Direct Force Measurements from the Laser Ablation of Aluminum

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Although there are only about 23,000 tracked pieces of orbital debris, there are approximately 500,000 pieces of 'space junk' that are large enough to do significant damage if they impact an operational satellite. They all travel at speeds of up to 17,500 mph, fast enough for a small piece of orbital debris to damage a satellite or a spacecraft. Laser ablation has been proposed as a method of debris removal, in which a spacecraft carrying a laser approaches large pieces of debris and ablates their surface, generating a directional plume of particles, which imparts an impulse on the debris. The debris is used as a propellant for the deorbit maneuver, removing the necessity to carry additional propellant for deorbit from Earth, increasing the mission lifetime. A low-cost method for direct force measurements from the laser ablation is presented. The laser ablates a target placed at the end of a cantilevered beam inside a vacuum chamber in order to remove any atmospheric effects. The deflection of the cantilevered beam is measured by tracing a low power laser spot that is reflected by a small mirror at the back of the beam.

Nomenclature

b	=	width of cantilever beam, m
C_m	=	momentum coupling coefficient, N/W
d	=	displacement of green laser outside chamber, mm
E	=	Young's Modulus, Pa
e	=	distance from beam tip to white plate outside chamber, mm
F	=	force applied at the beam for calibration, mN
f	=	frequency of laser pulse, s^{-1}
f_n	=	natural frequency of beam, Hz
h	=	thickness of cantilever beam in direction of deflection, m
I_y	=	moment of inertia of beam cross-section about the y-axis, m^4
k	=	spring constant of the beam, N/m
L	=	length of cantilever beam, m
m	=	mass of cantilever beam, kg
m_b	=	mass added to cantilever beam, kg
m_e	=	mass of ejecta, kg
n	=	number of tests performed for calibration
T	=	thrust due to ablation, N
$T_{oscillation}$	=	oscillation period of cantilever beam, s
$t_{ablation}$	=	time of ablation, s
v	=	horizontal velocity of beam inside chamber, mm/s
v_e	=	exit velocity of ejecta, m/s
w	=	width of small vertical target, mm
$w(x)$	=	displacement of cross-section of beam at position x along beam
δ	=	deflection of beam, mm
ε	=	energy per pulse, J
θ	=	angle of rotation of mirror due to ablation, deg

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I. Introduction

ORBITAL debris in low Earth orbit (LEO) is now amply dense that the usage of LEO space is susceptible to runaway collision cascading. The threat from debris had been anticipated more than thirty years ago[1], and now it demands serious attention. Smith et al.[2] have proposed the Laser Ablative Tug (LAT) as a promising method of debris removal, in which a spacecraft carrying a laser approaches large pieces of debris and ablates the surface of the debris. The LAT attaches itself to the debris object before deorbiting it, and then it goes with the debris to a low enough orbit where drag will deorbit the object. Then, the LAT breaks off a piece of the debris, so it can go to the next debris object. The advantage of the LAT over a conventional tug is that the LAT does not have to bring extra propellant since the debris itself is used as a propellant for the deorbit operation. The necessity to carry propellant for deorbit is eliminated, increasing the mission lifespan.

Many studies on the force from ablation have been conducted. This research project focuses on obtaining direct force measurements from the ablation largely to confirm that the force balance works, since we can compare the results to previous literature. The data obtained from the experiments can be useful to further develop laser technology in the area of debris removal.

All ablation has occurred inside a vacuum chamber in order to prevent any perturbations due to the atmosphere like additional drag from the air. Also, ablation plume may be affected by air pressure, which could effect force. A thin aluminum target has been placed in a calibrated cantilevered beam and has been ablated in different spots. All ablations have been recorded and the deflection of the beam due to the laser ablation has been documented and analyzed.

II. Method

The force measurements from ablation have been determined by the deflection of the aluminum beam. A low power green laser has been placed outside the chamber, facing a mirror on one of the sides of cantilevered beam. The low power laser is then reflected in the mirror and hits a white plate, also place outside the chamber. This green laser displacement determines the deflection of the beam.

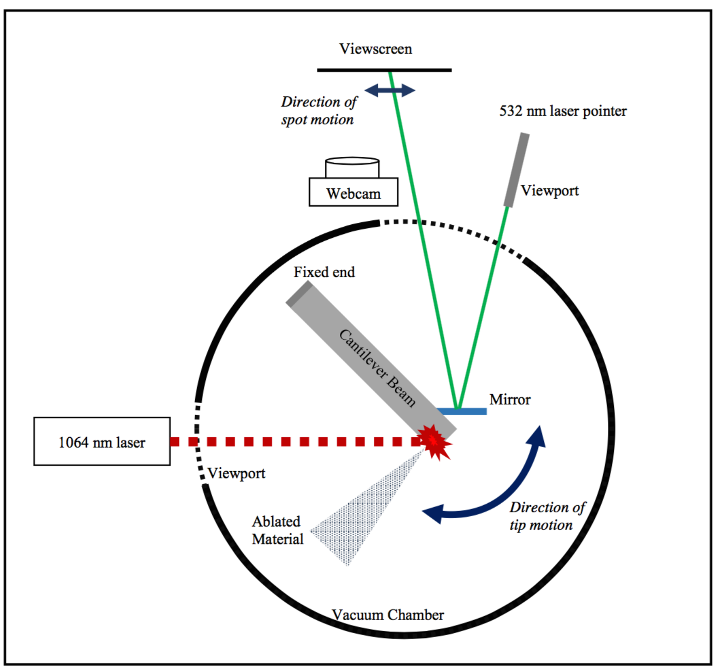


Figure 1. Top View of Force Measurement System, Not To Scale[3]

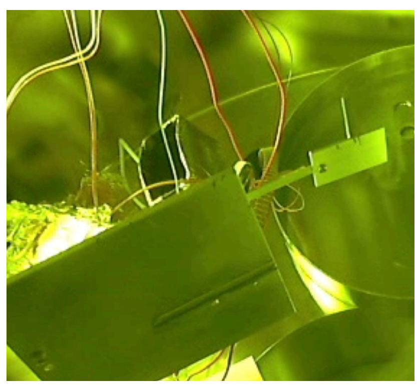


Figure 2. Cantilever beam with mounted vertical target inside the chamber

A. High Power Laser

The ablating laser used is a Photonics Industries Q-switched infrared pulsed laser, SN-1064-40, with nominal pulse width of 1 ns and 40 kHz operating frequency[4], which corresponds to 827 μJ per pulse.

B. Cantilevered Beam Calibration

The target to be ablated is placed at the end of the cantilevered beam. Tip-loaded cantilever beams are well understood and easy to model. The beam selected was previously designed so that it could fit inside the chamber and it did not deflect under gravity.

Usually, classical beam theory is used to model the deflection of the cantilevered beam when a load is applied at the tip. Although the ablation spot is not placed exactly at the end of the beam, tip-loaded cantilever beam equations were used for simplicity. The deflection *w(L)* of a cross-section of a cantilever beam of length *L* and a modulus of elasticity of the material *E* in which a load *T* is applied at a distance *x* along the length of the beam is:

$$w(x) = \frac{Tx^2}{6EI_y}(3L - x) \qquad (1)$$

Where *Iy* is the moment of inertia of the cross-section of the beam about the y-axis:

$$I_y = \frac{bh^3}{12} \qquad (2)$$

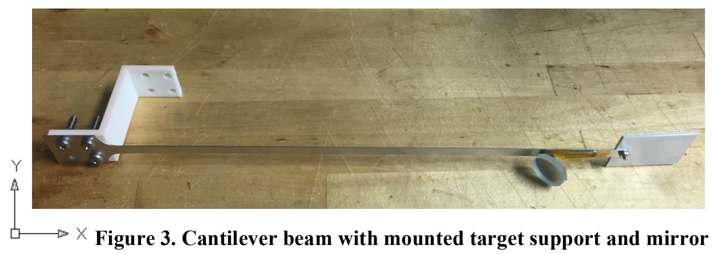


Figure 3. Cantilever beam with mounted target support and mirror

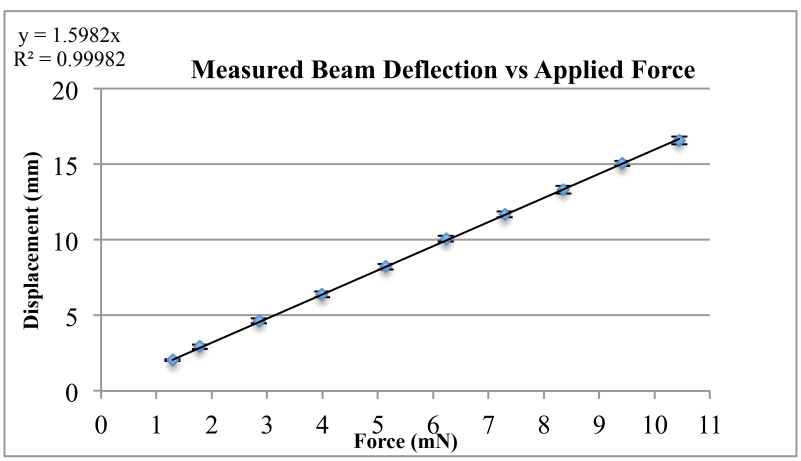


Figure 4. Measured beam deflection vs applied force

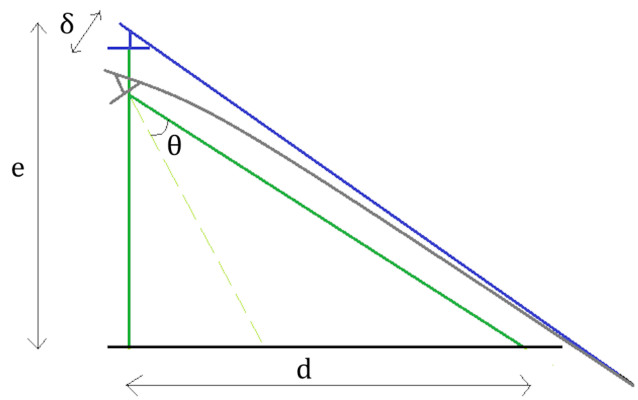
The calibration of the beam was done by placing different weights at the tip and documenting the deflection. A total of 100 measurements were taken in order to calibrate the cantilever beam and obtain a more accurate equation that relates force applied and deflection. The force was determined by simply using the equation $F = mg$.

Expected maximum deflection and real maximum deflection have been obtained and compared in order to determine the reliability of the equation obtained by calibration. The obtained relation shows a very high value for the correlation coefficient ($R^2 = 0.99982$), being almost perfectly linear as expected from Eqn. (1):

$$d = 1.6 * F \qquad (3)$$

C. Displacement Measurements

Figure 5. Green laser – mirror system. Not to scale.



The green laser-mirror system was needed in order to be able to determine, from the outside of the chamber, the deflection of the cantilever beam. Fig.3 shows a schematic representation of the system. The low-power laser starts at bottom-left. The blue line shows the beam at a neutral position with the small mirror in a perpendicular position with respect to the green laser. The grey line shows the deflected configuration, which is assumed to rotate, but not move. The green dashed line is normal to the mirror in the deflected beam.

The basic trigonometric relations used to determine the deflection are:

$$\tan(2\theta) = \frac{d}{e} \tag{4}$$

$$\delta = \frac{L}{3} * \operatorname{atan}\left(\frac{d}{e}\right) \tag{5}$$

A small angle approximation for theta was used. Also, only rotation was considered, being that translation is assumed negligible. The final relation is:

$$d = \left(\frac{e * 3}{L}\right) * \delta \tag{6}$$

Now, we need to calibrate the system to relate the deflection of the cantilevered beam to the position of the green laser. Note again that we already have the equations, and this will serve to confirm our theory and provide more accurate results. A total of 70 measurements were taken to obtain an alternative equation to determine the deflection of the beam. The cantilevered beam was manually deflected once inside the chamber, and the displacement of the green laser was recorded every time.

By means of a Matlab algorithm that fits a circle to the laser spot and determines the position of the center of the circle, the recorded data was processed and the displacement of the green laser as a function of the cantilevered beam deflection was determined. The final relation equation was obtained by means of a regression analysis.

$$\mathrm{d} = 0.0985(\mathrm{mm}) + 6.76 * \delta \tag{7}$$

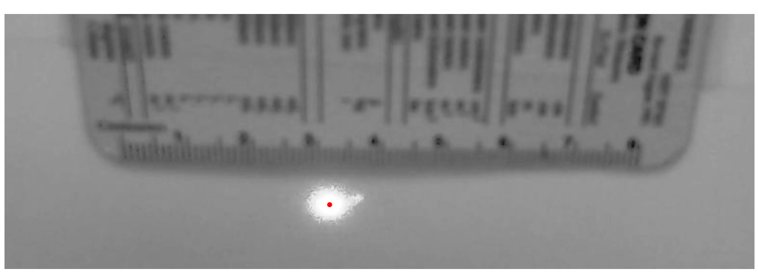


Figure 6. Processed image with spot identified

The residual of an observed value is the difference between the observed value from Eqn. (7) and the estimated value of the quantity of interest. The root mean square error (RMSE) is given by::

$$RMSE = \sqrt{\frac{\Sigma(residual^2)}{n-1}} \tag{8}$$

The RMSE can be interpreted in roughly the same way as the typical deviation of the points from a line or curve. The value obtained for the RMSE is 1.467 mm. In terms of beam deflection, this value represents the standard deviation of the differences between the predicted values and the observed values of the green laser displacement.

III. Vibrations Analysis

The position of the tip of the cantilevered beam can be modeled as a spring-mass-damper. This analysis will allow for a better understanding of how the aluminum beam behaves. In order to simplify the system, it is assumed that the beam tip moves in the x direction only, i.e., vertically up and down, and that all the viscous, spring and mass elements are pure and ideal.

The beam's natural frequency f_n that takes into account all the additional mass m_b (such as target and mirror mass), and the spring constant k of the beam are[3]:

$$f_n = \frac{1}{2\pi}\sqrt{\frac{3EI}{L^3(m + 0.236m_B)}} \tag{9}$$

$$k = \frac{3EI}{L^3} \tag{10}$$

The equation that models this kind of vibrating system is the following:

$$mu'' + ku = 0 \tag{11}$$

The solution to this partial differential equation problem:

$$u(t) = u_o\,\mathrm{Cos}(w_n t) + \frac{u'}{w_n}\mathrm{Sin}(w_n t) \tag{13}$$

If we compare the equation for the cantilever beam vibrations with the equation that relates force applied and deflection, we can spot the value for the spring constant *k*.

Two different values for the constant *k* are considered (the theoretical value obtained using Eqn. (10) and the slope of the obtained relations) in order to calculate the natural frequency of the beam and see if there is cohesion in the results. The two different values only diferred by roughly 0.15Hz.

$$f_{n1} = 9.2261\ Hz \qquad f_{n2} = 9.3701\ Hz \tag{14}$$

Since the slope of the equation gives us a more accurate number for the cantilevered beam used in this experiment, we used the real values for all the calculations that follow.

A. Impulse Signal Conditions

Instead of applying a constant force with the laser ablation, an impulse signal is applied. This is due to the fact that a constant force would not be constant if applied over a long period of time because of oscillations, focusing, and degradation of the target surface. Since the laser will be applying an impulse force, impulse function boundary conditions are applied to the solution:

$$u(0^+) = 0 \tag{15}$$

$$u'(0^+) = \frac{I}{m} \tag{16}$$

The resultant equation is:

$$u(t) = \frac{I}{m\,w_n} \sin{(w_n t)} \tag{17}$$

Since we have defined the relationship between force applied and beam deflection by means of the first calibration, the only unknown in the equation is time. By solving this unknown, we can know how much time it will take for the beam to deflect a certain amount when a specific force is applied.

IV. Impulse Simulation

In order to obtain an impulse signal from the high power laser, an additional vertical target was added to the initial target. The mechanical beam is then moved along its length (in the negative x direction as shown) inside the chamber so that the vertical target passes in front of the IR laser.. This way, the laser will only ablate the small target for the amount of time that we desire. The stage that moves the beam inside the chamber can be moved at a speed up to 16mm/s. However, the maximum velocity for our experiment was set to be equal or less than 12mm/s, in order to avoid too much movement of the mechanical beam due to vibration. Also, the ablation time had to be less than one tenth of the oscillation period so that it could be considered impulsive. We should note the tradeoff that a smaller ablation time would make the impulse smaller, and therefore harder to measure.

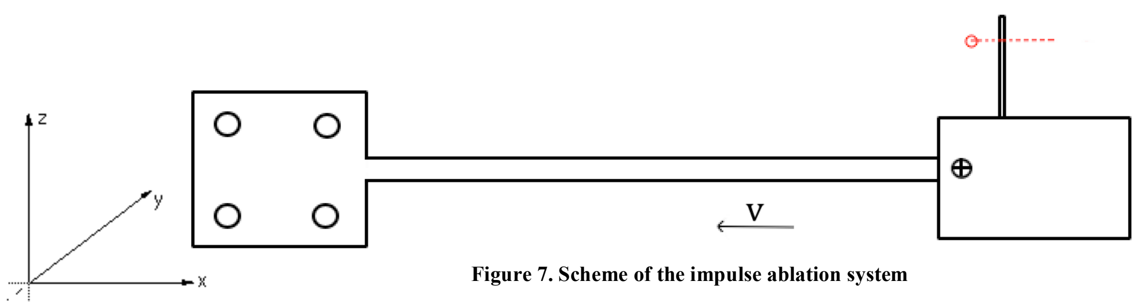


Figure 7. Scheme of the impulse ablation system

$$w = v * t_{ablation} \tag{18}$$

$$\frac{t_{ablation}}{T_{oscillation}} < 0.25\ or \sim 0.1 \tag{19}$$

The critical period of the beam was determined by making the beam oscillate manually and recording the displacement of the green laser. Later, the recorded video of the displacement of the green laser was processed, obtaining the vibrations plot for the beam, which allowed us to see the amount of noise after the initial displacement damped out.

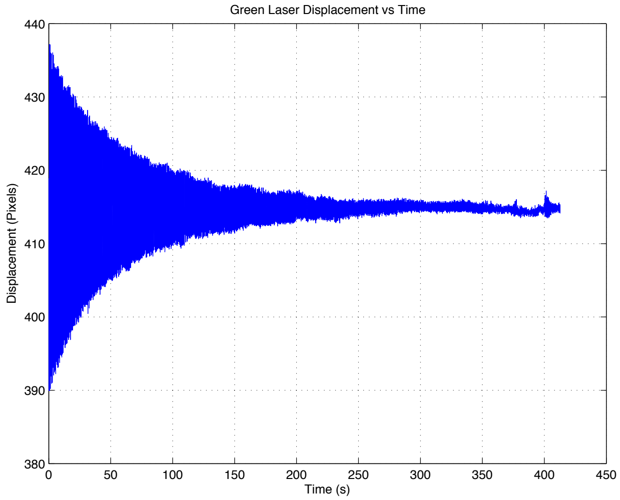


Figure 8. Oscillation of the beam after a manual impulse

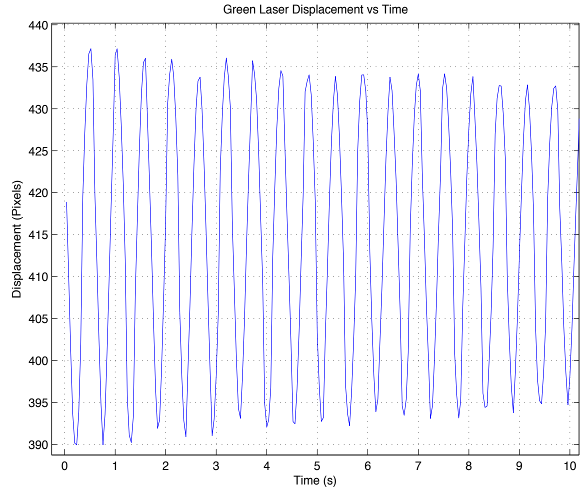


Figure 9. First oscillations of the beam after a manual impulse

The period of the oscillation was measured, being 0.5 seconds. Since the time of ablation and the critical period of the beam and the stage velocity were determined, the required width (*w*) of the vertical target could be obtained.

The ablation time had to be roughly one tenth of the oscillation period, or at least less than one quarter, and therefore the width of the target was calculated for the extreme values (w=0.1 and w=0.25) assuming V=12mm/s.

For a 1/10 ratio, w=0.6mm, but building a target that small was not possible.
For a 1/4 ratio, w=1.44mm, which was possible but was a bit far from the 1/10 ratio.

Since we needed the ratio to be as close to 1/10 as possible, *w* was set to be 1 millimeter, giving us an ablation time of 0.0833 seconds and a ratio of 0.1667, close enough to 0.1.

IV. Results

A total of 32 experiments were performed inside the vacuum chamber. Different values for laser power and laser focus were applied. Two different vertical targets were used in order to avoid repeated ablation on the same spot.

Since the impulse force applied by the high power laser was achieved by moving the horizontal stage of the beam, a noise analysis was performed in order to differentiate between the movement of the beam due to ablation and the one generated by the horizontal displacement of the beam inside the chamber.

In order to analyze the obtained data, the expected force is calculated. The ablating infrared laser was operating at 40kHz and a value of 827 μJ per pulse. The momentum coupling coefficient C_m is defined as:

$$C_m = {m_e v_e}/{\varepsilon} \tag{20}$$

By dimensional analysis, the expected force is

$$\mathrm{T} = \mathrm{f} * \varepsilon * C_m \tag{21}$$

And the expected total impulse is

$$I = \mathrm{f} * \varepsilon * C_m * t \tag{22}$$

Using Jamil et al.'s values for momentum coupling coefficient of aluminum[6] C_m = 0.0642 ·10-3 N·s/J, and taking into account that the target was ablated for 1/12 seconds, the impulse force applied is I=0.175 mN*s. For such values, the deflection of the beam can be easily calculated combining equations (3) and (7), which have been obtained after calibrating the different systems used.

In order to validate all our calibrations and relations, the beam deflection for the standard test has been recorded and analyzed, and will be compared to the theoretical value. Combining the equations (3) and (7), which relate the green laser movement and the force applied by the laser, we obtain the final relation:

$$I = \frac{6.76(mm)*d + 0.0985}{1.5982} \tag{23}$$

All data plots showing the relationship between the green laser displacement and time elapsed show an offset generated by the movement of the beam when being ablated by the laser. The peak downwards represents the deflection generated by the impulse force of the laser ablation. However, this peak has only been found in half of the data, and therefore it has to be analyzed carefully since the movement of the beam for the laser ablation could be having a larger role than previously thought.

A. Noise Analysis

The following plots show the movement of the beam, in pixels, while moving the horizontal stage. The noise test was performed for different velocities in order to not only determine the amount of noise, but also to see if a change in velocity varies significantly the noise generated. Figures 10 and 11 show the noise analysis at the highest and lowest speeds possible.

After analyzing the changes in noise at the different speeds, it was concluded that a change in the horizontal stage velocity does not alter significantly the noise generated by the displacement of the beam. No optimum speed that could minimize the noise was found, and therefore the standard test was set at a speed of 12mm/s.

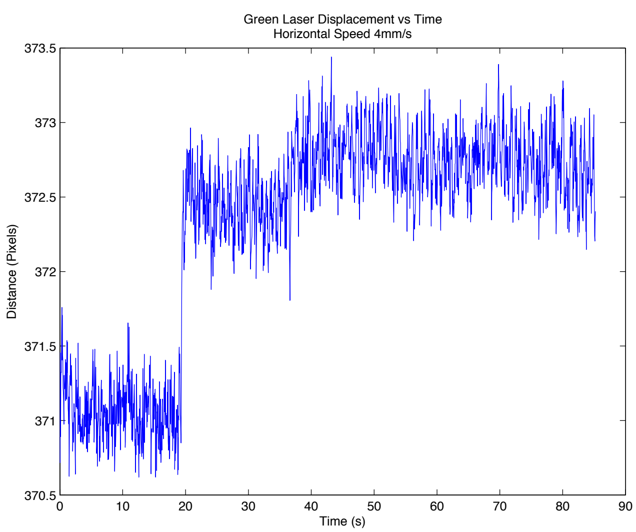


Figure 10. Noise analysis at a horizontal speed of 4mm/s

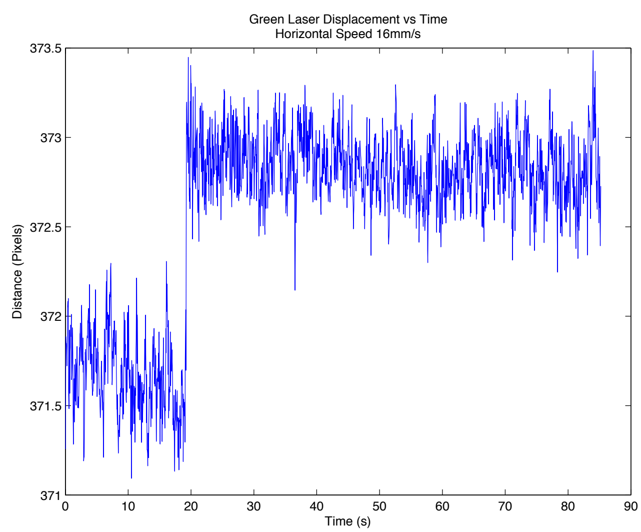


Figure 11. Noise analysis at a horizontal speed of 16mm/s

B. Variable Power Tests

Several tests were conducted in which the power percentage of the laser was changed while keeping the focus the same, and the stage speed at 12mm/s. Values for 20%, 40%, 60%, 80% and 100% of the laser power were tested in the ablation. Figures 12,13 and 14 show the analyzed data for the green laser displacement, generated by the beam deflection.

On Fig.12, the displacement of the green laser is shown by using only 20% of the total laser power. The peak that we observe in the lower part of the plot has an amplitude with respect to the initial position of 2.5 pixels, whereas the results shown when applying 80% (Fig.13) and 100% (Fig.14) of the laser power show peak values of 6 and 7.5 pixels, respectively. These were the results that were expected since it is intuitive to think that the more laser power applied, the bigger the beam deflection.

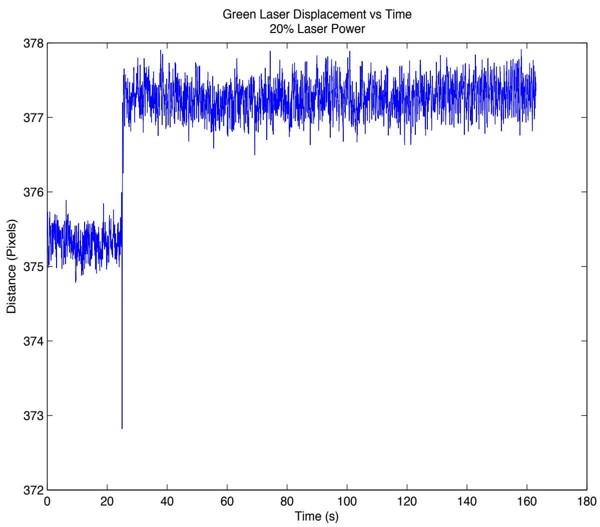


Figure 12. Ablation at 20% laser power

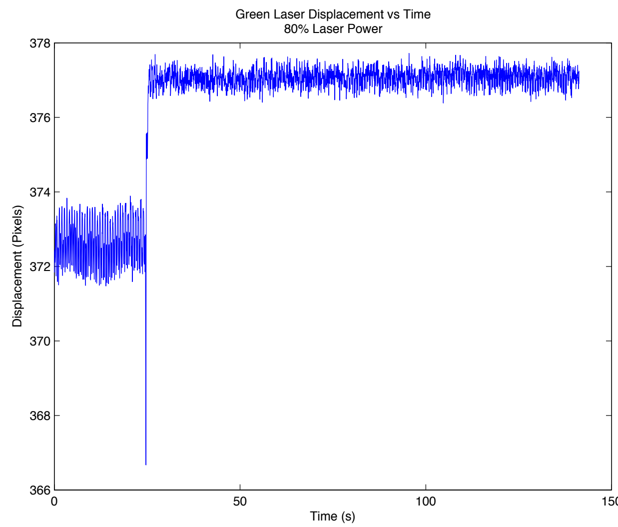


Figure 13. Ablation at 80% laser power

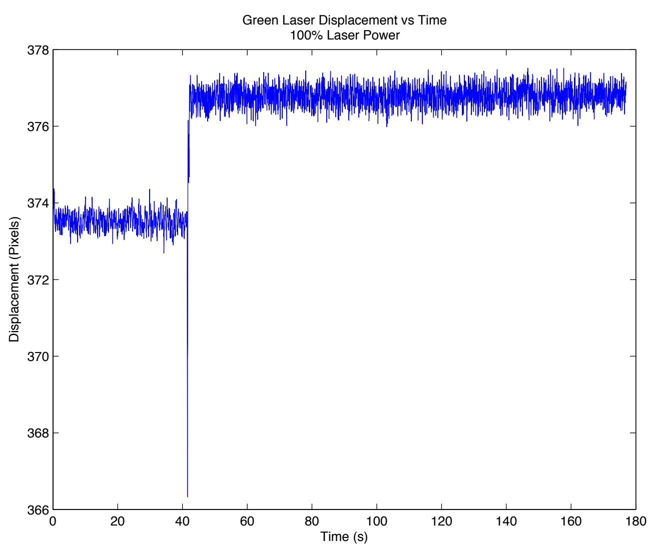


Figure 14. Ablation at 100% laser power

C. Standard Test

The standard test implies the laser power to be 100% and the horizontal stage velocity of the beam to be 12mm/s. All standard tests were performed intermittently during the testing process inside the vacuum chamber in order to detect any relevant changes on the behavior of the beam once several ablations had occurred.

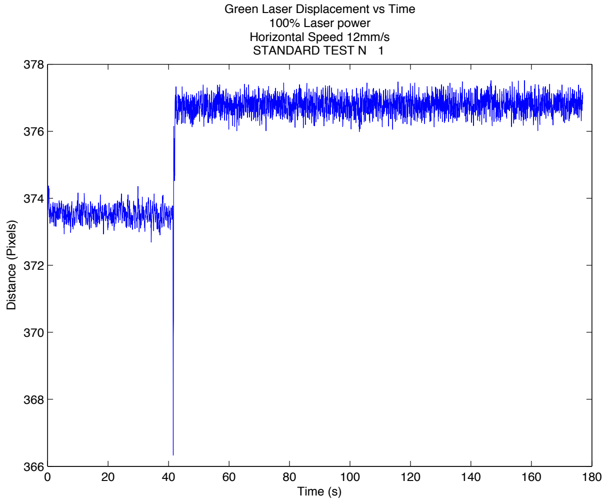


Figure 15. Standard test nº1

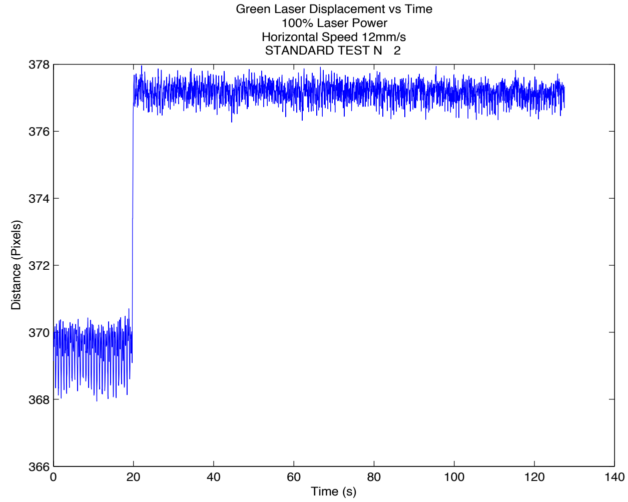


Figure 16. Standard test nº2

The standard test nº1 (Fig.15) shows a peak downwards that represents the ablation, as well as the characteristic offset generated by the movement of the beam. Fig.16 was obtained five experiments later. In Fig.16 we can see how the peak due to the ablation is absent and the offset is much wider than in the previous test. This shows a clear difference in the behavior of the beam in between experiments.

To determine if the noise generated by the oscillation of the beam was interfering with data collected, the expected displacement for a force of 2.1mN applied for 1/12 seconds is calculated and compared to the one generated by the noise. The expected displacement had a value of 0.026 milimeters (0.098 pixels), whereas the noise amplitude was of 0.159 milimeters (0.6 pixels).

For an impulse laser ablation of 100% laser power, the displacement of the green laser reflected by the mirror has a value of 0.6 cm, which corresponds to a force applied of 25mN. The maximum deflection observed was ten times larger than the noise. That means that a 2.5 mN force is required to give a deflection equal to the noise in steady state. Therefore, a much larger force would be needed to give an impulse which produces the same amplitude.

Even though the downwards peak that represents the beam deflection was present in half of the experiments, the effect of the horizontal movement of the beam to obtain the impulse signal should be further analyzed in future studies, since this might be the source of the peak. As the movement of the beam and the ablation of the target always occurred at the same time, it is hard to differenciate which plots show data that involve the laser ablation deflection. Also, displacement turned into to be noise within roughly 1 oscillation, so we may be limited by the framerate of the webcam.

V. Future work and improvements

Due to the complexity of the system for the experiments, which includes a vacuum chamber and a high power laser, the availability to perform experiments has been limited. The big difference between expected and real data highlights the fact that more research is needed in order to find a better way of performing impulse laser signals, which would ideally not imply moving the beam horizontally. Also, a much larger force would be needed to give an impulse which produces the same amplitude, and determining the diameter of the ablation spot as accurately as possible holds a lot of importance in order to find the optimum focus distance for the laser and the beam inside the chamber. More ablation tests are required in order to assess how different laser powers interact with the aluminum target, and a better laser focus with respect to the beam and the target should be found in order to transmit all the power to the target without losses.

VI. Conclusion

Concerns of an uncontrollable growth of the orbital debris population and the loss of key satellites that enable us to address our society's problems have prompted scientists to look for ways to remove junk from space. Amongst other methods, laser ablation has been proposed as a mechanism for deorbiting large space debris. This paper has addressed a low-cost method for obtaining force measurements of laser ablation of aluminum, which is a common spacecraft material. Studies like these are necessary in order to not only improve the method, but also to find other possible methods that might revolutionize the orbital debris removal area of research.

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