Experimental Study on Lodging a Metal Anchor into Free-falling Targets for Space Debris Mitigation*

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An experimental system for lodging a metal anchor into free-falling targets has been developed and the lodging behavior has been investigated. Lodging a metal anchor into space debris to capture it is a good candidate for gathering the debris in space debris mitigation systems. Being one of the simplest methods, it can be applied to most any system, such as the electrodynamic tether system or a propulsion system. Basically, a tethered anchor is fired into space debris to capture it. In our experimental setup, a test plate representing the target space debris is initially attached to a rigid frame using two electromagnetic mounts. A specially designed projectile anchor is fired into the target, in precise coordination with the release of the target test plate into a free-fall condition (i.e., controlled by optical sensors mounted on the acceleration tube and electromagnetic mount). As a result, the metal anchor impacts the target while free-falling through space. The experimental results show that an adequate anchor accuracy can be achieved with the appropriate projectile velocity for a non-fixed (free-falling) target. Moreover, we show that the penetration velocity differs predictably between fixed and non-fixed targets, as well as that predictability changes based on the distance of the projectile’s impact point from the target’s center-of-mass (CM). The equations derived for predicting penetration velocities for free-falling targets were validated through physical testing and the required penetration velocities were accurately predicted.

Key Words: Space Debris, Projectile Experiment, Metal Anchor, Free-falling Target, Docking

Nomenclature

- $m_1$: mass of a metal anchor
- $m_2$: mass of a test plate
- $v_{\text{fix}}$: penetration velocity for a fixed target test
- $v_{\text{free}}$: penetration velocity for a free-falling target test
- $v_{\text{total}}$: velocity of the metal anchor and test plate after capture
- $E_{\text{trans}}$: energy for penetration
  - $I$: moment of inertia of anchor-test plate system
  - $I_p$: moment inertia of test plate
  - $\omega$: angular velocity of system
  - $a$: distance between the impact point and the center-of-mass for the anchor-test plate system
  - $b$: distance from center-of-mass for the test plate and center-of-mass for the anchor-test plate system
  - $r$: distance between impact position and center-of-mass for the test plate

1. Introduction

Recently many satellites that are no longer operational due to failure are drifting in orbit and exist as space debris. Space debris mitigation systems have been studied. These methods require attachment of the mitigation system directly to the debris; for example, by catching the debris with a robotic arm and using propulsion to make the debris fall out of orbit. However, such designs create the potential for many problems, such as the expense and maintenance of a complex robotic system. Simplified methods for integrating debris mitigation systems with orbital debris have been proposed, including the lodging of a tethered anchor into a defunct satellite.

Previous studies into projectile anchors have been performed with exclusively fixed targets, which is most useful for determining the behaviors of anchor penetrating larger mass and momentum targets. However, the behavior of small and lower momentum targets has not been investigated. Pragmatically, the size of space debris varies significantly, making the fixed-target test results insufficient for determining the penetration velocity of smaller orbital debris. In this study, an experimental system was created to lodge a metal anchor into free-falling targets and to investigate the subsequent behavior. In addition, equations showing the relationships between the penetrative velocities of fixed targets and free-falling targets were derived and validated by comparison with experimental results. These equations allow for the accurate prediction of the needed projectile velocities for successful anchor penetration into free-falling targets using fixed target test data.

2. Experiments for Fixed-target Testing

2.1. Metal anchor

An anchor projectile will not penetrate the surface of a target if its velocity is too low, and will pass through the target

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when its velocity is too high. Additionally, once embedded, the anchor must withstand the forces generated during operation of the space debris mitigation system in order to avoid becoming dislodged from the target.

Dudziak et al.3) had previously experimented with a deployable “toggle” mechanism that increases an anchor’s resistance to being pulled out during mitigation system operation. In their study, the metal anchor included a mechanism that is deployed after the anchor is lodged in the target, increasing the mooring’s resistance to being pulled out. However, the complexity of this solution creates the potential for premature deployment of the toggle hook during launch or other failures as a result of the impact.

There is also the potential problem of the anchor passing too far into, or through the target, leaving the tether vulnerable to cutting by the raw edges of the impact hole made by anchor penetration.

The solution for these problems is to ensure that the metal anchor is lodged properly at the surface of the target upon initial impact. The anchors used for our study were designed to penetrate, but not pass through, the debris surface and thereby achieve the appropriate fixation without any additional mechanisms.5) The anterior of our anchor is thick enough to prevent the anchor from passing through the target, while the shaft has a narrowed section intended to increase the anchor’s resistance to being pulled out.5) The penetrating state is shown in Fig. 1(a), while an “over-penetrated” (passed through) state is shown in Fig. 1(b). In this study, “penetrating state” is defined as the state when the metal anchor penetrates the target plate and stops at the rear end of the metal anchor. Figure 2 shows the dimensions of the test anchor and a photograph of it. The anchor is made of SS400 steel, with a mass of 204 g.

2.2. Equipment for fixed-target testing

The experiments for fixed targets were performed in our previous study,3) and are used here for the comparison studies with the free-falling target tests. An air gun was used for projectile launch. An overview of the test equipment is shown in Fig. 3.

In the case of fixed-target experiments, the test target plates were fixed to a platform using four mounting jigs (shown in Fig. 4). For these tests, the target plate remains attached to the platform during impact by the projectile anchor, with the projectile velocity controlled by the air gun’s air pressure setting (adjusted at the platform’s control panel). The projection velocity was calculated by the time delay between the two pairs of optical switches (set 10 cm apart) within the acceleration tube measured by a counter. The test plates used in these experiments were aluminum alloy A2024-T3 measuring $250 \times 250 \times 1$ mm with a mass of 199.5 g.

2.3. Results for fixed-target testing

The test results for fixed-target testing are shown in Fig. 5. Three penetration conditions were recorded: non-penetrat-
ing, penetrating, and the anchor having passed through the target. It was clarified in our previous study that kinematic energy has a large effect on anchor penetration states and momentum has little effect. Therefore, kinematic energy is also indicated in the figure. From the graph, it is apparent that the correctness of the anchor penetration state is dependent on the kinetic energy. A visual example of an anchor with appropriate penetration is shown in Fig. 6.

3. Experiments for Free-fall Targets

3.1. Equipment for free-fall target testing

Electromagnetic mounts and optical sensors are employed to change the target test plate from a fixed state to a free-falling state during anchor impact. Test plates are initially fixed to the equipment frame using electromagnetic mounts, which are subsequently shut off at the point when the metal anchor projectile passes through the optical sensors in the acceleration tube. This halts current to the electromagnetic mounts, releasing the target plate into free-fall. As a consequence, the metal anchor hits the test plate during its free-fall state. An overview of the relay circuit, the experimental system, and appearance of the test plate during free-fall are shown in Figs. 7–9, respectively.

3.2. Evaluation of the test equipment for free-fall target testing

The time between the moment that the optical sensors detect the metal anchor and the release of the target plate by the electromagnetic mounts must be precise. If the anchor velocity is too fast, the target may still be attached to the frame at anchor impact; and if too slow, the test plate may gain undesired acceleration during free-fall. This precision is impossible to evaluate with the naked eye, so a data logger is used to compare the voltages applied to the optical sensors for velocity measurement (velocity sensors) and the optical sensor for the electromagnet to ensure the test plate is in a proper state of free-fall at the moment of anchor impact. With these measurements, we can position the velocity sensors and electromagnet’s optical sensor as shown in Fig. 8.
Charts evaluating the free-fall state are shown in Figs. 10 and 11. These data were collected during physical tests at different projectile velocities. In Fig. 10 and Fig. 11, the output voltages of velocity sensors 1 and 2 and the voltage of the electromagnet are indicated by the blue line, green line and red line, respectively. When a metal anchor passes the optical sensor for the electromagnet, the signal from the sensor is transferred to the relay circuit and the relay circuit cuts off power to the electromagnet, thereby releasing the test plate and putting it into free-fall. In Figs. 10 and 11, the red line of 0 [V] indicates the power being cut off and means free-falling state of the test plate. When the metal anchor passes velocity sensors, the output voltages of the velocity sensors change. Therefore, if the red line becomes 0 [V] before the blue and green lines change, the test plate is released before the metal anchor passes by the velocity sensor. This means that the test plate begins falling before impact. On the contrary, the test plate is released after impact if the red line is not 0 [V] when the blue and green lines change.

At a velocity of 29 m/s, the voltage to the electromagnets is reduced prematurely and the test plate falls before impact, while at 45 m/s, the test plate is still fixed at impact. The distance between the optical sensor for the electromagnet and test plate is 2.05 m as shown in Fig. 8. When the metal anchor passes the optical sensors, there is a delay time in the relay circuit to cut off the power to the electromagnet. We performed experiments to estimate the delay time and the result indicates that the delay is about 0.047 s. Therefore, the maximum velocity can be estimated as follows:

$$v_{\text{max}} = \frac{2.05}{0.047} = 42.7 \text{ m/s}.$$  

If the velocity of a metal anchor is over 42.7 m/s, the metal anchor will impact the test plate before the relay circuit is cut off and the test plate will not fall before impact.

### 3.3. Results for free-fall target testing

Anchors were shot into test plates and the resulting three main penetration states were investigated: non-penetrating, penetrating, and the anchor having passed through the target. Images from the free-falling target experiments are shown in Fig. 12. The results for free-fall test cases when the impact point is at the center-of-mass (CM) are shown in Fig. 13. We can see that the docking states differ depending on projectile velocity for both the fixed and free-falling test cases.

To evaluate the effects of boundary conditions, we compared the results of the free-falling target test cases with the fixed-target cases. There is a velocity range for penetration even for the free-fall test plates, and this range is predictably larger than that of the fixed targets.

To evaluate the effect of impact position on the free-falling plates, we performed experiments where the anchor’s point of impact was 5 cm off-centered from the target’s CM (Fig. 14).

Figure 15 includes a summary of all test cases’ penetration velocities. The graph indicates that the penetration velocity for free-falling targets is larger than that of the fixed targets, and that the penetration velocity increases when the impact is off-centered. Note that in the case of an off-centered impact, the test plate rotates after impact.

### 4. Equations Describing Penetration Velocity Relationships

While it is more difficult to achieve proper anchor penetra-
tion with a free-falling target versus a fixed target, there is a predictable relationship between the two. In this section, we derive equations that describe the relationships between free-falling and fixed-target penetration velocities as well as evaluate the validity of these equations through real-world tests.

Figure 15 shows that penetration velocity is greater for free-falling targets versus fixed targets; presumptively due to the fact that all of the kinetic energy from the anchor is given up to the plate’s deformation (penetration) in the fixed tests, whereas in free-fall tests, a portion of the anchor’s kinetic energy is transferred to the kinetic energy of the test plate. Henceforth, the term energy for deformation denotes the energy that is used for penetrating the metal anchor into the test plate, assuming that all of the energy for deformation is used for penetration in both fixed and free-falling plates.

A perspective for the penetration of an anchor into a free-falling plate is shown in Fig. 16.

For a fixed target, the equation for the energy conservation before and after impact is:

$$\frac{m_1 v_{\text{fix}}^2}{2} = E_{\text{trans}}$$  \hspace{1cm} (1)

For a free-falling target, the equation for the energy conservation before and after impact is:

$$\frac{m_1 v_{\text{free}}^2}{2} + \frac{m_2 v_{\text{target}}^2}{2} = E_{\text{trans}} + \frac{(m_1 + m_2)v_{\text{total}}^2}{2} + \frac{I\omega^2}{2}$$  \hspace{1cm} (2)

From Eqs. (1) and (2), we can obtain:

$$\frac{m_1 (v_{\text{free}}^2 - v_{\text{fix}}^2)}{2} + \frac{m_2 v_{\text{target}}^2}{2} = (m_1 + m_2)v_{\text{total}}^2 + \frac{I\omega^2}{2}$$  \hspace{1cm} (3)

By applying the momentum conservation law, we can calculate the velocity of a metal-anchor/test-plate system after impact as:

$$v_{\text{total}} = \frac{m_1 v_{\text{free}} + m_2 v_{\text{target}}}{(m_1 + m_2)}$$  \hspace{1cm} (4)

From Eqs. (3) and (4), we can obtain

$$\frac{m_1 (v_{\text{free}}^2 - v_{\text{fix}}^2)}{2} + \frac{m_2 v_{\text{target}}^2}{2} = \frac{(m_1 v_{\text{free}} + m_2 v_{\text{target}})^2}{2 (m_1 + m_2)} + \frac{I\omega^2}{2}$$  \hspace{1cm} (5)

An angular momentum conservation for free-falling target is obtained using:

$$m_1 \times v_{\text{free}} \times a - m_2 \times v_{\text{target}} \times b = I \times \omega$$  \hspace{1cm} (6)

The CM of the system after penetration is calculated as:
Equation (11) can be rewritten as follows:

\[ a = \frac{r \times m_2}{(m_1 + m_2)} \quad b = \frac{r \times m_1}{(m_1 + m_2)} \quad I \omega^2 = \frac{P \omega^2}{I} = \frac{(m_1 m_2 r (v_{\text{free}} - v_{\text{target}}))^2}{I(m_1 + m_2)^2} \]  

\[ I \times \omega^2 \text{ in Eq. (5) can be obtained using Eqs. (6) and (7) as follows:} \]

\[ m_1(v_{\text{free}}^2 - v_{\text{fix}}^2) + m_2 v_{\text{target}}^2 = \frac{(m_1 v_{\text{free}} + m_2 v_{\text{target}})^2}{(m_1 + m_2)} + \frac{(m_1 m_2 r (v_{\text{free}} - v_{\text{target}}))^2}{I(m_1 + m_2)^2} \]  

Equation (9) can be rewritten as follows

\[ [m_2(m_1 + m_2)I - m_1 m_2^2 r^2]v_{\text{free}}^2 - 2[v_{\text{target}}m_2((m_1 + m_2)I - m_1 m_2^2 r^2)]v_{\text{free}} + [v_{\text{target}}^2((m_1 + m_2)I + m_1 m_2^2 r^2) - v_{\text{fix}}^2(m_1 + m_2)^2 I] = 0 \]  

By solving for \( v_{\text{free}} \) in the quadratic equation (Eq. (10)), we have:

\[ v_{\text{free}} = v_{\text{target}} \pm \frac{\sqrt{v_{\text{fix}}^2(m_1 + m_2)^2 I - m_2(m_1 + m_2)I - m_1 m_2^2 r^2}}{v_{\text{fix}}^2 - \frac{(m_1 + m_2)I + m_1 m_2^2 r^2}{(m_1 + m_2)} v_{\text{target}}^2} \]  

Equation (11) can be rewritten as follows:

\[ v_{\text{free}} = v_{\text{target}} \pm \sqrt{\frac{(m_1 + m_2)^2 I}{m_2(m_1 + m_2)I - m_1 m_2^2 r^2} - \frac{v_{\text{fix}}^2}{v_{\text{fix}}^2 - \frac{(m_1 + m_2)I + m_1 m_2^2 r^2}{(m_1 + m_2)} v_{\text{target}}^2}} \]  

From Eq. (12), we can calculate the penetration velocity of an anchor into a free-falling target from the penetration velocity for the fixed target. Two velocities are obtained from Eq. (12) and the negative velocity indicates the condition in which the anchor is shot from the lower side to the target. Because the anchors were shot from the upper side in the experiments, only the positive value is employed in the following investigation.

To evaluate the validity of Eq. (12), we used it to estimate the penetrating velocity in the case of free-falling targets and compared the results with the experimental results. To calculate the velocity of the test plate after impact, we measured the time from when the test plate starts to fall until the moment of impact. When the velocity is about 29 m/s, this time can be estimated based on Fig. 13 and is about 20 ms. The velocity of the test plate can be calculated as follows:

\[ v_{\text{target}} = g \times t = 9.8 \times 0.02 = 0.196 \text{ (m/s)} \]

This velocity is small in comparison to the velocity of the metal anchor (about 0.7%); so in the estimate calculation, we can omit the terms included in Eq. (12) and obtain Eq. (13).

\[ v_{\text{free}} = v_{\text{fix}} \sqrt{\frac{(m_1 + m_2)^2 I}{m_2(m_1 + m_2)I - m_1 m_2^2 r^2}} \]  

Equation (13) can be transformed to Eq. (14)

\[ \frac{v_{\text{fix}}}{v_{\text{free}}} = \sqrt{\frac{m_2}{(m_1 + m_2)} - \frac{m_1 \times m_2^2 \times r^2}{(m_1 + m_2)^2 I}} \]  

The moment of inertia for the anchor-test plate system can be calculated as

\[ I = I_p + m_2 \times b^2 = I_p + \frac{m_2 \times m_1^2 \times r^2}{(m_1 + m_2)^2} \]  

From Eqs. (14) and (15), Eq. (16) can be obtained.

\[ \frac{v_{\text{fix}}}{v_{\text{free}}} = \sqrt{\frac{m_2}{(m_1 + m_2)} - \frac{m_1 \times m_2^2 \times r^2}{I_p \times (m_1 + m_2)^3 + m_2 \times m_1^2 \times r^2}} \]  

\[ v_{\text{free}} \text{ can be calculated from } v_{\text{fix}} \text{ as follows:} \]

\[ v_{\text{free}} = v_{\text{fix}} \sqrt{\frac{((m_1 + m_2)^2 I_p + m_2 \times m_1^2 \times r^2)(m_1 + m_2)}{m_2(m_1 + m_2)^3 I_p - m_1 m_2^3 r^2}} \]  

We used Eq. (17) to calculate the minimum penetration velocity of an anchor into a free-falling target from the minimum penetration velocity for the fixed target. From the results graph, we can see the range between the maximum non-penetrating velocity and the minimum penetrating velocity acquired from experiment results and the exact minimum penetrating velocity must be in this range. Therefore, the range of minimum penetrating velocity is summarized in Table 1. Table 1 shows the predicted and actual results for penetration velocity for three cases: a fixed target, a free-falling target when impact is at CM, and a free-falling target with an impact at 5 cm from CM. From Table 1, we can see that the error between predicted and penetration velocity is small (within 10%).
Table 1. The test results and predicted range of minimum penetrating velocity.

| Test case                          | Experiment value (m/s) | Predicted (m/s) |
|------------------------------------|------------------------|-----------------|
| Fixed target                       | 16.9–18.7              | —               |
| Free-falling target (impact point is target’s CM) | 25.0–27.2              | 24.2–26.8       |
| Free-falling target (distance between impact point and target’s CM is 5 cm) | 27.1–29.2              | 25.8–28.6       |

5. Conclusion

In this study, equipment and experiments were designed to measure the difference in projectile velocity and penetration results for three test cases: a fixed-target case, a free-falling target case with an impact point at the target’s CM, and a free-falling target case with an impact at 5 cm from CM. In all of the cases, the correct penetration states are confirmed, but the required anchor velocities for proper penetration differ. The anchor projectile velocity for free-falling targets is greater than that of fixed targets. In the case of free-falling targets, the velocity required for proper anchor penetration increases in the case of off-centered impact. Upon further investigation, we used the conservation laws to derive equations that accurately predict the correct anchor projectile penetration velocities for free-falling targets as derived from fixed-target data. The predicted velocities were compared with the experimental results and the error between them was small. The estimated equation derived is applicable when the difference of the deformation of the target structure between the fixed and free-falling conditions is small. The effectiveness of the estimated equation derived when the difference of the deformations after penetration is large will be investigated in our future work.

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