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# Generated datasets from dynamic reproduction of projectiles in ballistic environments for advanced research (DROPBEAR) testbed

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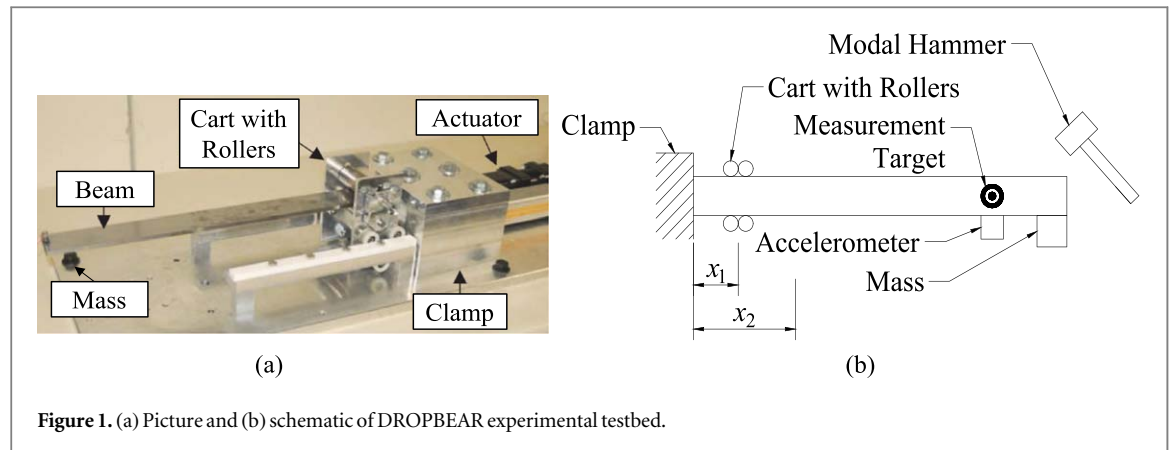
## Abstract

High-rate dynamics occur when a system's acceleration is larger than 100  $g_n$  over durations less than 100 ms. Structural health monitoring algorithms must be created for high-rate dynamic systems to maximize safety and minimize economic losses. There is a need to evaluate these algorithms for precision and accuracy prior to real-world implementation. An experimental testbed was created to simulate large-magnitude events while maintaining repeatability to accurately and robustly assess various structural health monitoring algorithms' capability to monitor high-rate dynamic systems. All previous datasets created on the experimental testbed are discussed, examining various sensor setups, excitations, and boundary condition changes to properly simulate near-high-rate events and provide robust experimental data to evaluate structural health monitoring algorithms.

## 1. Introduction

High-rate dynamic systems are defined as systems experiencing accelerations greater than 100  $g_n$  over a very short period of time, often less than 100 ms [1]. Examples of high-rate systems include adaptive airbag deployment systems, hypersonic vehicles, ballistic explosion events, and active blast mitigation mechanisms. The dynamics of these systems are uniquely defined by (1) large uncertainties in the external loads, (2) high levels of non-stationarity and heavy disturbances, and (3) unmodeled dynamics generated from changes in the system configurations, as described in an introductory paper [2].

Developing feedback capabilities for high-rate systems is critical to ensure safe and reliable operations. This includes producing state estimators with sub-millisecond capabilities, also known as high-rate structural health monitoring (HR-SHM). Given their large levels of complexities and uncertainties, an important first step towards their full-scale enablement is a rigorous evaluation on realistic datasets. The Air Force Research Laboratory Munitions Directorate has engineered a unique testbed to generate reproducible datasets for researchers pursuing the area of high-rate structural health monitoring (HR-SHM). The testbed is known as DROPBEAR, or Dynamic Reproduction of Projectiles in Ballistic Environments for Advanced Research, introduced in [3]. It consists of a cantilevered beam equipped with a rolling cart to reproduce fast changes in boundary conditions and an electromagnetic mass attached at its tip to reproduce a fast change in mass. While DROPBEAR is not a true high-rate system as defined by the HR-SHM community [4], it importantly provides researchers with datasets to test the critical time constraint posed by the HR-SHM problem, with the challenge to detect and estimate changes in boundary conditions and/or masses.



**Figure 1.** (a) Picture and (b) schematic of DROPBEAR experimental testbed.

Over the last few years, several datasets have been produced and utilized by different researchers in the HR-SHM community [5]. The objective of this paper is to synthesize the DROPBEAR datasets and disseminate their availability to researchers, along with providing a complete description of research efforts that leveraged DROPBEAR data, which will be useful for benchmarking future efforts.

## 2. DROPBEAR testbed

The DROPBEAR testbed, illustrated in figure 1, is described in detail in [3]. Briefly, it consists of a steel beam of rectangular cross-section clamped at one extremity, thus creating a cantilevered system. Note that the setup could be modified to have several different boundary conditions: clamped-free, clamped-clamped, clamped-pin-free or that the mass could be placed at different locations. The dataset presented is limited to the clamped-free or clamped-pin-free configurations. The beam is 51 mm (2 inches) wide, 503 mm (19.82 inches) in length, and 6.3 mm (0.25 inches) in thickness. It is equipped with a servo-controlled rolling cart (the pin boundary condition) and an electromagnet-controlled mass to mimic nonlinear changes in dynamics arising from a high-rate event. The cart can slide along the beam to reproduce a change in boundary conditions which results in a sudden change in stiffness. The electromagnet can be deactivated during tests to reproduce a change in mass.

Figure 1(a) is a picture of the DROPBEAR testbed showing the cantilever beam, detachable mass, clamp, and actuator. Figure 1(b) is a schematic of the 503 mm long cantilever beam highlighting the cart with rollers, impact hammer, and an example of a setup with an accelerometer and laser vibrometer target at 400 mm.

Several datasets were collected on DROPBEAR over nine different test setups. A PCB 086C01 modal hammer was used (in some test setups) to excite the beam to simulate external forces impacting the system. The beam's responses to the servo-controlled rolling cart, electromagnet excitation, and modal hammer force are recorded using multiple sensors that include accelerometers (acceleration states), strain gauges and an extensometer (strain state), and a laser vibrometer (velocity states). PCB 353B17 accelerometers were used for all datasets along with Kyowa KSPB-1-350-E4 semiconductor strain gauges and a Polytec laser Doppler Vibrometer (OFV323 with OFV-3020 controller) where applicable. All datasets, except for those under test setup 9, were collected using a Precision Filters 28 000 signal conditioner and recorded using a National Instruments NI 6133 card combination where the extensometer was the only sensor directly connected to the NI 6133 card. The accelerometers and modal hammer used precision filters 28 304 IEPE card, and strain gauges used precision filters 28 144 card. Datasets from test setup 9 used an NI cDAQ-9172 with two NI 9234 cards to record the accelerometers and modal hammer. Additionally for test setup 9, high-speed videos, used for displacement measurements, were captured at 30,000 FPS with a Phantom v1612 camera. All datasets had a sampling frequency of 25 kHz except for datasets produced under test setup 5 that had a sampling frequency of 1 kHz.

## 3. Available datasets

Table 1 summarizes the different test setups used in generating data. Different boundary conditions and mass conditions were investigated, marked with an 'x' in the table. Some test setups had the cart move back and forth between two different locations (from location  $x_1$  to location  $x_2$  and back to location  $x_1$ , identified as  $x_1$ - $x_2$  in the table), some had the cart at a fixed location ('static'). Some test setups with the sliding cart ('Dynamic cart') also include data taken over static locations. Some test setups had the beam equipped with a mass at the tip ('Mass'), some without a mass at the tip ('massless'), and some with the mass at the tip being drop during tests ('Mass

**Table 1.** DROPBEAR test setups used in generating datasets.

Test setup	1	2	3	4	5	6	7	8	9
Cart positions (mm)	47-147	50-200	50	50-200	50-200	50-200	100-300	50-200	48-168
1st frequency (Hz)	14.2-34	17.7-31	17.7	17.7-31	17.7-31	17.7-31	25-37.5	17.7-31	17.2-37.6
Static cart	x	x	x	x	x	x			x
Dynamic cart	x				x	x	x		x
Single hammer	x	x	x	x	x	x	x	x	x
Multi hammer						x	x		x
Mass	x	x	x	x	x	x		x	
Massless		x			x	x	x		x
Mass drop	x					x			x
Accelerometers	4	2	2	2	1	1	1	2	5
Strain gauges	0	0	0	9	2	2	2	9	0
Laser vibrometer	0	0	0	0	1	1	1	0	0
Extensometer	0	0	0	0	0	0	1	0	0
Number of tests	62	65	40	20	29	16	13	10	83

drop'). The measured first natural frequency range over the span of boundary conditions under each test setup is also listed in table 1. When the modal hammer was used to excite the beam, some test setups used a single hit ('Single hammer'), and some test setups used multiple hits ('Multi hammer'). During testing, the hammer on occasion would double tap the beam; user verification may be needed on a test-by-test basis for analysis. Table 1 also lists the number of available states through the number of sensors used in taking measurements. For all tests where the impact hammer excitation was used, the DAQ and moving cart (if used) were triggered based on the impact measured by the hammer using a pre-trigger of 250 ms–1 s. When the impact hammer was not used, the moving cart was manually triggered and the DAQ was triggered on the accelerometer measurement with an appropriate pre-trigger based on the test configuration. The nine test setups are described in more details in what follows.

Test setup 1 used four accelerometers (PCB 353B17) placed 200, 300, 400, and 500 mm from the clamp. Test setup 2 used two accelerometers (PCB 353B17) placed 300 and 400 mm from the clamp. These tests were conducted using the cart at static locations, namely 50, 100, 150, and 200 mm from the clamp. Test setup 3 used two accelerometers (PCB 353B17) placed 300 and 400 mm from the clamp. This setup kept the cart at 50 mm with the mass on the beam at all times. Test setup 4 used two accelerometers (PCB 353B17) placed 300 and 400 mm from the clamp and added nine strain gauges at 25, 75, 125, 175, 225, 275, 325, 375, and 425 mm from the clamp. These tests provided static cart action, 50 and 200 mm from the clamp. Test setups 5-7 used one accelerometer (PCB 353B17), two strain gauges, and a laser vibrometer, all 306 mm from the clamp. Test setup 7 used in addition an extensometer at 306 mm to measure the beam deflection. Test setup 8 used two accelerometers (SN 127 691 and 139 351) placed 300 and 400 mm from the clamp and nine strain gauges 25, 75, 125, 175, 225, 275, 325, 375, and 425 mm from the clamp. The beam was not equipped with a cart, but had an electromagnetic mass and a hammer excitation. Test setup 9 used 5 accelerometers (PCB 353B17) placed 200, 300, 400, and 500 mm from the clamp. Videos, with example image stills shown in figure 2, were recorded for this test setup to visualize the high-rate dynamic response.

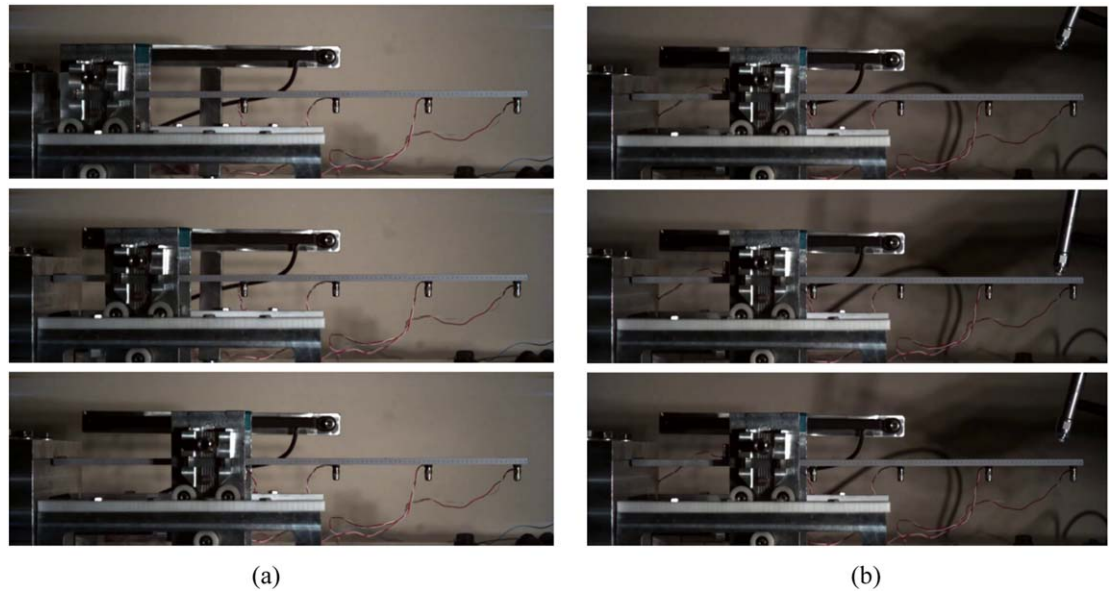
Overall, the DROPBEAR datasets are a robust combination of complex cantilevered beam systems with multiple sensor configurations to simulate repeatable high-rate dynamics.

### 3.1. Example data of HR-SHM dataset

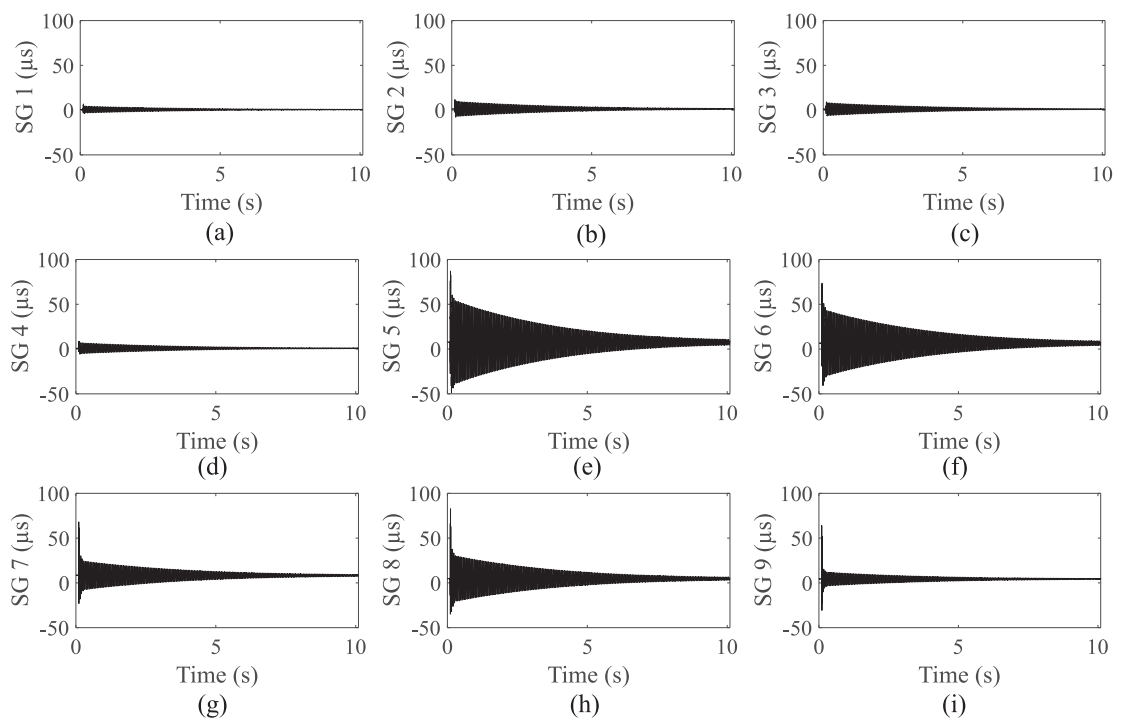
Figure 3 plots example measurements, here taken from the nine strain gauges (SG) used over test setup 4 (test #1). Data was taken under free vibrations after a modal hammer impact at the end of the cantilever. The largest amplitudes are under strain gauges 5 through 8 spanning 225 mm to 375 mm from the clamp.

Figure 4 plots example unfiltered data showing acceleration, velocity, and strain during cart movement, here taken from test setup 6 (test #12). This particular test did not use a hammer impact excitation. Measurements exhibit large and rapid changes as the cart moves back and forth along the beam. Only one test was conducted for this test condition. The large velocity spikes seen in the zoomed-in view appear to be an artifact of noise, whereas the spikes occur when the cart is stationary.

Figure 5 plots a typical acceleration signal from a moving cart under multiple hammer excitations, obtained from test setup 7 (test #12). In between the hammer impacts, the system undergoes free vibrations. The two zoomed-in portions each show 50 ms of the acceleration signal. The zoomed-in portion beginning near 0.6 s exhibits oscillations of higher frequencies, likely attributable to the cart movement, which is not observable when the cart is at rest as shown in the zoomed-in portion beginning around 1.25 s.



**Figure 2.** Image stills showing the DROPBEAR testbed with (a) a moving cart and (b) a hammer impact.



**Figure 3.** Example measurements from strain gauges used in test setup 4, with strain gauges located (a) 25 mm, (b) 75 mm, (c) 125 mm, (d) 175 mm, (e) 225 mm, (f) 275 mm, (g) 325 mm, (h) 375 mm, (i) 425 mm from the clamp.

#### 4. Results using DROPBEAR data

Data generated from the DROPBEAR testbed have been utilized in literature to evaluate the performance of algorithms towards realizing HR-SHM. Joyce *et al* [3] performed state estimation using a sliding mode observer. The study focused on estimating the cart position during location transition and showed convergence over 1 s. Hong *et al* [6] used DROPBEAR data to develop an analytical solution to a cantilever beam equipped with a mass at its tip and a moving boundary condition (i.e., moving cart). Downey *et al* [7] constructed a parallelized

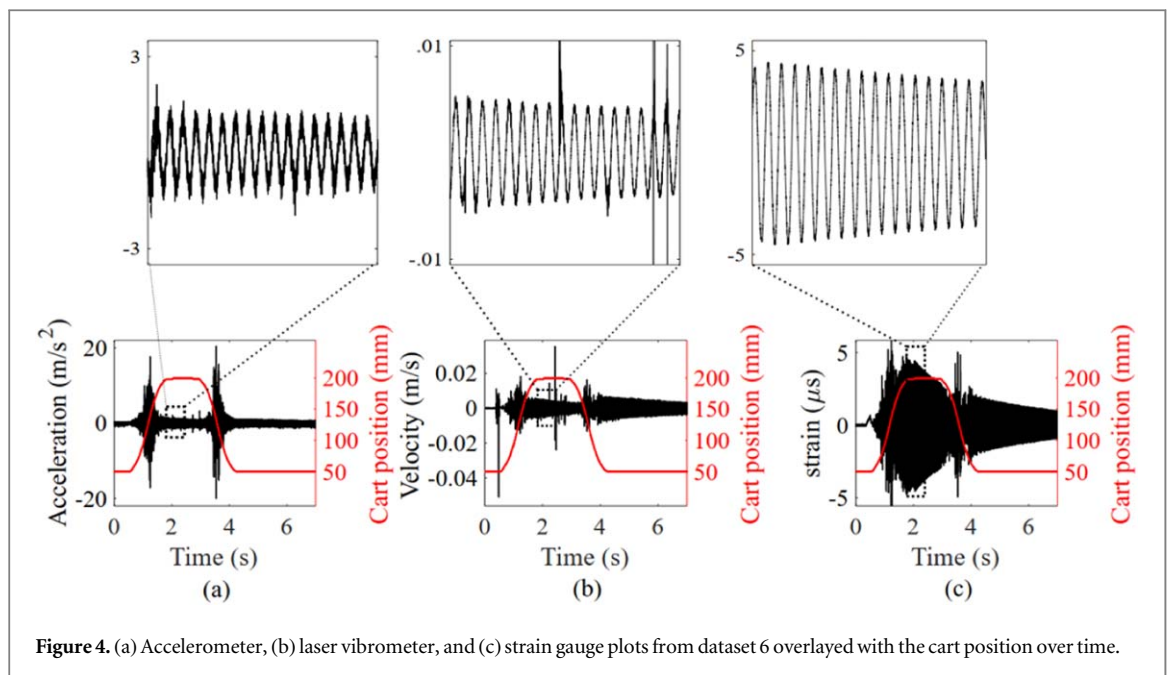


Figure 4. (a) Accelerometer, (b) laser vibrometer, and (c) strain gauge plots from dataset 6 overlaid with the cart position over time.

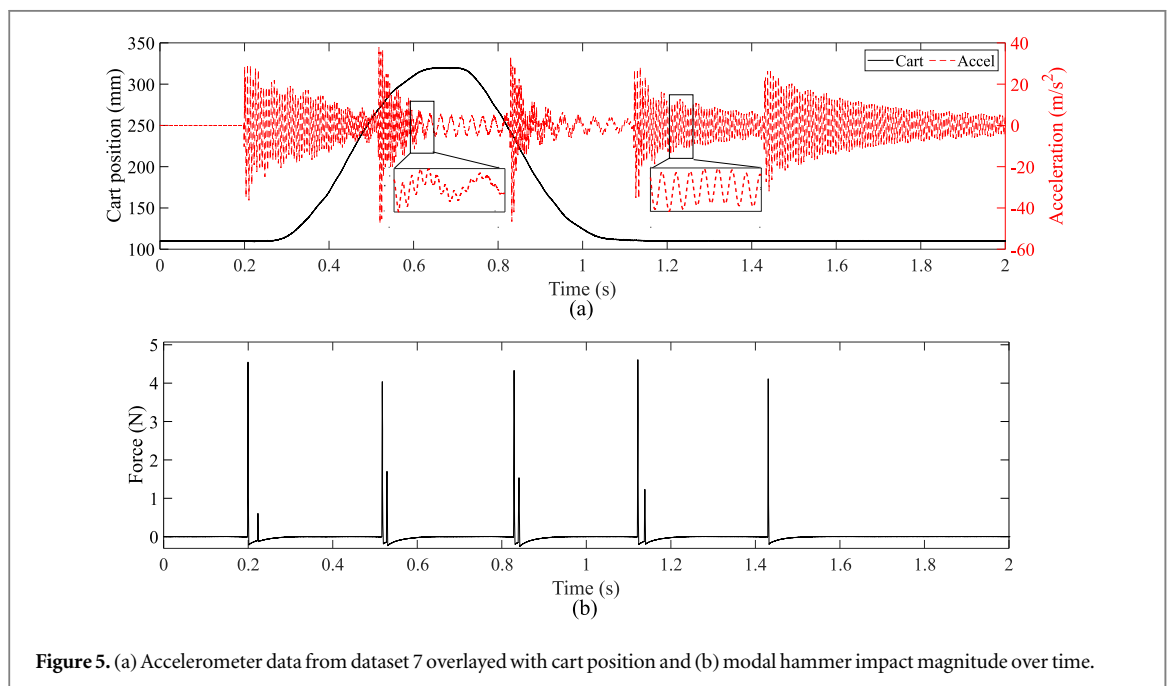


Figure 5. (a) Accelerometer data from dataset 7 overlaid with cart position and (b) modal hammer impact magnitude over time.

residual minimization model updating technique to track the system's lowest frequency in real time with reported computation speeds of 4.04 ms per time step. Yan *et al* [8] selected various frequency extraction techniques for DROPBEAR data and examined their applicability to HR-SHM. Yan *et al* [9] conducted real-time state estimation using a sliding mode observer (SMO) and showed computation time of 95  $\mu\text{s}$ . Nelson *et al* [10] combined Yan's SMO with an ensemble of recurrent neural networks (RNNs) to construct a hybrid predictive algorithm with zero timing deadline. Lander *et al* [11] studied an algorithm to approximate the input time history to DROPBEAR using acceleration only output measurements.

## 5. Conclusion

This paper presented unique datasets produced using the Dynamic Reproduction of Projectiles in Ballistic Environments for Advanced Research testbed (DROPBEAR), made available to the research community.



## Acknowledgments

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## Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI:[https://github.com/High-Rate-SHM-Working-Group/Dataset-6-DROPBEAR\\_data](https://github.com/High-Rate-SHM-Working-Group/Dataset-6-DROPBEAR_data).

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