. Introduction

Space debris as described above are very fast moving objects and can cause much more damage to objects than any sniper rifle available. This makes them extremely dangerous. Thus they are very difficult to shield against. Even Kevlar which is presently used in shielding ISS (International space station) is not completely useful against fast debris. Recent methods proposed for space debris removal include solar sails, slingshots, snagging and moving space junk, Huffing and puffing etc. Also laser systems (both ground-based and station based) have been extensively studied to remove space debris in low-earth orbits.

One of the most successful methods in clearing space debris of size less than 10 cm is the laser ablation method which uses high power pulsed laser beam to cause ablation (which in turn causes a reaction force) of debris and helps in deorbiting the debris. The larger size debris are removed in an uneconomical way by methods like nets. Also scanning for space debris is achieved using telescopes and other methods.

Thus this paper proposes a method to use this larger debris as an energy source for removing smaller ones. The basic intention is to design a model which can extract energy from the large sized debris.

The main problem which needs to be dealt is the high speed of the debris. Direct impact as in case of shielding can completely damage any shielding material. Thus in our method we try to convert this energy to useful energy so that impact damage is low. We follow analytical method for the investigation and discuss the practicality of the design.

II. DESIGN (AN OVERVIEW AND A FEW IMPORTANT PARAMETERS)

ENERGY TRANSFER OF THE DEBRIS

For our method we use an array of plates where one behind the other and the energy of debris reduce at every stage. The plates are free to spin about (friction resisting spinning must be kept very low to prevent damage to the system) horizontal axis as shown in figure.

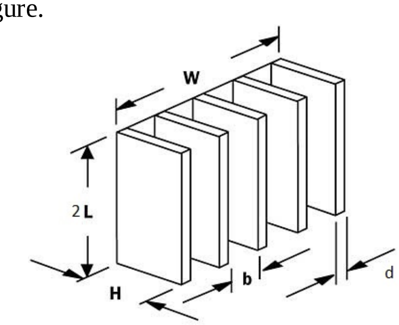

Figure 1: Array of plates, (Image not to scale. NOTE: b > L in actual model) [1]

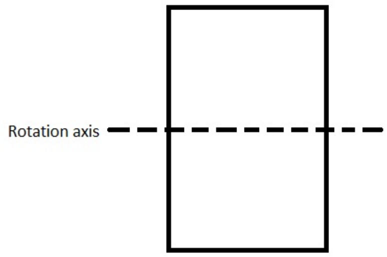

Figure 2: Plate and rotation axis

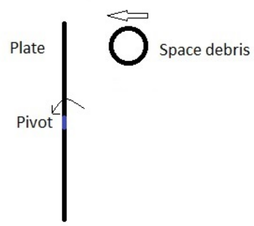

Figure 3: Representing the action of force on the plate by the debris

Now we use torque and energy equations to find the angular velocity and plate properties given the mass of debris.

Assumptions:

- Friction against rotation of plate is very low.
- Energy is conserved (elastic collision).
- Heat and vibration losses are not taken into account.
- Rotational effects of the debris are not considered.
- The actual way in which change of velocity is achieved is not considered.

The above assumptions allow the use of simple equations (without calculus) to understand the basic situation.

Torque equation:

$$T = \frac{m(U-V)\times y}{t_1}$$

Where,
T is torque about axis shown in figure 2 .
m is mass of debris.

U and V are velocities of debris relative to plate before and after collision respectively.
y is the distance of strike point from axis shown.
t is time taken for collision (from starting to ending of contact).

Also,

$$T = I\alpha$$

I is the moment of inertia of the plate about the axis shown in figure 2.

α is angular acceleration of plate about the same axis mentioned.

$$\alpha = \frac{\omega_2 - \omega_1}{t_2}$$

ω is angular velocity of plate about the same axis. Subscripts 2 and 1 refer to conditions after and before collision respectively.

$$I = \frac{M}{12}[4L^2 - d^2]$$

M is mass of plate.

Other symbols have usual meanings.

Let's assume ω_1=0

Now putting T = Iα in torque equation and also putting the value for α:

$$I\alpha = \frac{m(U-V)\times y}{t_1}$$

$$I\times\frac{\omega_2}{t_2} = \frac{m(U-V)\times y}{t_1}$$

Note that time for change in angular velocity of plate is same as that for change in velocity of debris (i.e. $t_1 = t_2$).

Rearranging we get:

$$\omega_2 = \frac{m}{I}(U-V)\times y = \omega \text{ (say)}$$

Energy equation:

$(K.E_{debris})_{Initial} = (K.E_{debris})_{Final} + (\text{Rotational energy})_{plate}$

$$\frac{1}{2}mU^2 = \frac{1}{2}mV^2 + \frac{1}{2}I\omega^2$$

Initial and final refer to before and after contact respectively.

Putting the value of I and ω in energy equation we get:

$$I = \frac{m(U-V)^2}{U^2-V^2}y^2$$

$$M = \frac{12m(U-V)^2}{U^2-V^2}\times\frac{1}{[4\frac{L^2}{y^2}+\frac{d^2}{y^2}]}$$

Consider L>>d and y approx.= L for better torque :

Therefore,

$$M = \frac{3m(U-V)^2}{U^2 - V^2}$$

Now to understand the physical significance of the the above equation consider a debris moving at 5 Km/s brought to 3 Km/s after collision with the first plate. Substituting these values in the equation:

$$M = \frac{3m(5-3)^2}{5^2 - 3^2}$$

$$M = 0.75m$$

For the next (second) stage:

$$M = \frac{3m(3-1)^2}{3^2 - 1^2}$$

$$M = 1.5m$$

Since U>V, the quantity $\frac{(U-V)^2}{U^2-V^2}$ will always be less than 1

In the first stage:

If M = m we see that if we assume a initial debris velocity of 5 Km/s then we get V=0.5 Km/s. This is a huge deceleration and we can argue intuitively that it will demolish the system.

This clearly states that for optimum energy transfer from debris to plate as rotational energy we need a plate of mass less than the mass of debris at least for the first stage. Otherwise the debris will be decelerated rapidly leading to damage as in case of shields.

For second stages and so on higher masses can be used as calculated above.

Thus debris mass cannot be low for this method as a plate of practical size cannot be designed to have very low masses.

It is worth noting that the angular velocity of plate will be of a very high order theoretically due to high debris velocity.

The design must be capable of allowing such huge velocities which is only possible for low friction cases. If the friction is high the plate will not only take more damage from the impact due to slow rotation but also the heat produced will be very high leading to loss of energy.

Now these plates must be coupled with a electric generator setup for energy extraction. The energy extracted can be stored in batteries.

The energy extracted is given by the difference in kinetic energy of the debris at each stage.

$$E_{Theoretical} = (K.E_{debris})_{Initial} - (K.E_{debris})_{Final}$$

$$E_{Theoretical} = \frac{1}{2}mU^2 - \frac{1}{2}mV^2$$

For U = 5 Km/s, V = 3 Km/s and m = 5 kg (first stage)

$$E_{Theoretical} = \frac{1}{2} \times 5 \times (5^2 - 3^2) \times 10^6 = 40\ MJ$$

Considering only 10% as usable we have 4 MJ of energy.

This energy is optimum enough to clear using other techniques like lasers.

III. STRENGTH OF MATERIALS

3.1 DESIGN CONSIDERATIONS

The material used for the plate is a very critical parameter in designing the turbine. As we know the velocity of the debris is assumed to be about 7 km per second. The impact of the debris on the plate is enormous. The turbine is made to rotate at an angular velocity. This paper aims at energy extraction from debris of mass of nearly 5 kg. Since the turbine is rotating a part of the energy imparted by the debris goes into rotating the plate. For these considerations, the mass of the plate is predicted to be less than that of the debris (at least for first stage) or it will lead to the failure of material.

3.2 STRESS ESTIMATION

- Assumptions
  - Mass of debris = 5 Kg
  - Velocity of debris before contact = 7km/s
  - Area of impact = 20X20 sq.cm

According to an experiment (reference: http://www.extremetech.com/extreme/185150-heres-what-space-debris-does-to-the-kevlar-shielding-protecting-the-international-space-station) Kevlar fails if held stiff before the moving debris (at nearly a relative speed of 7 Km/s).

This almost causes a velocity reduction from 7 to 0 km/s.

We use this as a reference and calculate the time of velocity reduction (from 7 to 0 Km/s) according to above assumptions and conditions. Since the material Kevlar is used widely as a shield and has been used in the failure test experiments as mentioned above, we use its strength value for the calculation of time of velocity reduction.

$$\text{Force of impact} = \frac{\text{mass} \times (\text{change in relative velocity})}{\text{time for velocity reduction}}$$

$$\text{Force of impact} = \frac{5 \times (7-0) \times 1000}{t}$$

$$\text{Stress} = \frac{\text{Force applied}}{\text{Area of contact}}$$

$$\text{Stress} = \frac{35000 \times 10000}{20 \times 20 \times t}$$

We equate this to tensile strength of Kevlar = 3.62 Gpa to get a reference time of velocity reduction.

$$\frac{35000 \times 10000}{20 \times 20 \times t} = 3.62 \times 10^9$$

$$t = 2.43 \times 10^{-4}\ s$$

Now we consider the reduction in velocity in our system which is 5 Km/s to 3 Km/s or 7 Km/s to 5 Km/s depending on mass of plate and debris. We can intuitively argue that the time of velocity reduction for the case of Kevlar failure has to be much lower (leading to huge force) than that for our system.

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Still we use this value for our calculations so that we get a safer value for strength of material.

$$\text{Force of impact} = \frac{5 \times (5-3) \times 1000}{2.43 \times 10^{-4}} = 4.115 \times 10^{7}\,\text{N}$$

$$\text{Stress} = \frac{4.115 \times 10^{7}}{20 \times 20 \times 10^{-4}} = 1.03 \times 10^{9}\ \text{pascals}$$

$$\text{Stress} = 1.03\ \text{Gpa}$$

This result is very interesting as it says that our model will not be damaged if we use appropriate material with a tensile strength of more than the stress calculated.

We conclude that Kevlar (presently used in many space debris shields) can itself be used if bending is prevented by using stiffening materials.

3.3 MATERIAL USED DATA ABOUT OTHER MATERIALS

In recent years, aramid ablatives represent the art of materials used for rocket applications. As time progressed people have implemented the usage of polymers and composites of different maerials due to their mechanical properties and high thermal stability.

Comparison of strength of Tawron, Kynol and silica polymeric materials is given below.

Materials	Max. Stress [MPa]	Max. Deformation [%]	Elastic modulus [MPa]
TWR	6.2 ± 0.4	96.7 ± 11.4	16.0 ± 1.7
KYN	6.0 ± 0.2	93.7 ± 7.5	14.3 ± 0.7
SIL	6.8 ± 0.5	172.9 ± 17.7	8.6 ± 0.6

Table 1: Tensile test results [2]

In this paper, a Polymer known as Kevlar is used for the material of the spacecraft. A Kevlar is a para-aramid synthetic fiber related to other aramids like Nomex and Technora. It is spun into ropes of fabric sheets and used as an ingredient in various composite material components. Its applications rnage from bycycle tires to armor sails and body armors due to its high strength to weight ratio. It is 5 times stronger than steel. Different variations of Kevlars used in recent times are Kevlar K-29, Kevlar K49, Kevlar K100 and Kevlar KM2 which is now used for ballistic resistance for armor applications

It has a tensile strength of 3.62 GPa. Its high strength is due to the inter-molecular hydrogen bonds and aromatic stacking interactions between adjacent strands.

As the following suggests advances in nano sciences has led to very high strength materials like carbon nano tubes. These can be put to use once developed.

Carbo colossal tube also has a very high strength.

Material	Tensile strength (MPa)	Density g/cm^3	Strength to weight ratio (KN. m/Kg)	Breaking length (Km)
Zylon	5800	1.54	3766	384
Vectran	2900	1.40	2071	211
Titanium	1300	4.51	288	29.4
Stainless steel	2000	7.86	254	25.9
Nylon	78	1.13	69.0	7.04
Magnesium alloy	275	1.74	158	16.1
Kevlar	3620	1.44	2514	256
Glass fiber	3400	2.60	1307	133
Concrete	12	2.30	5.22	0.44
Colossal carbon tube	6900	.116	59483	6066
Carbon-epoxy composite	1240	1.58	785	80.0
Carbon nanotube	62000	.037-1.34	46268-N/A	4716-N/A
Carbon fiber (AS4)	4300	1.75	2457	250
Brass	580	8.55	67.8	6.91

Table 2: Comparison of different materials and their tensile strength [3]

IV. CHARGED DEBRIS ENERGY EXTRACTION PROPOSAL (A QUALITATIVE OVERVIEW)

An interesting method of space debris disposal uses electron beam to charge large debris and involves contactless disposal using electrostatic techniques.

Here we propose the same as a safer means than the previous method involving impacts to extract energy from space debris. But we must note that producing electron beam and electric fields also require energy. Thus an efficient extraction may not be possible. But for sure the amount of energy spent otherwise can be reduced using this proposal.

The setup will involve similar array of plates as before but this time the plate has the same charge as the debris on the side facing the debris.

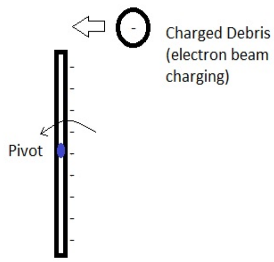

Figure 4: Charged plate and Debris

According Coulumb's law

$$F = K\frac{|Q_1 \times Q_2|}{R^2}$$

Where,
F is Force
Q is charge
R is distance b/w charges
According to Newton's Second law:

$$F = ma$$

F is Force
m is mass
a is acceleration

This suggests that the system must have optimum mass so that it resists motion due to electrostatic forces.

But the plates must have low mass so that optimum energy is extracted.

Thus the system must have a low mass of plates but a high overall mass.

The word 'high' here means an optimum amount which does not affect propulsive maneuvering of spacecraft to a large extent.

V. ADVANTAGES AND UNIQUE ASPECTS OF THE PROPOSAL

- This is the first proposal which investigates energy extraction from space debris.
- Extracted energy can be put to use by using it to clear smaller debris by laser techniques.
- In cases of deep space missions where solar radiation is negligible; this might be one of the ways in which energy can be obtained.
- Space expeditions to planets with rings like Saturn are facilitated by the system due to ready source of moving rocks as energy.
- Energy is saved in case of other removal methods like contactless electrostatic method.
- The system can be coupled to other spacecrafts to extract energy and use it for other spacecraft purposes.
- Lesser maneuvering to dodge the debris will be required with such a system as impacts with the system is not supposed to cause much damage (at least theoretically).
- If there are many charged incoming debris a fan like arrangement of charged plates can be used.

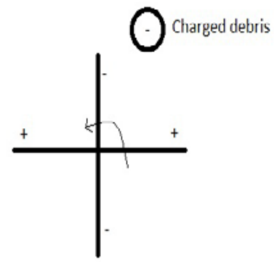

Figure 5: Two plates being used

VI. LIMITATIONS OF THE PROPOSAL

- Though the proposal is theoretically valid. The practicality must be completely verified. Certain advantages mentioned above may not be possible due to this.
- Three dimensional bending effects have not been considered in the theory an must be taken care of before design. This will cause twisting and may cause failure if not prevented.
- The actual direction of motion of debris may not be such that it moves from one stage to the next. Therefore proper maneuvering is necessary.
- The number of debris that strike at the same time must be limited according to velocity and mass considerations.
- Such a system will be practical in orbits which have large densities of required size space debris. Otherwise maneuvering will consume energy and resources and will increase the cost drastically.

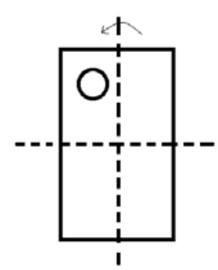

Figure 6: Situation which can cause plate twisting

VII. CONCLUSION

The models proposed for energy extraction in fact brings a new dimension to space debris removal. The future challenges are to find stronger materials that can be used practically to make such turbines. Future may also use these as an efficient method to extract energy for deep space missions. Presently the energy extracted can be used for implementing other removal methods.

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