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Design and Development of a Modular Ballistic Pendulum for High-Impulse Measurement in Contact and Near-Field Explosive Loading

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ABSTRACT

Measuring impulse from explosive charges in contact and near-field configurations presents practical challenges due to wide variation in impulse magnitude. Ballistic pendula are widely used for impulse measurement, but many existing designs are limited to narrow operating envelopes or are poorly suited to repeated contact testing and tamped charge configurations. This paper describes the design of a modular ballistic pendulum (MBP) for measuring explosive impulse in contact and near-field configurations; experimental validation and impulse behaviour are addressed in companion papers. The apparatus employs a horizontal pendulum configuration with interchangeable masses on a single supporting frame, allowing the measurement range to be adapted to different net explosive quantities. A review and classification of existing ballistic pendulum designs is presented to justify the selected configuration. The apparatus design and geometric operating limits are described. The geometric limits of the apparatus are examined to determine the maximum effective stand-off distance for which measurements remain representative, governed by the relationship between blast footprint and striker plate area. The resulting apparatus provides a repeatable, reconfigurable platform spanning approximately 2–2000 N·s, with defined geometric constraints and practical tolerances for contact and near-field charge testing.

1 | Introduction

Accurate measurement of impulse from explosive charges is required to allow investigations of configurations where loading occurs at very short stand-off distances or in direct contact with a target [1]. In such configurations, peak pressure alone provides an incomplete description of the loading environment, as the duration of the interaction and the transfer of momentum play a dominant role in the resulting mechanical response.

Ballistic pendula have long been used to measure impulse from explosive and impact events [2–4]. However, many existing pendulum designs are optimised for a narrow range of charge

sizes or stand-off distances [3]. Scaling a single pendulum design to accommodate impulses spanning several orders of magnitude often results in impractical increases in structural size, mass or complexity.

This paper is concerned exclusively with the design rationale, construction and operating envelope of the Modular Ballistic Pendulum (MBP) for impulse measurement. Experimental validation is addressed in companion papers.

The work presented here describes the design and development of a MBP. The apparatus employs interchangeable pendulum masses, or bobs, mounted on a common frame, allowing the

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measurement range to be adjusted to suit the expected impulse. The design emphasises robustness, repeatability and operational practicality.

2 | Overview of Ballistic Pendulum Measurement Principles

If a mass is accelerated vertically, its free flight is defined by Newtonian physics and the maximum height is determined by the momentum given to the mass [5].

When the mass or bob is constrained to rotate about a fixed pivot, the system is a ballistic pendulum. The angular displacement can be translated into angular momentum.

For a pendulum of mass m , rotating about a fixed axis with an effective radius r , the impulse J may be obtained from the maximum angular displacement θ using Equation (1).

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

where J is impulse (N·s), m is the pendulum mass (kg), g is gravitational acceleration (m/s^2), r is the distance from the pendulum centroid to the rotational axis (m) and θ is the angular displacement (radians).

This formulation assumes that energy losses, such as those due to friction at the pivot, air resistance and structural compliance, are small compared with the kinetic energy imparted by the explosive event, and that the impulse transfer occurs sufficiently rapidly that the pendulum may be treated as stationary during loading. These assumptions define the operating regime of the ballistic pendulum and inform the design choices discussed in subsequent sections.

3 | Classification of Ballistic Pendulum Designs

Literature highlights four main designs for ballistic pendula [3, 6, 7]. Type 1 is one in which the bob is suspended vertically on a single pendulum arm with the impulse acting horizontally [8] but is not particularly scalable because the physical size of the mass needs to increase significantly if a larger mass is used [9].

The second design (Type 2) is a variant of Type 1, with two parallel pendulum arms supporting a longitudinal mass along its length [3, 4, 10]. This allows larger masses to be used by having a high z-axis to x/y axis ratio, thereby increasing the mass without increasing the surface area being subjected to the impulse. This configuration makes it easier to analyse and interpret the acquired video data but is a slightly more complex design that requires multiple suspension points and a means of levelling the frame and mass, however the range of measurements is dependent on the mass of the pendulum [3]. This configuration allows larger masses to be used without increasing striker surface area.

The third design (Type 3) is a pendulum in which a rigid pendulum arm is mounted horizontally, and the impulse is applied vertically [4, 5, 7, 11, 12]. Type 3 is particularly useful for measuring very high impulses from large charges but are not suspended

TABLE 1 | Summary of Ballistic Pendulum Designs.

Type of Ballistic Pendulum	Pros	Cons
Type 1	Simple to make	Does not scale well: ideally should be able to use different masses from a few tens of kg up to several hundred kg to be suspended
Type 2	Good for small tests of up to 100 g More scalable than Type 1 Suitable for testing charges ranging from a few grams up to several hundred grams	No major cons. Requires the mass to be swapped between scales, Requires lifting equipment to change masses
Type 3	Good for large-scale testing Additional mass can be added Compact design Good for charges buried in the ground	Hard to fix charges when in contact with mass Decelerating the falling mass can be hard
Type 4	Simple design Best suited to buried charges Can be made with large masses	Hard to fix charges when in contact with mass Large frames needed to support mass

from a frame. This design allows mass to be easily added to the pendulum to match the impulse. Fixing charges to the pendulum can be challenging as they need to be fixed to the underside.

The fourth design is not technically a pendulum but a restrained mass in free acceleration [8, 13, 15]. 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. Defence Research and Development Canada (DRDC) Suffield has a small test apparatus called the Piston Rig with a 47 kg mass which has been used for land mine blast testing with 25 g C-4 charges [14]. Sheffield University has a larger apparatus with a mass of 1,500 kg that is used for scaled (625 g PE4) testing of landmine impact on vehicles [1]. The even larger vertical impulse measurement fixture (VIMF) at the Army Research Laboratory (ARL), Aberdeen Proving Ground, MD has a 12.5 ton mass capable of full-scale (10 lb TNT) testing of anti-tank mines producing up to 95,000 N.s of impulse [7]. These are summarised in Table 1.

4 | Design Requirements and Target Operating Envelope

The present work focuses on contact and very small stand-off loading. It describes the design of a testing method for measuring impulse from contact and near-field explosive charges over a wide range of magnitudes.

The apparatus was therefore designed to provide:

- Survivability and rapid reset between successive shots
- Repeatability with consistent geometric boundary conditions
- Modularity to span a wide impulse dynamic range
- Compatibility with contact, near-contact and tamped charge configurations
- Controlled and well-defined stand-off geometry

When designing a ballistic pendulum, it is necessary to establish the approximate range of impulses that the system is required to measure. The open literature does not provide an envelope of impulse values spanning charge type and scale.

An initial scoping review of published impulse measurements was therefore undertaken to identify order-of-magnitude impulse levels relevant to contact and near-field explosive loading.

On the basis of this scoping assessment, the target operating envelope for the MBP was defined to span approximately 2–2000 N s.

4.1 | Bounding Impulse Requirements From Published Data

There is a paucity of available data for incident impulse from charges in direct contact or at very small stand-off distances. A literature review was conducted to find impulse measurements from different types of charge. At the lower end of the impulse scale, a data set for bare charges as small as 0.75 g reports impulse measurements as low as 2 N.s with a stand-off of between 58 and 87 mm [6]. Additional data for 10 g metal backed charges producing impulses of between 80 and 132 N.s at ranges of 40 and 50 mm [15].

Upper-bound impulse values were identified from an unrestricted report by the Battelle Memorial institute in which EOD Disruptors were tested using a large ballistic pendulum [5]. A summary of relevant measurements from the Battelle Report is given in Table 2. The reported impulses, reaching up to 8600 Ns from water-projecting charges with over 1700 g of sheet explosive at zero stand-off, represent conservative upper-end values.

While the upper-bound impulse values reported in the literature were used to ensure adequate structural capacity, typical contact and near-field tests involving small charges fall well below these extremes. Published data for PE4 and similar explosives in the 10–600 g range [4, 6, 15] indicate impulse levels of order 2–500 N.s, which lie within the operating range of the lighter and medium pendulum configurations. These mid-range values

represent most practical test conditions, with the upper-bound data providing a conservative design margin rather than a typical use case.

Based on the impulse data found in literature [5, 6, 15], a useful working range for a ballistic pendulum for future work would go from as low as 4 N.s to over 8600 N.s. The literature data this is based on is summarised in Table 3.

5 | Preliminary Scaling and Rejection of Alternative Concepts

A series of preliminary scoping trials were conducted. These involved attaching explosive charges to the underside of heavy steel plates such that they would be projected vertically (Figure 1). The maximum height to which they were projected was then used to estimate the approximate impulse from the charges.

These vertical impulse tests used charges ranging from approximately 30 g bare charge up to 400 g tamped with water which were fixed to the underside of steel plates weighing between 60 and 125 kg. The steel plates were projected vertically in free flight. The maximum height to which the plates were projected was estimated by scaling from video imagery (Figure 1). The impulse required to achieve that height was calculated. Estimated impulses ranged from 94 to 1250 N.s. Based on the camera resolution and manual video scaling used in these indicative tests, the uncertainty in the derived impulse is estimated to be in the order of $\pm 10\%$ – 20% .

It was found that attaching both bare and tamped charges to the underside of steel plates was challenging as the charges tended to pull away from the target. Pendulum Types 3 and 4 were therefore rejected.

6 | Modular Ballistic Pendulum Design

6.1 | Frame and Suspension System

Based on the findings of literature, a Type 2 design was selected (Figure 2b), comprising two parallel pendulum arms supporting a longitudinal mass along its length [3, 10]. This configuration provides a more scalable design in which increased mass can be achieved by extending the length of the mass, increasing its diameter or increasing the density, for example by adding weights. The pendulum arms can also be used to prevent torsional rotation meaning that the pivots can be made much less massive as they do not need to constrain twisting. The pendulum bob remains horizontal throughout the swing.

6.2 | Modular Mass Concept

One common problem of contact charge testing is the tendency for damage to occur to the apparatus due to the excessive forces produced by explosive charges [1, 16, 17] but the general robustness of the pendulum must be considered in the design. The mass of the pendulum must be matched to the size of the charge being fired to ensure the swing of the pendulum.

TABLE 2 | Battelle Pendulum Tests Performance Data (converted to metric units) (1).

Tool	Explosive Type	NEQ (g)	Stand-Off (mm)	Impulse (N.s)	Impulse/NEQ (N.s/g)
Bootbanger*	C-2 Sheet	431	0	2,438	5.7
Bootbanger	C-4 Sheet	860	0	4816	5.6
Exit *	C-2 Sheet	508	0	2271	4.5
Exit	C-4 Sheet	1025	0	4293	4.2
MLVD*	C-2 Sheet	861	0	4926	5.7
MLVD	C-4 Sheet	1755	0	8651	4.9
Bootbanger	C-2 Sheet	426	305	2269	5.3
Bootbanger	C-4 Sheet	862	305	4061	4.7
Exit	C-2 Sheet	521	305	1811	3.5
Exit	C-4 Sheet	1023	305	3166	3.1
MLVD	C-2 Sheet	902	305	3751	4.2
MLVD	C-4 Sheet	1752	305	5533	3.2

TABLE 3 | Range of Impulse Data from Literature.

Source	Charge type	Stand-off (mm)	NEQ		Impulse	
			(min) (g)	(max) (g)	(min) (N.s)	(max) (N.s)
Arnold (18)	Bare Charge	0	2	6	4.49	8.09
Fjällgren (2)	Bare Charge	58-87	2	49	2	75
Veldman (8)	Bare Charge	127	114	680	97.7	549.2
Curry & Langdon (17)	Metal-Backed	40-50	10	25	80	132
Battelle Institute (1)	Water-Tamped	0-305	355	1,755	264	8,651

**FIGURE 1** | (a) Charge positioned on underside of steel plate, (b) Steel plate projected vertically to estimate the impulse from explosive charges.

Spanning the required charge range—from a few grams to several 100 g would necessitate pendulum masses, making simple mass addition impractical. An alternative approach of achieving the desired range of use is to build a pendulum frame that has interchangeable masses which can be switched to best match the charge load or expected impulse. The pendulum length and mass

required to measure impulses Within different impulse ranges were calculated. The final selection of bobs with their masses is given in Table 4. A system capable of measuring 8500 N.s would require a 2.5 ton mass which would be impractical, however measuring up to 2,000 N.s would be possible with a 750 kg mass which is far more practicable.

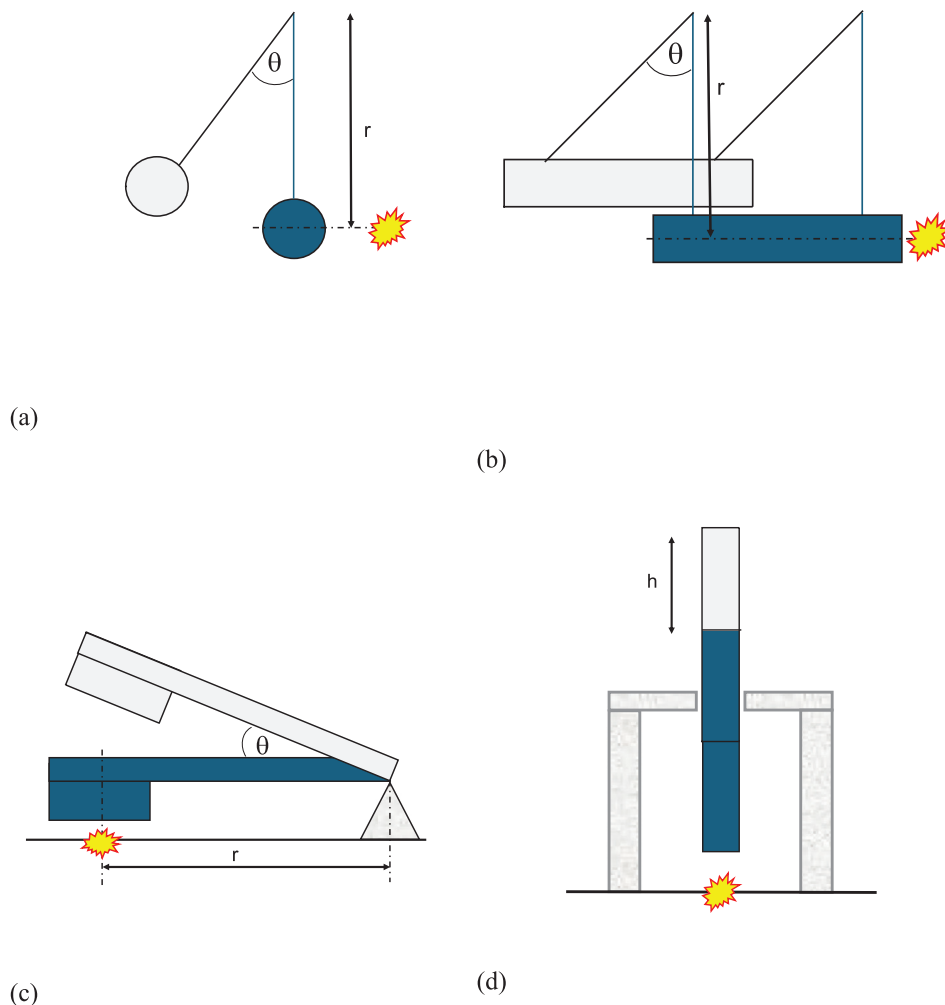


FIGURE 2 | Ballistic pendulum designs (not to scale) (a). Type 1 – simple horizontal pendulum, (b) Type 2 – horizontal pendulum with two supports, (c) Type 3 – vertical pendulum, (d) Type 4 – vertical impulse apparatus.

TABLE 4 | Summary of final pendulum bob (mass) details.

Mass	Chains / Cables (kg)	Gross weight inc. chains (kg)	Impulse range (N.s)	Striker Palate (mm)	Notes
V. Light	0.88	29	2 - 75	200x 400mm x 30mm x 1	Scaffold Pole (48.3mm OD, t. 4mm)
Light	0.88	114	7 - 300	200x 400mm x 30mm x 2	178 × 102 × 19 UB
Medium	15.4	328	20 - 850	200x 400mm x 30mm x 2	Fabricated I-section 270 × 260 × 20 × 20
Heavy	15.4	758	50 - 2000	400x 400mm x 30mm x 3	BLU-109 Bomb Case

6.3 | Pendulum Masses, Anvil Design and Structural Components

A steel frame 3 m long, 2 m high and a 1 m deep was constructed to support the mass as illustrated in Figure 3.

Four principal pendulum bobs were fabricated for the MBP: *very light*, *light*, *medium* and *heavy* (Table 5). The very light bob was

constructed from a pair of 1 m lengths of 60.3 mm OD with a 6.3 mm wall thickness, “scaffold” poles welded between end striker plates. The light and medium bobs were fabricated from Universal Steel Beam sections. Striker plates were welded onto either end of the central support member.

In this paper, the term ‘striker plate’ is used to refer to the steel plate forming the impact interface between the charge and the

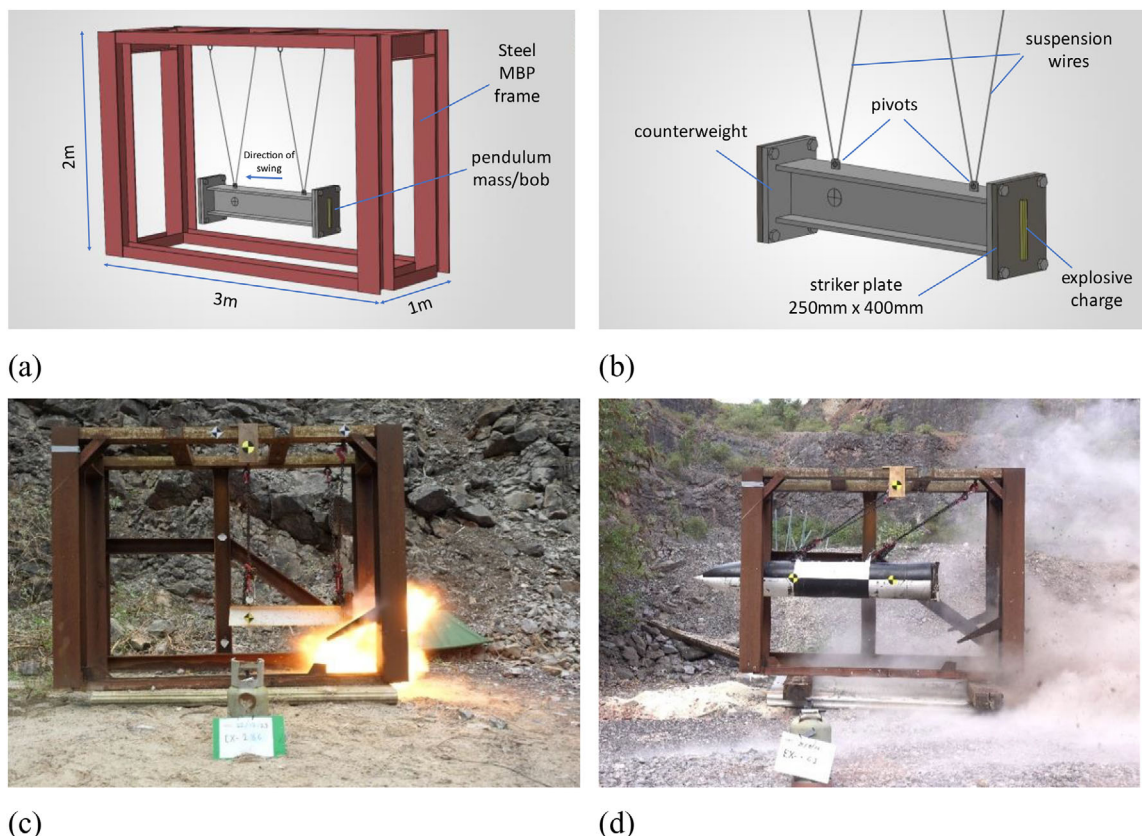


FIGURE 3 | (a) Illustration of MBP frame and mass, (b) The 86 and 170 kg pendulum masses are fabricated from forged I-beam sections and the explosive charges are fixed directly to the striker plate, (c) I-section 86 kg mass (d) The 763 kg mass is a repurposed BLU-109 bomb case shown with protractor overlaid for measuring angle of rotation can measure up to 2000 N.s.

TABLE 5 | Scaled Distance and example charge sizes and distances.

Scaled distance (m/kg ^{1/3})	Stand-off (m)	NEQ
0.3	5	4.6t
0.3	10	37t
0.3	20	296t
1.4	5	45kg
1.4	10	364kg
1.4	20	2.9t

pendulum mass. The striker plates on the small to medium mass bobs consisted of 250 × 400 × 30 mm steel plates with 20 mm holes drilled in each corner to allow the attachment of additional semi-sacrificial striker plates. These plates could be flipped or replaced if damaged without the need to repair the main pendulum mass. The charge sizes used were insufficient to cause bending or permanent deformation of the striker plates, which were strongly supported by the welded striker plates. Plates were typically reversed to present a fresh surface and were ultimately replaced once the surface became visually rough and pitted. In the blast and explosive loading literature, contact configurations refer to cases in which the explosive charge is placed in direct physical contact with the target surface and the term “near-field” is commonly used to describe small stand-off distances at which

the target interacts strongly with the detonation products and the resulting blast wave, and where classical far-field assumptions are not fully applicable [1]. This is sometimes simplified to lying “inside the fireball” while the far-field lies “outside the fireball” [18]. This is typically at scaled distances under 0.8 m/kg^{1/3} [19].

For near-field tests with suspended charges at stand-off distances between 100 and 800 mm, the rectangular striker plates on the light and medium bobs were replaced with pairs of circular steel discs approximately 500 mm in diameter and 40 mm thick.

The heavy bob was fabricated from an empty BLU-109 bomb case: A 400 × 400 × 30 mm steel striker plate was welded onto the base of the bomb casing, giving a total steel thickness of 90 mm. The total mass of the bomb pendulum, including suspension chains, was 758 kg. The bomb casing was fitted with aircraft suspension lugs spaced at 762 mm, and all pendulum bobs were standardised to use the same suspension spacing.

The range of swing angles that could be reliably measured using the optical tracking system was approximately 0.5° to over 45°, at which point the frame began to obscure the bob and chains. This angular range defined the effective operating range of the MBP and corresponded to a total measurable impulse range of approximately 2–2000 N.s across the different pendulum masses.

The final masses of all pendulum configurations are summarised in Table 5.

The lighter pendulum bobs were suspended using paired wire ropes rated to 2 ton. The heavier bob was suspended using a pair of standard two-leg lifting chain slings rated to 2 ton. This suspension arrangement provided additional torsional stability and limited rotation of the bob.

6.4 | Optical Data Capture

The MBP is designed to determine incident impulse from the maximum angular displacement of the pendulum mass following an explosive event. As such, the primary measurement requirement is the reliable determination of pendulum rotation.

A non-contact measurement interface was selected rather than a mechanical means of measuring the rotation. Optical recording of pendulum motion provides a robust and non-intrusive means of capturing angular displacement.

The pendulum geometry, suspension arrangement and frame layout were therefore designed to be compatible with optical tracking of the pendulum motion in a single plane.

The practical implementation of optical recording, including camera configuration, video analysis software and measurement accuracy, is addressed in a companion paper.

7 | Geometric Stand-Off Limits of the Modular Ballistic Pendulum

7.1 | Determination of Maximum Effective Stand-Off

Data from charges with stand-off distances between 150 and 800 mm were plotted as impulse versus net explosive quantity for Emulex 2+ and PE4 (Figure 4). For both explosives, linear behaviour was observed up to a stand-off approximately 400 mm, beyond which a plateau was reached. This behaviour indicates the maximum effective stand-off of the pendulum in the tested configuration. Secondary contributions from slab reflections cannot be excluded.

The Hopkinson–Cranz scaling law is defined as:

$$Z = \frac{R}{W^{\frac{1}{3}}} \quad (2)$$

where: Z = scaled distance, R = stand-off distance, W = charge mass. Impulse was plotted against Hopkinson–Cranz scaled distance on log–log axes (Figure 5).

The initial configuration of the MBP employed rectangular striker plates with dimensions of 250 × 400 mm. Rectangular striker plates were initially selected for compatibility with linear and strip-type contact charges.

Testing with charges at increasing stand-off distances highlighted a geometric limitation associated with the finite area of the striker plate. At stand-off distances approaching the geometric limit of

the system, an increasing proportion of the expanding blast front bypasses the rectangular striker plate.

For tests involving stand-off loading in the near-field and beyond, circular striker plates provide more uniform angular interception of the blast. Stand-off tests were subsequently conducted using 500 mm diameter circular striker plates to improve angular interception at larger stand-off distances.

Rectangular plates remained suitable for contact testing, while circular plates were preferred for stand-off measurements. Based on the observed behaviour, stand-off distances up to approximately 250 mm are recommended as the standard operating range for stand-off testing in the present configuration. The fraction of the expanding blast intercepted by the pendulum decreases as stand-off increases and the angular extent subtended by the plate reduces. When the angle between the charge centre and the outer edges of the striker plate falls below approximately 50°–55°, a substantial proportion of the expanding blast front bypasses the pendulum.

The observed behaviour indicates that angular interception provides a useful qualitative guide to the geometric limits of impulse measurement for finite striker plates. For the rectangular plate configuration shown in Figure 6, this consideration corresponded to a practical upper stand-off limit of order 400 mm.

As shown in Table 5 the equivalent charge sizes and distances that represent the maximum typical range of scaled distances used with the pendulum (0.3–1.4 m/kg^{1/3}) and the top-end of scaled distances used during testing.

8 | Instrument Limitations and Measurement Considerations

The MBP was developed to provide a practical and robust method for measuring impulse from contact and near-field explosive charges over a wide range of magnitudes. Several limitations and sources of measurement sensitivity exist. These are discussed here. A detailed uncertainty analysis and experimental validation of the optical measurement approach and impulse derivation are presented in a companion paper (Table 6).

8.1 | Frame Motion and Support Conditions

The MBP frame is constructed from universal steel beam and U-section members with a total mass exceeding 500 kg. The frame was ultimately mounted to a reinforced concrete base.

For experiments conducted with the light and medium pendulum masses (bobs), no observable frame motion occurred. For test firings involving the heaviest pendulum mass (BLU-109) and larger charge sizes, however, limited motion of the support structure was observed at large swing amplitudes. In particular, for angular displacements exceeding approximately 15°, the frame exhibited visible torsional deformation.

Such deformation effectively alters the boundary conditions at the pendulum supports and represents a practical upper limit to

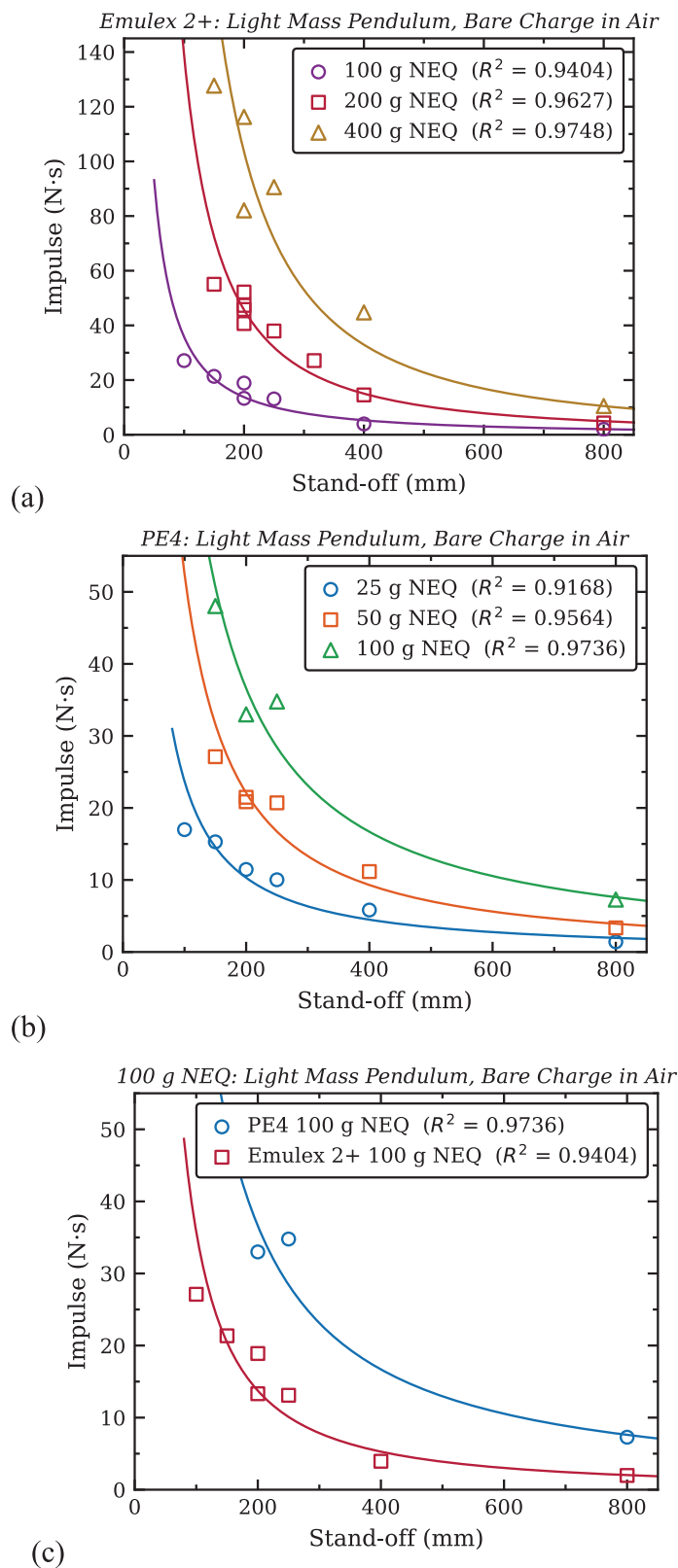


FIGURE 4 | Measured impulse as a function of stand-off distance for selected fixed charge masses. (a) Emulex 2 charges and (b) PE4 charges for 25, 50 and 100 g net explosive quantities (NEQs). In both cases, approximately linear behaviour is observed up to stand-off distances of order 400 mm, beyond which the measured impulse deviates from the initial trend, consistent with geometric under-capture associated with the finite striker plate dimensions. (c) Comparison of impulse measurements for 100 g charges of Emulex 2 and PE4.

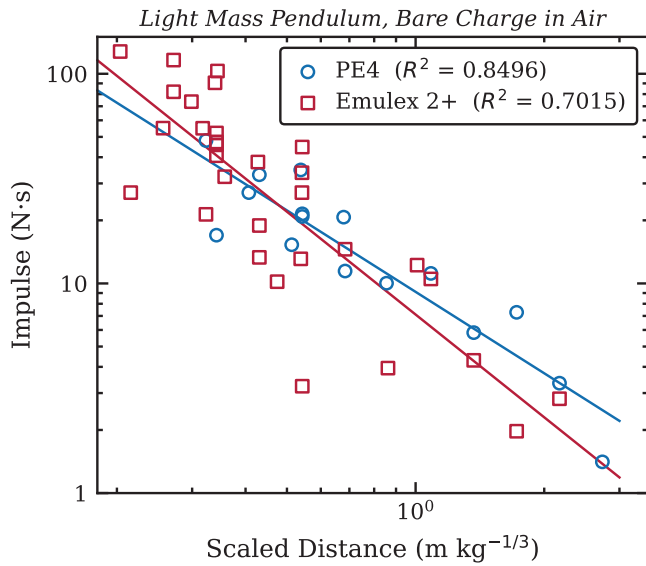


FIGURE 5 | Impulse as a function of Hopkinson–Cranz scaled distance for Emulex 2+ and PE4, plotted on log–log axes. The figure includes the combined dataset across multiple net explosive quantities and stand-off distances. When expressed in scaled-distance form, the data for both explosive types follow approximately linear trends over the range tested, consistent with power-law behaviour.

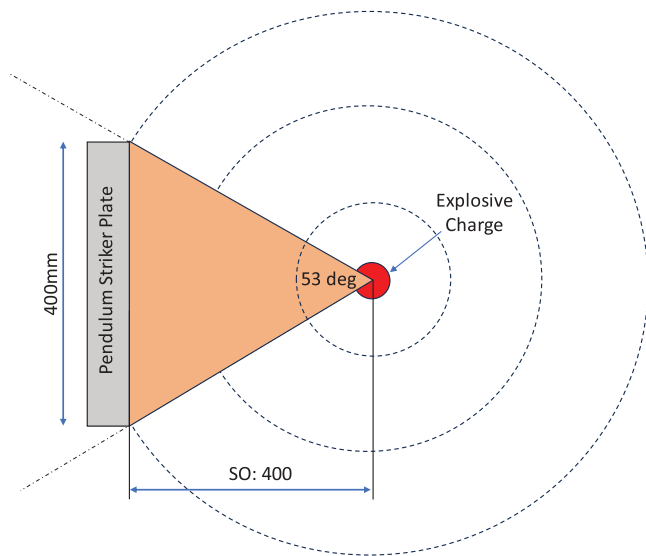


FIGURE 6 | Illustration of angular interception for a rectangular striker plate: the arc centred on the explosive charge subtends an angle of approximately 53° at a stand-off distance of 400 for a 400 mm wide plate, beyond which geometric under-capture becomes significant.

the usable angular range for the heaviest mass configuration. On this basis, angular displacements of approximately 15° define the upper operating limit for the heavy (BLU-109) pendulum mass.

It represents a known limitation of the current configuration. Further mitigation could be achieved through increased frame stiffness, additional lateral bracing or increased foundation mass. The lighter pendulum masses remained well within the rigid-frame regime.

TABLE 6 | Calculations of expected impulse for different pendulum length and mass and angles helped design the pendulum.

Target Impulse (Ns)	Length of pendulum (m)	Pendulum mass (kg)	Angle (Deg)
5	1.5	50	3.7
20	1.5	150	2
100	1.5	50	30
100	1.5	150	10
100	1.5	750	2
150	1.5	50	46
500	1.5	150	46
500	1.5	750	10
1000	1.5	750	20
2000	1.5	750	41
8500	2	2500	45

8.2 | Sensitivity to Charge Alignment

Explosive charges are ideally positioned on the central axis of the pendulum striker plate. Small deviations from the centreline were observed to have a limited influence on the measured impulse.

Larger offsets, particularly those approaching the edges of the striker plate (extreme case), can induce yaw or torsional motion of the pendulum mass and may reduce the apparent impulse by up to 10%. Charges should therefore be positioned within approximately ± 40 mm of the centreline of the striker plate.

8.3 | Mechanical Losses and Pivot Friction

The suspension system introduces minor mechanical losses associated with friction in the lifting hardware; however, these were not considered to dominate the measured impulse trends.

8.4 | Striker Plate Surface Condition and Erosion

Repeated firings resulted in gradual pitting and erosion of the mild-steel striker plates. The striker plate was designed as a semi-sacrificial component that can be rotated or replaced. Plates were rotated or replaced once surface roughening became visually significant.

No systematic change in measured impulse was observed as the striker plate surface condition degraded. The use of replaceable striker plates therefore provides a practical means of maintaining consistent contact conditions.

9 | Conclusions

A MBP has been designed to enable impulse measurements from explosive charges in contact and near-field configurations

over a wide range of magnitudes. The design is based on a horizontal pendulum configuration with interchangeable masses, allowing the measurement range to be adapted to different charge sizes.

A review of existing ballistic pendulum configurations was used to inform the selection of a dual-arm horizontal design that offers favourable scalability, torsional stability and practical robustness for contact testing. The resulting apparatus can measure impulses from 2 N.s to approximately 2000 N.s across contact and near-field regimes.

The geometric limits of the apparatus were examined to establish a maximum effective stand-off. For the current striker plate dimensions, this limit was found to be approximately 400 mm, beyond which a significant proportion of the blast does not interact with the pendulum.

Known limitations including frame motion, charge alignment, mechanical losses and striker plate surface erosion define practical operating tolerances.

The MBP provides a practical and adaptable platform for comparative impulse measurements from contact and near-field explosive charges.

Acknowledgments

The authors have nothing to report.

Ethical Statement

The authors confirm that this manuscript is original, has not been published previously, and is not under consideration elsewhere. The work presented reflects the authors' own research and analysis and is reported accurately and in full. All contributors who meet authorship criteria are appropriately credited, and all authors have made substantial contributions to the work and approve the submitted version. Relevant prior work is properly acknowledged, and all sources are cited in accordance with academic standards. The authors confirm compliance with the publication's ethical policies and accept responsibility for the integrity of the work.

AI Use Declaration

Large language models were used as structured dialogue tools during the development of this work. Specifically, ChatGPT (OpenAI), Google Gemini (Google DeepMind) and Grok (xAI) were used to assist in organising author-generated notes, developing manuscript structure and section framing and refining phrasing. All outputs were treated as provisional and were not incorporated without critical assessment and substantive modification by the authors. The authors conducted iterative review and refinement to ensure technical accuracy and coherence. The conception of the work, interpretation of results, synthesis of arguments, all technical positions and final technical conclusions, and all literature identification and referencing remain the authors' exclusive original intellectual contribution. AI tools were occasionally used to suggest potential literature directions; however, all sources were independently identified, retrieved and verified using conventional academic databases, and no AI-generated references have been included. These tools were not used for citation generation or as sources of factual authority. All technical content has been independently verified by the authors, who assume full responsibility for the accuracy, originality and integrity of the work.

Conflicts of Interest

Roland Alford has a relationship with Alford Technologies Ltd, including board membership, employment, equity ownership, non-financial support and travel reimbursement. He is also the majority shareholder, Chairman and CTO of the Alford Group. Roland Alford is named on patents held by Alford IP Ltd.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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