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Title of Research Report: The Sound of Stress: Listening to Deformations During Paper Crumpling

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The Sound of Stress: Listening to Deformations During Paper Crumpling

Evan Huang

Abstract

Crumpling a sheet of paper into a ball produces localized deformations and a complex crease network. Instabilities arising from geometric frustration during crumpling produce acoustic emissions. This study investigates whether these acoustic emissions can provide meaningful information about the macroscopic compactness and crease network of the crumpled paper ball. Through audio recordings of hand crumpling paired with post-crumpling crease network imaging, acoustic and structural information of crumpled paper balls varying in compactness was extracted through Fourier and wavelet-based analyses. Five separate image-complexity metrics were computed, all of which demonstrated strong correlations with the compactness of crumpled paper balls (with Pearson r ranging from 0.712 to 0.815). Additionally, during re-crumpling of the same paper sheet, relative changes in the macroscopic compactness of a crumpled paper ball showed strong positive correlations with acoustic energy in the 1-10 kHz frequency band emitted during each crumpling cycle ($r = 0.859$), and the correlation remained strong after controlling for cycle number in a partial correlation ($r = 0.800$). Paper-paper friction, light hand crumpling, and repeated facet buckling were separated in spectral flux-kurtosis acoustic feature space, with different acoustic signatures. Quantitative event detection of facet buckling-based acoustic emissions during crumpling encountered significant noise from frictional events, motivating examination of an individual deformation event: stress-induced d-cone propagation. Synchronized audio-video recordings captured acoustic emissions associated with the propagation of d-cones across paper. This acoustic emission, the movement of the d-cone, and the resulting crease were observed qualitatively. Therefore, our observations suggest that acoustic emissions can provide information regarding the macroscopic deformation history in crumpled paper sheets. Further investigation with controlled loading procedures is necessary to achieve a more quantitative description of this connection, particularly for observations of the d-cone.

Keywords: paper crumpling, crease networks, acoustic emission, developable cone (d-cone)

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Introduction

Hold a flat sheet of paper between your hands and move your hands inwards. This confines the sheet into a smaller volume, preventing it from remaining flat. A network of creases forms on the sheet as the paper is compacted into a ball (Fig. 1). This process is known as crumpling. These creases are manifestations of the deformations of the paper sheet as it transforms from a two-dimensional plane to a roughly three-dimensional ball [1]. Because the paper sheet must abide by geometrical constraints as it is forced into an increasingly smaller volume, it develops regions of non-zero Gaussian curvature and in-plane strain [1], [2].

However, these regions do not develop uniformly. The Föppl-von Kármán equations provide a framework that describes the scaling of bending and stretching energies with respect to the thickness of the sheet, h . While bending energy scales with h^3 , stretching energy scales with h . In paper sheets with thickness around 0.1 mm , this implies that bending is significantly cheaper energetically than stretching. Therefore, when accommodating geometrical constraints during crumpling, paper avoids stretching whenever possible. As a result, in-plane strain to accommodate geometrical constraints is focused onto one-dimensional stretching ridges and point-like singularities [3].

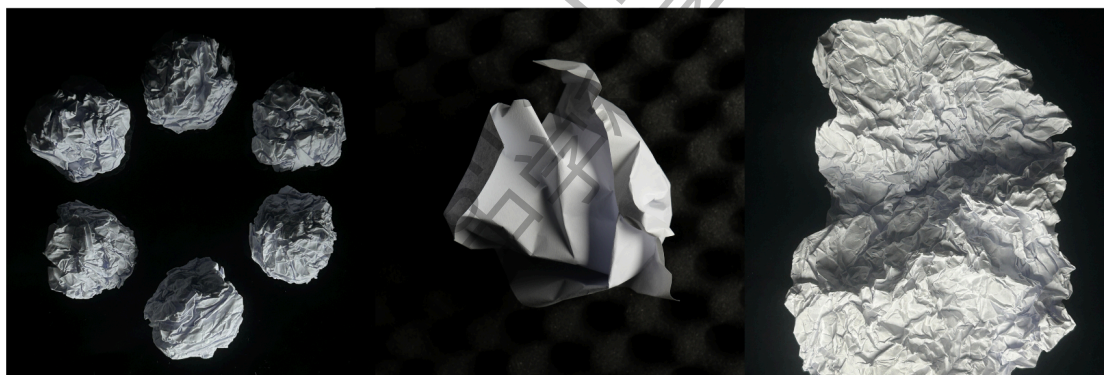


Figure 1. Six tightly crumpled paper balls (left), one loosely crumpled paper ball (center), and an uncrumpled sheet showing the crease network produced by tight crumpling (right). Image dimensions are approximately 176×176 mm.

When a series of ridges and vertices form, they intersect, dividing the paper into relatively flat polygonal regions called facets. As the paper is further compacted, ridge and vertex nucleation is paired with the buckling and branching of existing ridges. This subdivides existing facets into smaller new ones, creating an increasingly complex deformation network which can be observed visually after unfolding a crumpled paper ball [4], [5], [6].

Importantly, individual ridges can become mechanically frustrated within this complex deformation network. When a stretching ridge nucleates between two existing vertices, it must satisfy the geometric constraints imposed by the surrounding facets and vertices. However, these

constraints are not necessarily compatible with each other, meaning the ridge may not be able to fulfill the geometric requirements of both vertices simultaneously. This often leaves a ridge and the facet it confines geometrically frustrated and in a higher-energy configuration [3]. During the process of crumpling, if enough force is applied on the facet (or a collection of neighboring facets), it can overcome an energy barrier and transition to its other metastable configuration in the form of a snap-through instability [9]. This rapid mechanical rearrangement of the facet releases stored elastic energy and creates sudden disturbances within the sheet. Similar to striking a drumhead, this sudden motion of the facet produces a transient acoustic emission, which has a frequency in the kHz range and a duration in the ms range [10]. Therefore, the mechanical changes that occur during crumpling may be audible in the form of acoustic emissions.

Since imaging of the crease network within crumpled paper can also reveal its deformation history, this begs the question: is there a connection between the acoustic emission emitted during the crumpling process and the resulting permanent deformation produced on the sheet itself?

Experimental Setup

All experiments were conducted using Deli No. 7362 A4 70 gsm multipurpose paper. Acoustic emissions with a 32-bit resolution were recorded either at a 131072 Hz sampling rate using a PULSE acoustic measurement system (cyclic crumpling and event detection) or at a 192 kHz sampling rate using a UGREEN CM592 USB desktop microphone (hand crumpling vs. paper-paper friction vs. facet popping). Audio recordings took place within a 45 x 45 x 45 cm box surrounded on five sides by 4 cm thick acoustic foam padding, with an opening at the top to position the microphone. Crease network images were captured within the same enclosure using an iPhone 14 camera with fixed settings (2x zoom, -0.3 exposure, 1:1 aspect ratio), placed above the paper sheet facing down through an opening in the top of the acoustic foam-padded box. Imaging took place in a dark room with an LED light panel as the source of light. Synchronized 60 fps video was recorded for cyclic crumpling and d-cone propagation using an iPhone 14. Additional experimental procedures and data analysis pipelines are described below and available in supplementary materials.

Structural Deformation in Crumpled Paper

From visual observation, a greater degree of crumpling typically produces a more compact paper ball and complex crease network [7]. By crumpling a paper sheet into a ball, unfolding it back into a sheet, and then photographing the crease network, we can attempt to characterize the ridge-vertex patterns to understand the structural events that occurred during crumpling. Several

approaches were considered for image analysis. Previous experimental studies have performed three-dimensional topographical reconstructions of a crumpled sheet utilizing laser profilometry to extract the underlying ridge network [6], [7], [8]. Even so, automated extraction of the crease network from three-dimensional topographical reconstructions is prone to noise and over-fragmentation, requiring manual segmentation [4].

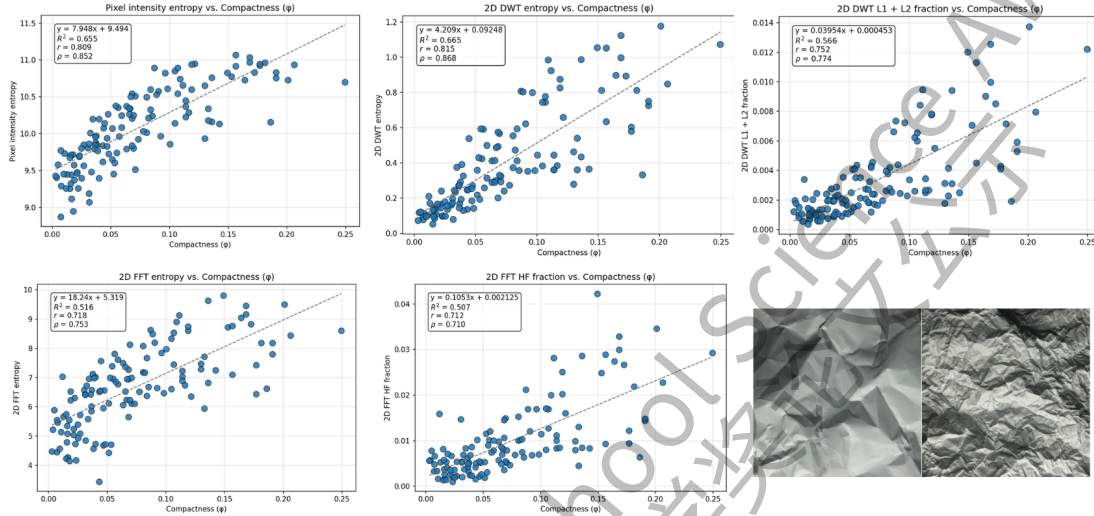


Figure 2. Crease network image complexity metrics demonstrate strong positive correlations with the compactness of a paper ball. A paper sheet crumpled repeatedly develops a more complex ridge-vertex network (bottom right).

Thus, we attempted a semiquantitative characterization by measuring the level of complexity and detail present in crease network photographs. A two-dimensional Fast Fourier Transform (2D FFT) was applied to calculate spatial frequency distributions across crumpled paper images. In the frequency-domain representation of each image, higher spatial frequencies correspond to small-scale changes in pixel intensity, reflecting finer structural details within a crumpled sheet. The high-frequency power fraction (HF power fraction) was calculated as a metric to estimate ridge network complexity by determining the fraction of the spectral power with a spatial frequency greater than 0.1 cycles per pixel (approximately 1.734 cycles per mm). Furthermore, a two-dimensional Discrete Wavelet Transform (2D DWT) was applied using the Daubechies 4 (db4) wavelet with maximum decomposition level 5 across crease network images. The fraction of total wavelet energy in level 1 and level 2 was recorded as a metric to estimate the level of detail within crease network images. The complexity of the images were measured in three different ways. Firstly, we computed Shannon entropy on grayscale crease network image pixel intensities to quantify the variation in brightness across the image. Next, we calculated variations in energy across spatial frequencies by finding the entropy on the normalized 2D FFT power spectrum. Finally, we calculated entropy on db4 wavelet subband energies to represent the spread of energy across different scales and orientations.

Altogether, these five metrics (2D FFT HF power fraction, 2D DWT level 1 + level 2 energy fraction, pixel intensity entropy, 2D FFT entropy, 2D DWT entropy) helped depict the level of complexity and fine detail within the crease network. We also quantified the degree of crumpling by measuring its dimensions to estimate its volume. From this, we defined the compactness ϕ of the paper ball as the ratio of the volume of the flat paper sheet to the volume of the paper ball:

$\phi = \frac{V_{flat}}{V_{ball}}$. The volume of the flat paper sheet was set at 5.925cm^3 for all sheets, found by multiplying the thickness of the sheet by the area (A4). The volume of the ball was measured with a ruler as the distance between two parallel vertical planes on both sides of the crumpled paper ball. Measurements from three orthogonal directions were averaged to compute the average radius of the crumpled paper ball and calculate its volume using the volume of a sphere.

Across eight separate datasets ($n = 128$, with each sheet representing a datapoint) with varying hand crumpling procedures, all five metrics demonstrated a strong correlation with compactness, suggesting that more compressed paper balls, in which the sheet is forced into a smaller space, exhibit more complexity and detail in their final crease networks (Fig. 2). This relationship suggests that the macroscopic degree of compaction of a crumpled sheet is associated with the complexity of its resulting crease network. Although the metrics used do not provide a detailed reconstruction of the crease network, they provide measurable information regarding final structural state of the sheet and degree of compaction undergone to reach it.

The Sound of Paper Crumpling

To identify connections between the structure and acoustics of crumpling paper, we tracked the development of the crease network and acoustic emission as the same sheet was repeatedly crumpled. Each paper sheet was hand crumpled for 30 seconds while high-resolution audio was recorded, measured for dimensions, uncrumpled to an approximately flat state, before being photographed of its crease network. This process was repeated for a total of five crumpling cycles on eight sheets.

Acoustic data was processed and quantified in a range of temporal, frequency, energy, and event-based metrics. We chose 1-10 kHz frequency band acoustic energy, calculated from a Parseval-scaled one-sided FFT, to represent the acoustic energy produced during deformation events, as most facet “clicking” events occurred within that frequency range. Since the compactness of the paper ball is measured after each crumpling cycle but acoustic data is measured during each crumpling cycle, relative change in compactness could represent the incremental change in macroscopic structure after each crumpling cycle.

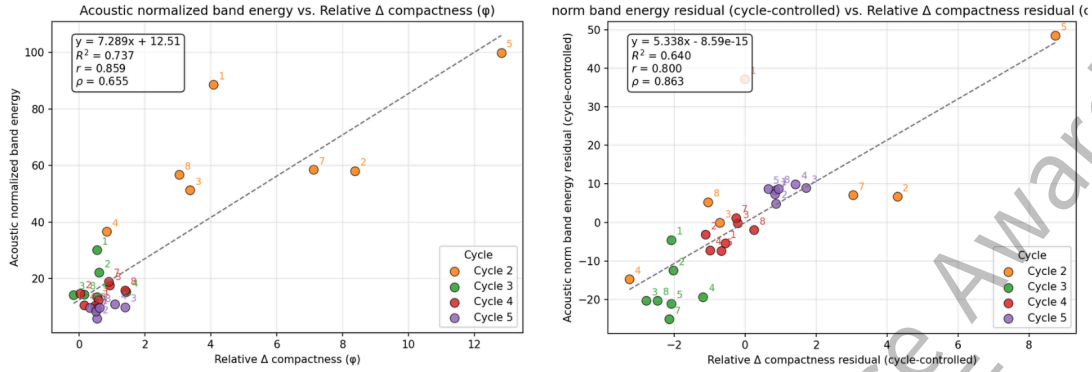


Figure 3. Relative change in compactness across crumpling cycles shows a strong positive correlation with time-normalized 1-10 kHz acoustic energy (left), and the correlation remains after controlling for cycle number (right). Later cycles appear to have less variation in both relative change in compactness and 1-10 kHz acoustic energy.

Relative change in compactness across crumpling cycles demonstrated a strong positive correlation with 1-10 kHz band acoustic energy ($r = 0.86$). However, we observed that the change in compactness between each cycle decreased in later cycles (Fig. 3). Similarly, the acoustic emission during crumpling decreased in later cycles. This “saturation” in both the acoustic and structural aspects in crumpled paper could be because the same sheet is being crumpled repeatedly, which allows it to deform along the existing ridge-vertex network instead of undergoing the energetically costly process of forming new deformations during crumpling. To account for the influence of cycle count, we computed a partial correlation between relative change in compactness and 1-10 kHz band acoustic energy controlling cycle number by correlating the residuals of the linear regression of each variable with respect to cycle number. This partial correlation also revealed a strong positive correlation with $r = 0.80$, implying that even within comparable cycle numbers, greater acoustic emission was accompanied by greater macroscopic change in the compactness of the paper ball (Fig. 3). This suggests that cycle count alone is not enough to explain the trend between structural change and acoustic emission in paper crumpling.

Because facet rearrangements occur through sudden mechanical rearrangements, the acoustic emission from crumpling paper typically consists of a series of discrete pulses [9], [10]. By detecting acoustic signals of these pulses from recordings of crumpling paper and extracting event-based statistics, we can better understand the acoustic emissions from crumpling paper.

We first applied a time-binning single threshold energy approach for event detection, used by [10]. However, crumpling paper by hand to a tight ball experimentally introduced multiple sources of acoustic emission, such as hand-paper friction as well as paper-paper friction as more layers of the paper sheet stack when forced into a smaller volume [10], [11]. These overlapping sources created a convoluted acoustic signal from crumpling paper, limiting the ability of the

event detector to distinguish between softer facet pops and frictional sounds, and requiring tuning of the threshold amplitude across trials.

In order to improve the event detection system, we needed to better understand the acoustic signatures of specific crumpling sounds. Since crumpling as a whole was too noisy, we focused on collecting a dataset of specific reproducible events. To test this, loosely crumpled paper balls were split into two experimental groups (each with $n = 5$ sheets of paper). The first underwent repeated cycles of light compression and relaxation to generate acoustic emissions from paper-paper friction, followed by repeated hand-induced facet popping without further compression. The second underwent continued compression to a compact ball. Acoustic statistics were calculated and averaged across trials for each group.

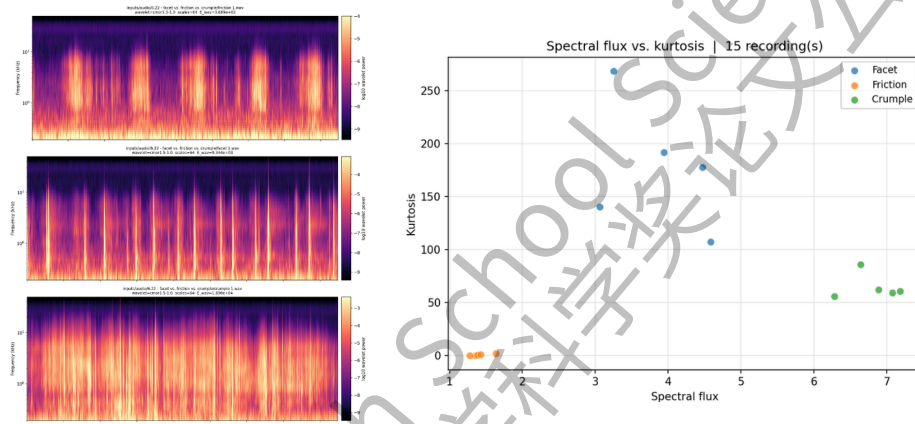


Figure 4. Left: Scalograms displaying the acoustic signature of paper-paper friction induced from repeated compression and release of loosely crumpled balls (top), isolated hand-induced facet buckling between bistable configurations (middle), and light hand crumpling (bottom). Right: Distribution of recordings of acoustic events in spectral flux-kurtosis feature space, in which facet buckling, paper-paper friction, and crumpling occupy distinct regions.

As shown in Table 1 and visualized in Fig. 4, hand crumpling and facet buckling exhibited similar high-frequency band fractions (0.841 and 0.779) along with spectral centroids (2592 and 2568 Hz), while paper-paper friction displayed significantly lower high-frequency band fraction and spectral centroid values (at 0.166 and 614, respectively). Facet buckling also showed significantly higher normalized signal energy compared to paper-paper friction (50.0 vs. 3.27 a.u.), suggesting that facet buckling events contribute more strongly to the recorded acoustic energy during crumpling compared to paper-paper friction. However, these statistics may be influenced by variations in event density even in recordings of equal duration.

Table 1. Average acoustic statistics across different crumpling event types. Normalized signal energy was calculated as the sum of squared amplitudes on a normalized waveform with a range of -1 to 1. High-frequency band energy fraction represents the fraction of total acoustic energy within the 1-10 kHz frequency range.

event type	normalized signal energy (a.u.)	high-frequency band energy fraction	spectral centroid (Hz)
hand crumpling	88.5	0.841	2592
facet buckling	50.0	0.779	2568
paper-paper friction	3.27	0.166	614

Thus, to further characterize the intrinsic acoustic features of each event type while reducing sensitivity to event density within recordings, recordings from all three event categories were projected into spectral flux-kurtosis feature space (Fig. 4). Facet buckling and paper-paper friction occupied distinct regions of feature space, with facet buckling events exhibiting higher spectral flux and kurtosis compared to paper-paper friction events. Examinations of the spectrograms for each event type revealed that facet buckling consists of short, transient, high-energy pulses extending into the 10 kHz range, while paper-paper friction produces longer-duration, lower-intensity events primarily concentrated below approximately 6 kHz. Crumpling appears as a combination of the characteristics of both mechanisms, possessing both transient high-frequency pulses associated with facet buckling along with longer-duration low-energy events associated with paper-paper friction. This supports the clustering observed in the spectral flux-kurtosis feature space, where facet buckling is characterized by greater impulsiveness and larger variations in frequency over time.

With these observations in mind, we developed a new event detection algorithm with the goal of capturing the acoustic signal of facet “clicks” that span several decades of energy from an evolving background noise floor. We first computed the instantaneous Teager-Kaiser Energy Operator (TKEO) [12] on a high-pass filtered acoustic signal to better listen for transient acoustic emission. Then, we introduced a moving short-term average (STA) and long-term average (LTA) to calculate dual STA/LTA onset/offset ratios as triggers. In this way, if a facet event were to occur with frictional sounds in the background, then the elevated LTA would mitigate false positives during event detection. However, in reality, this new event detection algorithm introduced too many parameters and could not always accurately detect facet events across different datasets. Moreover, upon listening to some of the acoustic recordings, we observed a unique acoustic emission source that behaved impulsively like facet clicks but sounded slightly more muffled. Upon manual inspection of synchronized video, audio, waveform, and event data, these acoustic emissions did not appear to be associated with any visible changes in facet configurations, and primarily occurred during the early stages of hand crumpling. This suggests that additional deformation mechanisms may be responsible for the acoustic emission produced during crumpling, motivating further investigation of their origin.

Listening to Propagating D-Cones

After investigating the synchronized video and audio of paper crumpling, we observed and heard the presence of this acoustic emission in all eight sheets during their first cycle of crumpling in the cyclic crumpling experiment. This acoustic emission coincided with the visual movement of a d-cone (developable cone), a localized point defect around a vertex, across the sheet (Fig. 5). Furthermore, the d-cone left behind a jagged crease in the path of its propagation [13], [14].

To better understand this phenomenon, we used hand crumpling procedures to induce isolated formation and propagation of d-cones. Synchronized video and audio was recorded of the d-cone movement, and photos were taken afterwards of the resulting d-cone for qualitative observation. A Morlet Continuous Wavelet Transform (CWT) was computed on acoustic data, and wavelet power was calculated by squaring the absolute value of the wavelet coefficients. The acoustic signal was visualized using a scalogram with log-scale frequency, time, and wavelet power represented as color intensity.



Figure 5. Consecutive video frames displaying an apparent discrete “flip” near the vertex of a d-cone during a single propagation step. Video was recorded at 60 frames per second; the top and bottom rows show two separate examples. Image dimensions are approximately 50×50 mm.

The tightening of the d-cone vertex before movement appeared to produce discrete acoustic “clicks”, similar in acoustic nature to the popping of facets between different mechanical configurations. This may help explain why the improved event detector still struggled to accurately identify facet events if other acoustic emissions with similar acoustic characteristics were present in the acoustic signal.

These clicks extended well into the kHz range, often with substantial acoustic energy above frequencies of 10 kHz. Clicks were spaced with waiting times on the order of tens of milliseconds, but this could be influenced by the inconsistent hand-based loading procedure. The propagation of the d-cone across the sheet also appeared to produce discrete acoustic clicks, extending into similar frequency ranges as the tightening of the d-cone vertex before movement. However, the scalograms displayed greater wavelet power concentrated within the 1-10 kHz range during propagation (Fig. 6).

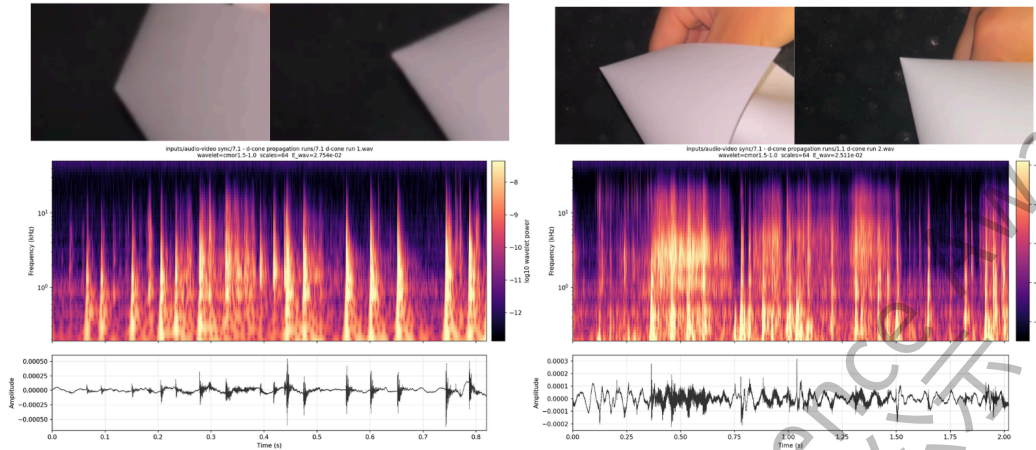


Figure 6. Video frames, scalograms, and waveforms showing d-cone events and acoustic emissions recorded during d-cone focusing (left) and subsequent propagation (right). The d-cone initially narrows, with its opening angle decreasing (top left) before propagating across the sheet (top right). The top-left image (approximately 46×27 mm) is shown at $3\times$ the magnification of the top-right image (138×81 mm). Within each column, the video frames correspond to the first (left) and last (right) video frames of each synchronized video-audio recording.

We hypothesize that these acoustic emissions are associated with mechanical and structural events within the paper sheet. As force is focused into the d-cone, the curvature near the vertex increases by sevenfold before the d-cone begins propagating across the sheet [13]. One possible explanation is that the heterogeneous fiber network within the paper sheet could cause the d-cone to encounter spatially varying resistance as it moves across the sheet. The vertex of the d-cone often appeared to undergo brief periods of limited or halted motion followed by more rapid advancement, which could reflect the nonuniform resistance it faced from the sheet. It is possible that this sudden acceleration could produce a mechanical disturbance in the sheet, emitting transient discrete acoustic emission bursts. In terms of the more continuous-looking concentration of acoustic energy in the 1-10 kHz range on the scalogram for d-cone propagation, it could be connected to the friction sounds of the d-cone as it moves forwards, or the deformation of the flat paper sheet into a wrinkled-looking furrow.

The d-cone also leaves behind a rugged crease in its path. We hypothesize that this crease can be modeled as an approximate polyline, where each individual segment may correspond to a discrete “jump” forward of the d-cone vertex during propagation. The polyline nature may reflect the irregular advancement of the d-cone during propagation, during which it may encounter spatially inconsistent resistance from the heterogeneous structure of the paper fiber network. Therefore, if the discrete acoustic emission pulses can be temporally associated with individual forward movements of the d-cone, then it may be possible to connect acoustic information during d-cone propagation to the structure and geometry of the resulting crease.

We did not identify previous reports of acoustic emissions associated with d-cone propagation in the literature we examined. Many previous experimental studies have used thin polymer sheets

such as Mylar [4], [13], [15], [16], [17], [18], whereas observations of d-cone propagation in paper appear to be more limited. Polymer sheets including Mylar have different material properties and microstructures compared to paper, which could impact the propagation dynamics and acoustic emission of d-cones.

A possible explanation is that the organized polymer chains in plastic sheets such as Mylar could create a more uniform microstructure that supports more constant motion during the propagation of d-cones. This could limit the sudden accelerations and more jerky nature of d-cone propagation observed in paper sheets, which may affect the ability for d-cone propagation in plastic sheets to produce acoustic emission. Moreover, the proposed smoother nature of propagation could also lead to the observed straighter creases left behind in the path of the d-cone in plastic sheets, unlike the rugged creases from paper. These contrasting material properties could potentially influence the different propagation dynamics and acoustic emissions between paper and polymer sheets, but our current observations are unable to isolate material composition as the cause.



Figure 7. Crease produced by the propagation of a d-cone in a PET sheet under hand-induced loading (left) and a paper cylinder under uniaxial compression (right). The PET sheet was photographed between two crossed linear polarizers. Image dimensions are approximately 88×88 mm (left) and 120×120 mm (right).

Conclusion and Future Work

This study investigated the deformation undergone by a sheet of paper during crumpling through two orthogonal viewpoints: the acoustic emission produced during crumpling and the crease network structure imprinted onto the paper afterwards. On the visual side, the complexity of the crease network of a crumpled paper sheet, characterized with 2D FFT HF power fraction, 2D DWT L1 + L2 wavelet energy, 2D FFT entropy, 2D DWT entropy, and pixel intensity entropy, showed a strong correlation with the macroscopic compactness of crumpled paper balls (lowest $r = 0.712$, highest $r = 0.815$). On the acoustic side, frictional noises from interlayer paper sliding and facet buckling acoustic emission were characterized with unique acoustic signatures

on spectral flux-kurtosis feature space. Experimental noise during hand crumpling limited the accuracy of acoustic crumpling event detection in full hand crumpling recordings. Nonetheless, a strong positive correlation ($r = 0.859$) was observed of relative changes in the macroscopic compactness of crumpled paper balls across crumpling cycles with acoustic energy in the 1-10 kHz frequency band emitted during each crumpling cycle. Later cycles appeared to have decreased spread in both relative change in compactness as well as 1-10 kHz acoustic energy, but the above correlation remained similar in strength ($r = 0.800$) after controlling for cycle number through a partial correlation,

This supports the idea that acoustic emission measurements may be useful to track structural evolution over time. Additionally, synchronized audio-video recordings revealed temporal association between acoustic emissions with the focusing and propagation of d-cones across paper sheets. This deformation event also left behind jagged creases on paper sheets. These observations provide a qualitative description of connections between the structure and acoustic emissions of an isolated deformation event during the crumpling process, but the specific causal chain remains an open question. By observing crumpling through different perspectives, such as both imaging and acoustic, the physical mechanisms that guide the deformation of paper to a crumpled state can be better understood.

Nevertheless, this investigation had several limitations. Firstly, the imaging and audio data collected was only used semiquantitatively to describe the overall structural state or acoustic emission from the crumpled paper ball as a whole. Quantitative characterization of specific crease networks was not done due to difficulties with image processing. Similarly, extraction of specific crumpling events from full crumpling records involved significant signal processing challenges. Therefore, a better approach to understand the mechanics behind crumpling paper is to identify specific crumpling mechanisms and observe them individually in a more controlled experimental environment. By sufficiently understanding the structure and acoustics of each type of crumpling event, it may be easier to distinguish each individual crumpling event type from each other from the overall acoustic signal of paper crumpling.

Additionally, this investigation utilized hand crumpling to induce deformation and crumple paper sheets. Hand crumpling is uncontrolled, so it naturally varies between trials and increases experimental uncertainty, hindering the extraction of quantitative experimental data. It can also introduce unwanted frictional noise with the contact of hands and the paper sheet. Moreover, variations in the acoustic emission from propagating d-cones in paper could be attributed to natural inconsistencies in the hand-based loading procedure. Therefore, proper quantitative description of the acoustic emission from propagating d-cones in paper sheets should involve a controlled force loading system. Simultaneous measurements of force, d-cone vertex position, and acoustic emission combined with imaging of the resulting crease network could allow for a definite relationship between the discrete acoustic “clicks” and rugged crease to be formed. For instance, acoustic energy and waiting time between acoustic events could be measured against

displacement propagated. Furthermore, d-cone propagation and its acoustic emission could be examined across different materials and sheet thicknesses to better understand its origin and behavior. Continued investigation in this direction would support greater understanding of the d-cone in paper crumpling. Combined with inquiry on other deformation structures in crumpled paper, these studies could provide a better understanding of the complex mechanisms underlying paper crumpling and its broader connection to crumpling-like deformation in other physical systems.

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Acknowledgements

The idea for this research project came from observing the crease network from paper crumpling, and a curiosity to understand what physical processes were responsible for it. As I explored methods to image and characterize the crease network, the scope of the project expanded after I listened to the acoustic emissions from the deformation of the paper. This naturally led to the idea of whether these acoustic emissions can track structural changes and deformation within paper sheets.

This project began in spring 2026 with exploratory experiments using self-purchased equipment including a DIY acoustic box formed from a lightbox covered with acoustic foam. Most of the data was collected using both a commercial UGREEN desktop microphone and a PULSE acoustic measurement system while at an acoustics laboratory in the School of Frontier Sciences at Nanjing University Suzhou Campus.

During the two and a half weeks spent at this laboratory, Prof. Bao and his team offered guidance in how to collect data using the PULSE acoustic measurement system, suggested possible experimental designs and analyses techniques to characterize the acoustic emissions from crumpling paper, as well as recommended reading materials to improve my understanding of acoustic analysis. I then applied these ideas through independent data collection and analysis, while Prof. Bao and his team offered comments on some of the experimental results. All guidance was unpaid.

The main challenges faced during this research project was with data analysis, most of which was conducted independently after the two and a half weeks spent at Prof. Bao's laboratory. Data was extracted and computed using python scripts. Throughout this project, an ongoing literature review was conducted that strengthened my knowledge in this field. New literature was consulted when new experimental and analytical questions and directions arose. Papers were read and annotated on Zotero. I also independently contacted a few researchers with published work relevant to this project. Their unsolicited responses provided clarification on existing literature and informed subsequent research decisions. No compensation was provided for their responses. Specific information regarding correspondence is provided in the supplementary materials, with personal information redacted (but available on request when appropriate). The research report writing phase was conducted independently with no external support.

AI tools provided assistance in multiple stages of the project. ChatGPT 5.3-5.6, Claude Sonnet 4.5-5, Gemini Flash 3.5-3.6, and DeepSeek V3.2-4 provided different perspectives on data analysis results and suggested possible follow-up steps based on those results. These models also assisted during the literature review by explaining unfamiliar concepts and identifying possible connections across papers. However, each AI-derived claim was verified afterwards against

literature to ensure accuracy. During the thesis writing phase, they also provided advice in the structure of a research paper and feedback on writing created by me. Cursor (Auto, Cursor Grok 4.6, and Claude Opus 4.6-5) assisted in the implementation and debugging of these python scripts, translating the pipeline and analyses steps I provided into code. The outputs and figures produced were reviewed by me before being used in this report. Overall, AI was used most frequently during the programming and troubleshooting phase of this project.

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