Chapter 8
Measurement and Visualization of Nonlinear Vibration Response Using Neuromorphic Event-Based Sensing

Gabriella Gallegos, DaJae Doral, Suzanna Gilbert, Deborah Fowler, Fernando Moreu, Benjamin Moldenhauer, and Tariq Khraishi

Abstract Accurately capturing full-field vibration responses provides valuable insight for understanding nonlinear structural dynamic behavior, particularly in systems with large deflections, contact interactions, or bolted joints. However, when it comes to monitoring nonlinear systems, traditional sensors have limitations like limited spatial coverage and constraints on sensor channels, which can make it difficult to capture the full complexities of the system. In this research, we propose using neuromorphic event-based cameras to capture high-resolution, low-latency, and asynchronous data for structural responses of a nonlinear system in a laboratory setting. The test structure, consisting of a wing with an attached pylon, exhibits nonlinear behavior. This behavior is driven by impacts that occur between the attachment blocks of the pylon structure during the dynamic response. Using a neuromorphic event-based camera the full pylon structure was imaged. Using post-processing techniques, a region of interest within the images can be selected. These regions of interest enable the extraction of dynamic response from various areas of the structure using a single data set. This study compares vibrational responses from modal expansion results, accelerometer data, and neuromorphic event-based sensing data of the structure. The results of each method were comparable, supporting the development of advanced structural monitoring techniques using neuromorphic event-based sensing suited for low-latency applications such as vibration control and digital twin implementations.

Keywords Neuromorphic imaging · Event-based sensor · Region of interest (ROI) · Modal expansion · Nonlinear dynamics · Accelerometers · Asynchronous sensing.

Introduction

An understanding of the vibrational behavior of structures is necessary to predict their performance and failure. In industry, there is a significant focus on studying linear behavior of structures as robust tools exist for such characterization. Many structures exhibit significant nonlinear vibration responses due to large deflections, contact between parts, nonlinear material properties, or other sources of nonlinear physics. This nonlinearity can have a significant effect on the performance of these structures. Thus, this study is motivated by investigating the challenging task of characterizing nonlinear structural responses.

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Conventionally, analogue sensors like piezoelectric accelerometers have been used to measure structural responses. These sensors are limited by their invasive nature, with mass-loading effects often modifying the dynamic behavior of the structure. Additionally, they are difficult to implement on thin features and/or unsmooth surfaces and only provide a local measurement. Contactless measurement techniques such as laser doppler vibrometers (LDV), and digital image correlation (DIC) have also been used conventionally and can provide a more global measurement of structural responses. LDVs are comparable in their accuracy to accelerometers but are costly and are limited to discrete measurement points, requiring a time-intensive repetitive test procedure when a full-field response is required. DIC produces high accuracy, full-field characterization, but involves structure surface preparation, requires the use of expensive high-speed cameras for capturing dynamic events, and is computationally expensive, requiring extensive post-processing to achieve response data.

An emerging type of optical sensor, neuromorphic event-based sensors are characterized by their ability to capture high resolution, low-latency data with micro-second range temporal resolution [1]. Unlike traditional cameras, these sensors only detect changes in light intensity. When the change in light intensity across a given pixel on the sensor is over the determined threshold, data is recorded. These changes are recorded as asynchronous “events” and occur on a pixel-by-pixel basis. Light intensity shifts can occur on the surface of a structure due to displacement. This detection of displacements can be used for vibration response studies. Some studies have been conducted using neuromorphic sensors for measuring the vibrational responses of cantilever beams [2–3], objects on a shaker table, and a speaker diaphragm [4]. This work proposes the use of neuromorphic sensors to study a more complex, nonlinear structure. This study investigates the use of neuromorphic sensors to capture light intensity shifts of a nonlinear structure and resolve frequency responses which can change drastically with response amplitude in systems exhibiting nonlinear behavior. Various processing techniques were used to isolate and resolve various frequency responses of different regions of interest using a single data set. In addition to resolving frequency response, the structure was visualized using frame reconstruction techniques.

Approach

Three methods were used in this study to measure the nonlinear response of a wing-pylon structure: (1) accelerometers, (2) neuromorphic sensing, and (3) a modal expansion technique.

Experimental Set-Up for Vibration Tests

The structure under investigation in this study is comprised of a wing-shaped plate secured to a large aluminum block on one end, with a pylon attached to the opposite tip. The pylon consists of two upper blocks, a narrow strip running down the center of the blocks, and a lower block attached to the bottom of the strip as shown in Figure 1.

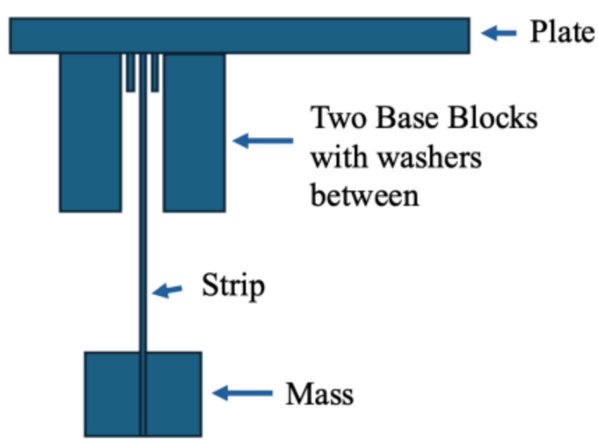
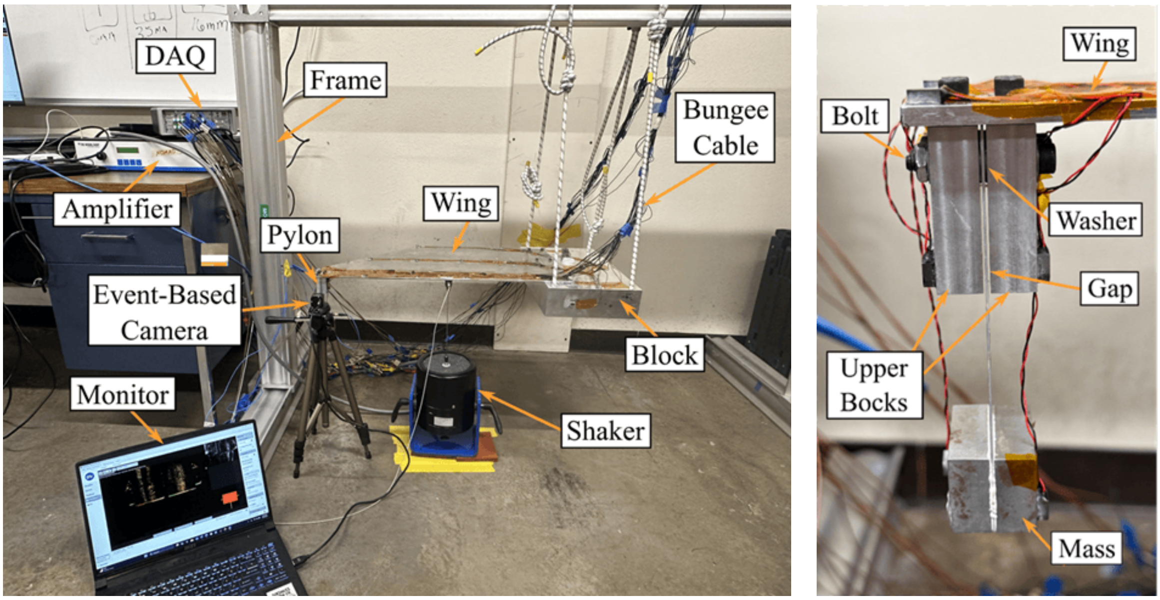


Fig. 1 Schematic of pylon structure

The entire structure was suspended using bungee cords to simulate free-free boundary conditions. A mesh of 24 uniaxial accelerometers was attached to the wing plate, block and pylon. A load cell was attached to the underside of the wing plate at the drive point, and a floor-mounted shaker was attached to the load cell. Force and acceleration responses were recorded by Siemens Testlab [5] and a Simcenter SCADAS Mobile data acquisition system. A neuromorphic camera (DVXplorer Mini by Inivation) was mounted to a tripod and pointed directly at the pylon from a distance of a few centimeters. Data from the camera was collected using the DV software [6]. The wing-plate structure, pylon, and experimental setup are shown in Figure 2.



(a) (b)

Fig. 2 Experimental setup (a) and close-up of pylon structure (b)

The goal of this testing was to excite motion in the pylon at large enough amplitudes to cause contact to occur between the pylon strip and upper blocks. Then, both accelerometer and neuromorphic sensor measurements were taken to investigate if these sensors could measure the onset of contact. The structure was driven near resonance of a mode that induces large deflection of the pylon strip (∼94 Hz) via constant sine excitation for a period of 20 seconds. This was repeated at four different forcing levels: 1.9, 4.8, 5.5 and 5.7 N. The two lower force levels did not induce contact between the strip and upper blocks, and the two upper force levels did induce contact. Note, the driving frequency was not adjusted as the excitation level increased, because the mode of interest was known to not experience a significant frequency shift within the amplitude range observed. At each force level, data was recorded simultaneously with both the accelerometers and the event-based camera.

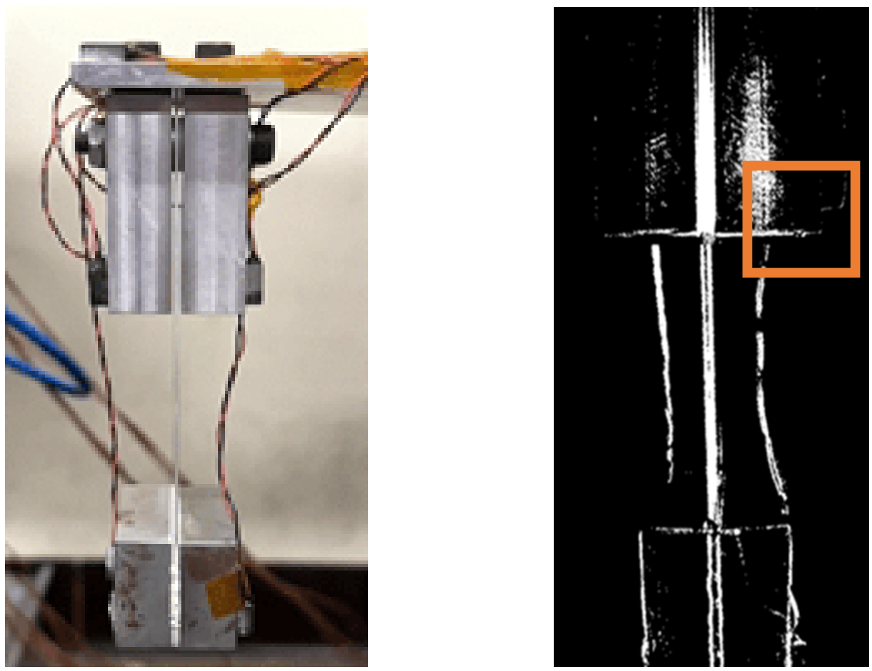
Event-Based Sensing

The camera used in this study was an event-based sensor by Inivation, the DVXplorer Mini. Event-based sensors are differentiated from conventional camera sensors by their ability to record asynchronous data in the form of “events” based on changes in light intensity rather than uniform frames of light intensities. Each event has an associated time stamp, x and y pixel coordinate, and a positive or negative polarity. An event is detected based on a light intensity change threshold. When a change in light intensity occurs over a given pixel that is greater than the defined threshold, an event at that location is generated. The event is positive or negative depending on if the light intensity increased or decreased. As the structure is vibrating, positive and negative events are generated and exported into a data stream. Using this data stream and processing techniques, the frequency behaviors of the structure can be resolved.

Results and Analysis

Camera post-processing

Due to data being collected asynchronously, event-based data packages require unique processing techniques. The neuromorphic sensor captured the entirety of the pylon structure during each experiment in this study. To characterize the frequency behavior of specific areas of the pylon structure, event-based data was parsed into smaller packages. This data parsing was done by creating regions of interest (ROIs) defined by sensor pixel dimensions. For each ROI, only events generated within the bounds of the region are considered in the analysis. To define a ROI, event frame reconstruction is conducted. This process involves using the positive events measured over a determined time frame of recorded data. By mapping all of the positive events in their respective pixel locations in white, an image of the structure can be constructed. This image is used to hand-select a rectangular region of interest on the structure and resolve the corresponding dimensions in pixels of the area. Figure 3 features images of the pylon using a conventional camera on the left, while the frame using reconstructed events is shown on the right. For this work, four ROIs were selected to correspond to the accelerometer locations, a fifth ROI is positioned on the strip, and a sixth ROI is placed at the contact point. ROI #2 is shown with a box in Figure 3, at the location of one of the accelerometers. A key novelty of this approach is the ability to select ROIs based on engineering judgment, allowing the analysis to focus on critical structural features rather than being restricted to predefined sensor positions.



(a) (b)

Fig. 3 Image of pylon structure using a conventional camera (a) and frame reconstruction from positive event accumulation, with a box around ROI #2 (b).

With the region of interest selected, three post-processing methods were compared: time binning, event clustering, and Lomb-Scargle spectral analysis [7]. Time binning creates a time-series signal from event counts within each time bin, event clustering groups events into clusters, and Lomb-Scargle handles non-uniformly sampled data sets. Event clustering was chosen for analysis as the method resulted in clearer spectral peaks.

Comparison of Results from Accelerometers, Event-Based Sensor and Expansion

The three methods used in this study, accelerometer responses, event-clustering of neuromorphic sensor data, and modal expansion [8], are compared by overlaying the FFTs, as shown in Figure 4. These results are all from ROI #2, pictured in Figure 3, which covers one of the accelerometer locations. All three methods capture the same major frequency components: the driving frequency and a harmonic of the driving frequency. The magnitudes shown are normalized, as the camera post-processing method did not involve converting to physical units. The left graph in Figure 4 shows the results from the lowest-force test before the onset of contact (1.9 N), where contact is defined by auditory observation during the test; the right plot shows the results from the 5.5 N test, during which contact was occurring. The case where contact was not observed still shows harmonic behavior at twice the drive frequency – this indicates that there was an additional source of nonlinear behavior, possibly the bolted joint nonlinearity, large deflection of the pylon, or even the beginnings of contact that were not yet audible. When contact audibly occurs, the FFTs show richer harmonic content. Strong harmonic behavior at 0.5x, 1.5x and 2x the driving frequency can be clearly seen by all three observation methods; this indicates that the nonlinearity resulting from the contact behavior is observable using the neuromorphic sensing method. The harmonic behavior at 0.5x the driving frequency could represent either a subharmonic resonance, or a period-doubling bifurcation

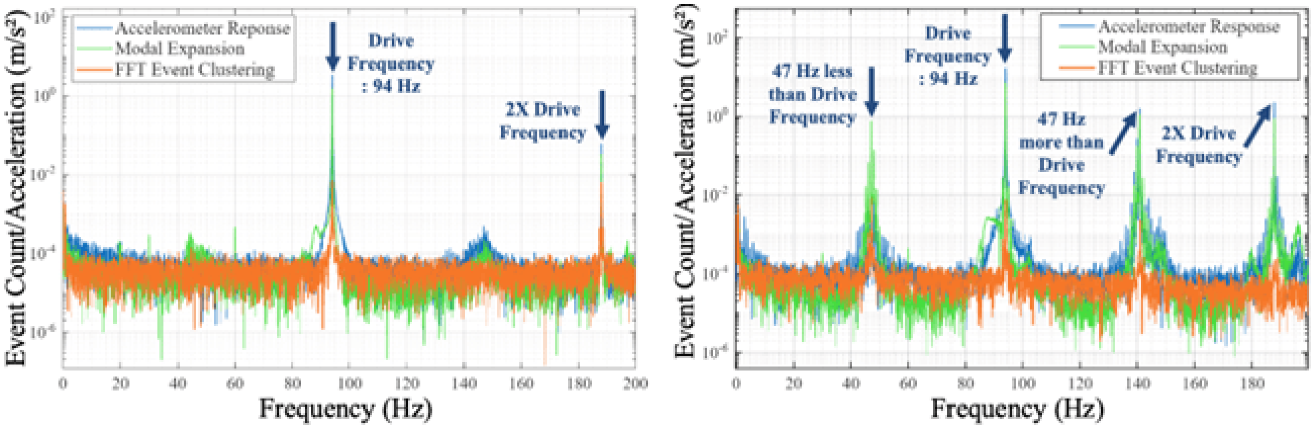
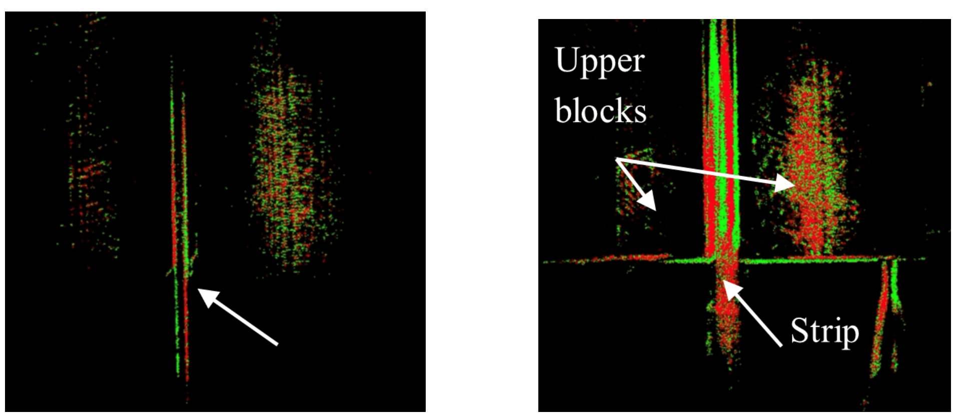


Fig. 4 FFTs of the accelerometer response, event-clustering and modal expansion results for ROI #2. The left plot is from the 1.9 N test where no contact is observed audibly, and the right plot is from the 5.5 N test where contact occurs.

In addition to quantitative data, the neuromorphic sensor is characterized by its ability to visually represent the structure. There is a noticeable increase in events observed on the structure when there is contact occurring compared to when there is no contact, as shown in Figure 5; this is likely due to the increased displacement in the case where contact occurs, resulting from the increased forcing amplitude as well as the contact behavior itself.



(a) (b)

Fig. 5 Positive (green) and negative (red) event accumulation frames without contact (a) and with contact (b).

Conclusion

This work demonstrates that neuromorphic event-based sensors can provide comparable frequency response results to traditional accelerometers and modal expansion techniques when measuring nonlinear vibration response data. Multiple post-processing methods for event-based data can be used to capture the frequency domain: time binning, event clustering, and Lomb-Scargle spectral analysis. Additionally, the event stream from the camera can be visually captured through event accumulation, offering an alternative way to observe response behavior. The ability to define regions of interest based on engineering judgment further strengthens the approach, allowing the analyst to focus on structural features most relevant to their application. These findings highlight the potential of neuromorphic sensing as a low-latency, non-contact sensor for structural vibration analysis and dynamic behavior characterization.

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