

Modular Ballistic Pendulum for Measurement of Impulse from Tamped Explosives

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Abstract

The ballistic pendulum is a well-established piece of test equipment originally developed for estimating the velocity of bullets and projectiles. When trying to understand the effects of different tamping methods on explosive performance, the ballistic pendulum is an excellent tool allowing calculation of explosive charge impulse. Most ballistic pendula for this application are limited to narrow impulse ranges as the pendulum mass determines the angle of swing; and a mass capable of being moved by a small charge would be far too small for a larger charge. This paper describes a modular design (the Alford Modular Ballistic Pendulum) which overcomes this problem.

Introduction

To be able to study the performance of various means of tamping explosive charges, a reliable method of measuring the effect is needed. As the tamping effect affects explosive pressure over time, the impulse of a charge is the most significant and important thing to measure. While there are a few different means of doing this, the most widely used is the ballistic pendulum which uses conservation of momentum to derive the momentum imparted by the explosive charge. Originally used as a means of calculating the velocity of projectiles, it was also widely used as a means of measuring the relative power of explosives. [1]

In its simplest form, a ballistic pendulum consists of a mass suspended from a fulcrum. A horizontal force is applied to the mass which swings freely. The maximum angle of rotation, the length of the arm and the mass can be used to derive the impulse.

To obtain useful data across a wide range of charge sizes and configurations, a series of different ballistic pendula could be used, each with a working range covering part of the range of charges being studied. This would require several systems to be designed, constructed, and suitably located at a test site.

The alternative is to design a single system, capable of being used across the entire range of charges. While this might, at first, appear to be a poor design choice given that at the extremes of explosive yield range there would be either too little or too great a swing to give accurate readings. A modular design in which the mass could be adjusted or changed has the attraction of requiring only one frame to be built; and given that this is the largest component of the design, this approach was the one taken forward.

This paper describes the design of a ballistic pendulum that meets these criteria, and which can be fabricated relatively easily without the need for complex or costly specialist equipment.

Experimental set-up

Experimental considerations

To start designing a ballistic pendulum, it is important to understand the likely range of impulses that are going to be measured. This was done initially by conducting a literature review and finding relevant impulse measurements. Reference 2 provided some historical test results in which some early models of explosive charges produced by the author's company were characterized using a vertical pendulum. [2] The data represented some of the upper-end impulses from large-explosive-charge vehicle-borne IED disrupters. Explosive charges ranged from 400g to 1000g (0.9lb to 2.2lb) of sheet explosive at both 12" (305mm) and zero stand-off.

A second set of trials data was found in reference [3] in which a small, conventional ballistic pendulum was used to measure the impulse from water bottle charges having central charges consisting of different sizes of detonating cord. Charges ranged from 5g to 50g (77 grains to 770 grains) of detonating cord with stand-offs ranging from 0.1m to 0.4m (0.33 ft to 1.3 ft)

Using the available data, the expected range of impulse to be measured was predicted to be between 10Ns and 8,500Ns. However, the above-mentioned trials used charges designed to project water at the pendulum, which is significantly different from the tamped charges for which the pendulum is to be designed.

A series of tests was conducted to measure the impulse from representative charges to confirm the predicted range of impulse. These simple tests involved projecting simply supported steel plates vertically by attaching charges to the underside of the plates and filming their flight to measure the maximum height

reached. Two steel plates were used depending on the size and net explosive quantity of the charges. One was 60kg (132lbs) and the second 125kg (276lbs). Charges ranged from 29g (1oz) of detonating cord to 380g (13.4oz) of dynamite, both bare and tamped charges resulted in impulses of between 94Ns and 1466Ns.

This data was used to inform the design of the final ballistic pendulum.

Types of ballistic pendula

Research found four main designs for ballistic pendula. Type 1, the simplest form, which should be considered the most conventional is when the mass is suspended vertically on a single pendulum arm with the impulse acting horizontally. For small-scale testing, this design works well but is not particularly scalable.

The second design (Type 2) is a variant of this with two parallel pendulum arms supporting a longitudinal mass along its length. [4] This allows larger masses to be used by using longer masses without increasing the surface area being subjected to the impulse. The pendulum arms can also be used to prevent twisting and by having equal lengths of pendulum arm, the mass swings in an arc that remains parallel to the ground.

The third design (Type 3) is a pendulum in which a rigid pendulum arm is mounted horizontally, and the impulse is applied vertically. It is essentially like type 1 rotated through 90 degrees. [5]

The fourth design (Type 4) is not technically a pendulum but a restrained mass in vertical free-acceleration. [6] This design is particularly suitable for testing blast from large, buried charges as it is a particularly simple design without pivots or other fixings that could break.

Another type of pendulum is the Ballistic Mortar which has historically been used to measure the power of explosives. [7] A 10g (154 grain) charge of explosive is placed into a chamber and a projectile fitted behind it. When the explosive is detonated, the projectile is ejected from the pendulum and the pendulum swings in the opposite direction. The angle of swing may be measured and compared to those of other explosives.

Alford Modular Ballistic Pendulum design

Alford Technologies future research is focused on impulse from tamped explosive charges. Experience has shown that unlike burying charges in the ground in which charges are easily positioned, fixing charges to the underside of a vertically launched target, and ensuring that it is in close contact can be difficult, which can lead to a slow testing tempo. Ground effects such as reflections from the ground would also affect the blast effects on the target plate so pendulum Types 3 and 4 were rejected. While the Type 1 pendulum is simple to fabricate, Type 2 allows greater flexibility, by using larger masses for larger explosives charges. Thus, a Type 2 pendulum was selected.

A modular ballistic pendulum (Alford Modular Ballistic Pendulum or AMBP) was designed for research over a wide range of charge types and sizes to give accurate, consistent, and correlatable measurements. The charge sizes of interest range from as little as one or two grams (15-30 grains) of un-tamped explosive up to as much as six hundred grams of tamped and geometrically optimized explosive in direct contact with the base plate of the mass. A single mass would not be capable of giving accurate measurements over

the entire range, however, having a single test frame with interchangeable masses would allow the entire range of measurements to be made using only one basic test apparatus.

Ideally, there should be an overlapping range of use between each of the masses allowing similar charges to be used against each of the masses to give corresponding data with each mass. They should give similar results despite the large differences in mass and possibly pivot arm length and this would give a means of ascertaining both experimental accuracy and correlation between experiments.

The overall design of the frame was driven by the need to suspend a mass of at least 750kg (1,653lbs). The mass identified was an empty BLU-109 bomb case which the author had on-hand. This weighs approximately 600kg (1,323lbs) (fig. 1a). The bomb case has lifting lugs 30" (762mm) apart which was used as a design parameter for the location of the pivots. An existing steel frame was adapted and reinforced to support the mass.

A base plate was welded onto the base of the bomb to act as an anvil against which the test charges could be applied. The base plate was made from a 400mm x 400mm x 30mm (15.75" x 15.75" x 1.18") steel plate with 20mm (0.79") holes drilled in each corner for fixings. Future work will be done with a set of at least three plates bolted together to provide enough thickness to prevent the anvil from becoming deformed and damaged during testing. The total bomb mass was 633kg (1,396lbs).

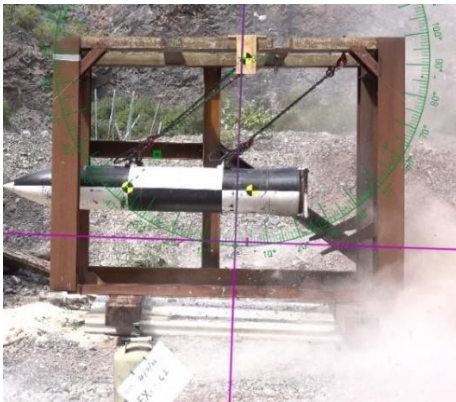


Fig. 1a. Large mass (633kg) with protractor overlaid for measuring angle of rotation



Fig. 1b. Test apparatus with medium mass (122kg)



Fig. 1c. "V" suspension reduced torsional rotation

A second, smaller test mass was fabricated from a 1m length of Universal Steel Beam. Suspension lugs were welded on 30 inches (762mm) apart to allow the same suspension locations to be used on the frame. A 300mm x 400mm x 30mm (11.8" x 15.75" x 1.18") base plate was welded onto one end. This smaller assembly weighs 122kg (269lbs). (Fig. 1b)

A third mass is being constructed with a target mass of approximately 20-30kg (44-66lbs) but has not been tested at the time of writing.

Heavy duty lifting chains were used to suspend the mass. These come ready made with end clips and features for adjusting their length. As standard items, their length is very consistent and so there was no need for further fine adjustments. Two chains were used upside down in the sense that the large lifting ring which is normally attached to a crane or jib was attached to the mass and each of the two lifting clips

was attached to one of the four fixing rings on the steel frame. This has the advantage of providing torsional stability, limiting mass swaying if the force from the charge is not completely symmetrical.

The AMBP also is designed so that a mortar section can be bolted onto the base of the large mass allowing it to be used to measure the explosive power of different explosives.

Data capture considerations

Literature searches showed that numerous methods of capturing data from ballistic pendula have been used successfully; but often the data capture and recording methods limit the number of tests that can be conducted in a day.

The method selected uses video to record the swing of the pendulum and video analysis software to measure the angle of rotation and horizontal movement. Slow-motion cameras have often seemed to have been the default choice; but these can take a significant amount of time to download and store the video. Thus, they are best operated by someone who is able to focus on the data capture, and tests instrumented in this way normally require two operators. Furthermore, it was recognized that even a standard frame rate would allow the apogee of the swing to be found and the angle measured. Slow-motion would only be needed if the acceleration of the pendulum is to be measured. It was therefore decided to focus on using standard video to capture the data as this would allow a single operator to conduct the trials.

Initial tests in which the pendulum, rather than the fidelity of the data, was being tested were done using the slow-motion video setting on a Samsung S10+ phone. This does not actually record true slow-motion video but appears to slow down standard video. It was found that it was relatively simple to capture events and to use suitable analysis software to measure the rotation and horizontal displacement. However, resolution was very poor and when zooming in on images, the degree of pixilation was significant. It was still possible to identify the apogee of the motion and to make relatively accurate measurements. Thus, although the data was useful, it had a greater degree of error. (Figs 2a-c)



Fig. 2a. Full frame from video shot using Samsung S10+phone

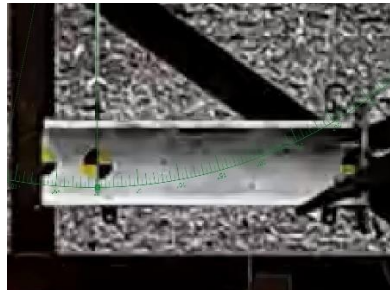


Fig. 2b. Image zoomed in on ballistic mass



Fig. 2c. Image zoomed in further



Fig. 2d. Full frame shot on Sony Cyber-Shot RX10 camera

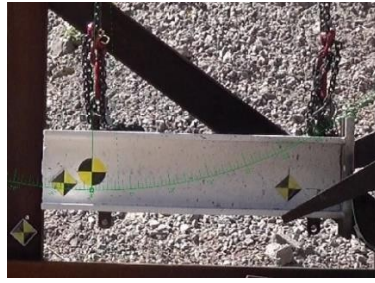


Fig. 2e. Image zoomed in on ballistic mass

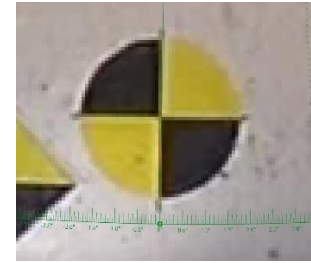


Fig. 2f. Image zoomed in further

A Sony Cyber-Shot DSC RX10 camera with a fixed lens and video recording facility was used to film at full-HD resolution to see if the video, would be good enough to obtain good data. The frame size was 3840x2160 pixels (HD), the frame rate was 25 fps. Filming at HD resolution allowed the camera to be positioned far enough from the AMBD to use the camera zoom at a neutral 50mm focal length to reduce parallax effects on the image while enabling digital zooming for setting scales and datum points for accurately measuring the angles of rotation and horizontal resolution. (Figs. 2d-f) Importantly, the camera could be switched on and left running at the start of test shots so that individual clips could be recorded by simply pressing the start and stop record button on the camera. Filming in 4K may have allowed greater zoom levels to be used without loss of resolution but the video file sizes would have been significantly larger with the camera more prone to overheating.

Filming with the above settings gave images that were significantly better than those produced with the phone camera. With the images captured on the phone, a straight vertical line would be located over a line two pixels wide, requiring a degree of estimation to identify the actual centre line, whereas images recorded at HD resolution had the same line far better defined, requiring far less estimation.

Equations, Units and Calculations

Derivation of impulse for a horizontal pendulum

There are a few derivations of equations for calculating impulse for a ballistic pendulum in literature. Reference 2 has one of the better derivations but is for a vertical pendulum (the mass is projected vertically). All the derivations are based on conservation of momentum and derive the horizontal or vertical component of the momentum depending on which plane the impulse is acting. The following derivation is adapted from Ref. 2 but resolves to a slightly simpler final form for a horizontal rather than vertical pendulum.

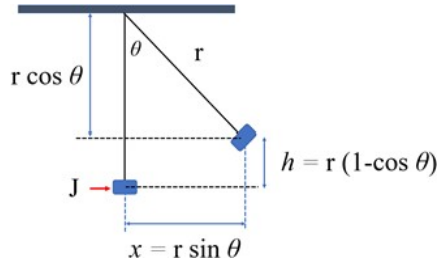
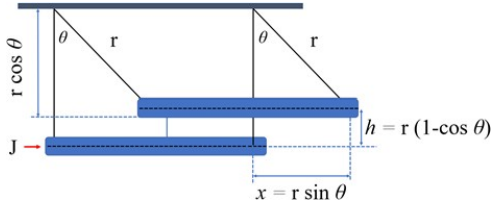


Fig. 3a. Horizontal Pendulum

m	Mass of the pendulum	kg
r	Distance from the centroid of the pendulum to the rotational axis	m
I	Moment of Inertia $I = \frac{L}{\omega} = mr^2$	kg m ²
w	Angular velocity $\omega = \frac{v}{l}$	
L	Angular Momentum $L = I\omega$	
Θ	Final angle of the pendulum	degrees
v	Velocity	m/s
J	Impulse from charge (change in momentum) $J = Ft$	N s or kg m / s
h	Height raised	m
F	Force $F = ma$	N or kg m ²
a	Acceleration	m/s ²
p	Momentum $p = mv$	kg m/s ²
PE	Potential Energy $PE = mgh$	kg m/s ²
g	gravity	m/s ²

Fig. 3b. Definitions

According to Backofen, the propulsion of the mass occurs in two phases, the first brisant propulsion phase and the second gas propulsion phase. [8] The first phase occurs during the detonation of the explosive and the second during the gas expansion phase. The pendulum motion is mostly due to the second phase and will be on the order of milliseconds while the impulse will be due to the imparted in microseconds to a few milliseconds depending upon the explosive and the method of tamping.

Impulse from the charge will cause the pendulum centre of mass to have an initial velocity (v) causing the pendulum to have an initial angular velocity (ω). Gravity will do negative work against the pendulum motion ceases.

For the rotation of a rigid body around a fixed point, the energy-work equation is:

$$\underbrace{\frac{1}{2} I \omega_{(initial)}^2}_{(work)} + \underbrace{mgh_{(initial)}}_{(PE)} = \frac{1}{2} I \omega_{(final)}^2 + mgh_{(final)} \quad (1)$$

Under the initial conditions, h is zero. Under the final conditions, when the pendulum has stopped, w is zero. So, the energy-work equation becomes:

$$\frac{1}{2} I \omega_{(initial)}^2 = mgh_{(final)} \quad (2)$$

Since $\omega = \frac{v}{r}$ and $h = r (1 - \cos \theta_{(final)})$ is the final angle of the pendulum, the equation becomes:

$$\frac{1}{2} I \frac{v^2}{r^2} = mgr (1 - \cos \theta_{(final)}) \quad (3)$$

Since $I = mr^2$

$$\frac{1}{2} mv^2_{(initial)} = mgr (1 - \cos \theta_{(final)}) \quad (4)$$

ie. $KE = PE$

$$\frac{1}{2}v^2 = gr(1 - \cos \theta) \quad (5)$$

Solving for v :

$$v = \sqrt{2gr(1 - \cos \theta)} \quad (6)$$

Conservation of momentum dictates that the initial angular momentum divided by the length of the arm will be equal to the momentum of the pendulum centre of gravity from the impulse of the charge:

$$J = I\omega/r_{(\text{pendulum})} = Iv/r^2_{(\text{pendulum})} = mv_{(\text{final})} - mv_{(\text{initial})} \quad (7)$$

Impulse is the change in momentum, $mv_{(\text{final})} - mv_{(\text{initial})}$. Since $mv_{(\text{initial})}$ is equal to zero the Impulse (J) from the charge so:

$$J = mv_{(\text{final})} \quad (8)$$

Therefore

$$J = m\sqrt{2gr(1 - \cos \theta)} \quad (9)$$

Units of Impulse

Data from the United States still tend to use the rather obscure imperial unit of slug foot per second (slug-ft. /sec) for impulse while older references use pre-SI metric units such as lb. sec./in.² [9] whereas most newer researchers use the SI unit of Newton seconds (Ns). When analyzing the historical pendulum data available, it was first converted into SI units and then the impulse calculated and used as a means to verify the author's calculations and ensure consistency.

Data processing

An Excel spreadsheet was developed to allow the impulse to be quickly calculated using equation (9) derived above. It allows both the angle of rotation and the horizontal displacement to be used as the input. It also has a convenient predictor in which the expected impulse can be entered to check what the likely angle or rotation and horizontal displacement will be. It can also calculate the impulse for vertical free flight in which a mass is kicked vertically as was done during the initial benchmark tests.

A video analysis program called Tracker, developed as part of Open-Source Physics was used to measure the angle of rotation and the lateral movement. [10]

Experimental errors

There are a number of known experimental errors that can be reduced in the future work. The first is parallax errors due to the fact that the mass is suspended centrally in the frame so the distance from the camera to the front of the frame and to the mass is different. The datum mark for the front fulcrum is on the plane of the frame whereas the datum for the centre-of mass is in the centre of the frame. Moving the camera away from the frame and using a 50mm (or longer) focal length on the camera reduces the parallax effect.

The frame is made from steel RSJs and weighs over 500kg (1,100lb). When used with the medium mass, the frame is heavy enough to not move, but when larger charges were fired against the heavy mass, the frame was seen to jump, moving the fulcrum. With the largest charges and the large mass, the entire AMBP frame moved significantly on the concrete base. Fortunately, the majority of this occurred after the first swing of the pendulum. In the most extreme case this horizontal movement resulted in the frame shifting approximately 33mm (1.3") resulting in an angular change of 0.1 degree.

A solid, concrete base should be cast directly onto the ground and the frame levelled and bolted down to avoid any movement.

When many tests were being conducted with detonating cord, the surface of the steel base plate began to become eroded. The precise location of the charges was then varied slightly to avoid the eroded areas. Thus, a sacrificial plate bolted on to the main base plate should be used during future tests.

With the larger tests, the base plate became deformed and the contact area between the charge and the base plate was not perfect. The steel plate should be thickened by adding additional steel plates of steel to ensure that it cannot be deformed by charges.

The Tracker software allows the angle of rotation to be conservatively measured to within ± 0.5 degree. In the case of one of the larger firings that led to the frame shifting (a tamped charge not included in the results shown) leading to a spread of 40Ns (2.3% of the total impulse) and the angular deviation encompassed the error that might have been introduced by the frame moving.

Horizontal measurements are also easy to measure using Tracker with the horizontal swing estimated as being measured to within ± 5 mm. This resulted in a spread of only 21Ns (1.3%) If, however, the horizontal movement of the frame is included, this has a more significant effect on the accuracy of the impulse calculation, resulting in a spread of 86Ns (5.3%). It is also likely that the horizontal movement is subject to greater parallax as the camera was set up in line with the centre of mass being measured and was therefore in the same vertical axis as the pivot.

Therefore, it was decided to use the impulse derived from the angular measurements for analysis and the horizontal measurement used as a back-up to help calculation errors.

Currently, few repeat firings have been conducted to determine the inevitable deviation between similar shots.

Experiments and Results

Explosive charge configuration

Various charges were used consisting of different sizes of detonating cord, both as single strands and bundles as well as other charges of Eurodyn 2000, a nitroglycol-based dynamite made by Orica. The smaller NEQ charges were used against the medium mass and the larger Eurodyn 2000 charges against the large mass. Net Explosive Quantities (NEQ) were converted into Net Explosive Weight (NEW),

otherwise called TNT equivalent. The TNT equivalencies, also known as relative effectiveness factor (RE factor) used came from Wikipedia. [11]

Combinations of detonating cord gave 5g/m, 10g/m, 12g/m, 15g/m, 17g/m, 24g/m, 40g/m, 60g/m, 80g/m charges 250mm long and 84g/m and 108g/m 300mm long in flat raft configuration as opposed to bundles.

Charges were cut and measured to length and stuck to a strip of Breacher's Tape made by Breachers Tape Inc. [12] This is 30 mils thick (0.762mm) and was positioned between the explosive and target plate on all shots.

The Eurodyn 2000 charges were kept in their original paper packaging. Cartridges were initiated by taking a length of 10g/m detonating cord doubled over and taped to the back of the cartridge. If bundles of cartridges were used, they were initiated along their centre line and with three cartridges, they were attached in a linear pyramid initiated along their back.

Results

An initial series of tests were conducted using the AMBP apparatus. The purpose of these tests was to confirm the linear relationship between the quantity of explosive and the impulse using two types of explosive and two masses over a very wide range of charge sizes - 2.5g up to 600g (40 grains - 21 oz).

The outlying points above the line at 54g NEW (1.8 oz) correspond to charges where similar detonating cord charges were either arranged in a bundle or in a flat raft laid on the target (higher impulse). This should be investigated further.

This set of trials was conducted to prove the linear relationship between NEW and Impulse over two orders of magnitude of charge size as well as to test the effectiveness of the AMBP design. Unfortunately, no other data sets for impulse from bare charges in direct contact with targets was found in literature for comparison to the data that was produced.

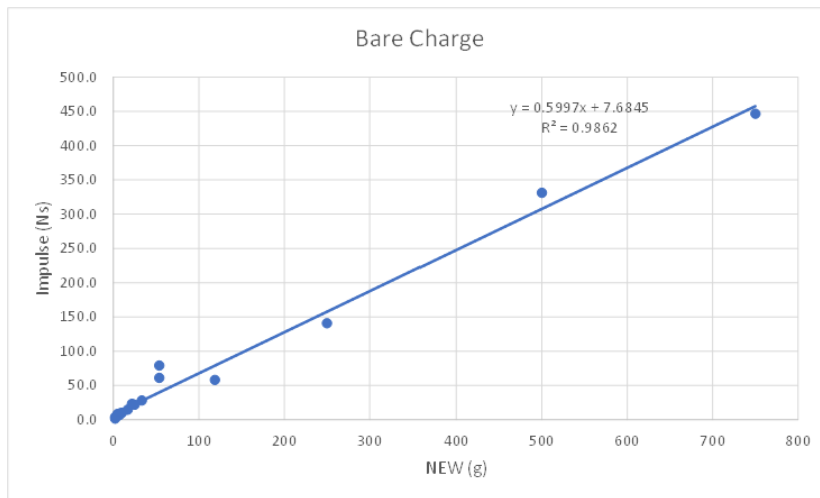


Fig. 4a. Graph showing the linear relationship for the first 18 tests.

Explosive	NEW g (TNT)	Impulse J Ns
5g/m	2.1	1.6
5g/m	2.1	3.9
17g/m	7.1	7.0
24g/m	10.0	10.1
10g/m Detcord	4.2	6.2
12g/m	5.0	8.6
20g/m	8.3	9.3
2 x 20g/m = 40g/m	16.6	14.8
1 x 20g/m 1x40g/m = 60g/m	24.9	21.8
2x40g/m = 80g/m	33.2	28.0
7 x 12g/m = 84g/m (bundle)	21.6	23.3
9 x 12g/m = 108g/m (raft)	53.8	78.9
9 x 12g/m = 108g/m (bundle)	53.8	61.2
1/2 x Poladyn 31 Eco - 28mm	118.6	58.0
1 x Poladyn 31 Eco - 28mm	250.0	140.8
2 x Poladyn 31 Eco - 28mm	500.0	331.1
3 x Poladyn 31 Eco - 28mm	750.0	446.6

Fig. 4b. Table of results for bare charges

Conclusions

The modular design of the AMBP has proven to be versatile and easy to use. The main features are:

- Robust steel frame capable of suspending a range of ballistic masses
- Masses range from 15kg to 750kg (33lb – 1,650lb)
- Uses standard camera filming HD video at 30fps
- Data extracted using Tracker software
- Spreadsheet used to calculate the impulse based on derived equation
- Initial testing was conducted using two pendulum masses with explosive charge sizes ranging over three orders of magnitude
- Explosive quantities converted to a TNT equivalent allowed different types of explosives to be used
- Results showed a highly linear relationship

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