Influence of Concurrent Boiling Events on Acoustic Nucleation Rhythms in Cryogenic Systems

Andrew Martinez
Department of Statistics
California Polytechnic State University
San Luis Obispo, CA
amart89531@gmail.com

***Abstract*—The interaction between concurrent boiling events and their effect on nucleation rhythms in cryogenic systems remains an open question relevant to monitoring and safety applications. Building on prior acoustic machine learning analyses, this study quantifies these interactions by comparing the standard deviations of inter-nucleation time intervals. Statistical analysis of monitored, hand-labeled data indicates that simultaneous boiling sources significantly influence the rhythmic behavior of individual nucleation sites at the ($\alpha = 0.05$) level. These findings offer valuable insights for enhanced monitoring and improved understanding of boiling dynamics in cryogenic environments.**

***Index Terms*—boiling interaction, cryogenic systems, nucleation rhythm, acoustic signal analysis, rhythmic interference**

I. Introduction

Cryogenic fuels are critical for modern spaceflight, offering high energy density and efficient propulsion. However, storing these fuels safely presents substantial challenges, particularly under microgravity conditions where convection is suppressed and localized heating can induce unstable boiling. In such conditions, even minor heat leaks along the tank walls may trigger incipient boiling, generating vapor rapidly and producing pressure spikes that can compromise tank integrity and mission safety.

Traditional approaches to monitoring cryogenic tank stability, such as thermal sensors, are limited in their ability to detect the earliest indicators of boiling. These sensors typically provide delayed feedback and are not designed to capture the fine-grained temporal dynamics of bubble nucleation—particularly in microgravity, where boiling behavior differs significantly from that on Earth.

Recent work suggests that boiling events produce distinct acoustic signatures that can be captured using accelerometers mounted externally on the tank. The formation, growth, and collapse of vapor bubbles generate high-frequency energy that propagates through the tank walls and appears as sharp transients in acoustic data. These acoustic patterns reflect the underlying nucleation behavior and offer a promising non-intrusive signal for early-stage detection.

While prior studies have focused on classifying isolated boiling regimes using machine learning and signal processing, the interaction between multiple concurrent boiling events remains unexplored. Specifically, it is unknown whether the presence of one active boiling source influences the rhythmic nucleation patterns of another. Such interactions, if present, could provide physical intuition for future work in how systems are constructed.

This study investigates whether simultaneous boiling sources affect the regularity of nucleation events. Using hand-labeled accelerometer data from cryogenic boiling experiments, standard deviations of inter-nucleation intervals are compared across isolated and concurrent boiling conditions. Statistical tests at the $\alpha = 0.05$ level are used to assess whether rhythmic disruptions occur in the presence of multiple active sites. The findings provide new insight into the dynamic interplay between boiling sources and inform the design of more robust acoustic monitoring frameworks for cryogenic systems.

II. Dataset Description

This study uses data from 441 boiling experiments conducted by NASA, each lasting between 1 and 30 seconds.

A. Experimental Setup

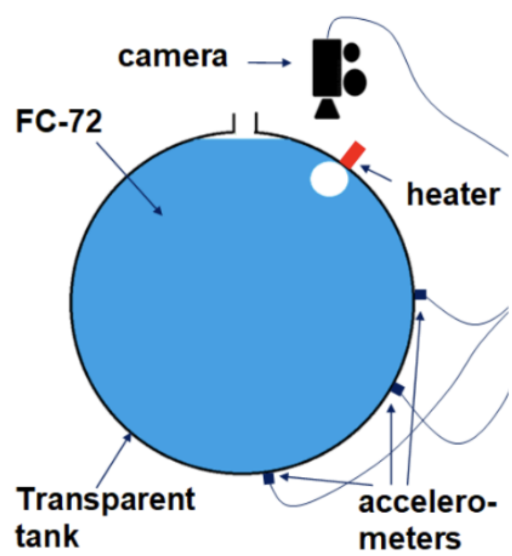

Fig. 1. Experimental setup: cryogenic tank with accelerometers.

Each experiment involves a spherical cryogenic tank containing liquid and outfitted with accelerometers attached to the tank wall, as shown in Figure 1. During each run, a controlled heat source initiates boiling activity near the tank boundary. Two accelerometers capture the resulting acoustic signals at a sampling rate of 10,000 Hz. A single channel is selected for analysis to minimize redundancy while retaining all necessary signal characteristics.

B. Data Format and Visualization

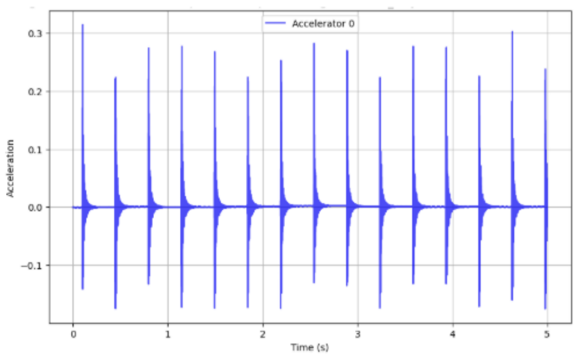

Fig. 2. Raw time-domain signal from a single experimental run.

Each experimental run is stored in a CSV file that includes timestamped accelerometer readings. The raw acoustic data is visualized in the time domain as amplitude plotted against time, as shown in Figure 2. Peaks in this signal correspond to individual bubble nucleation events and serve as the foundation for rhythm-related feature extraction.

C. Physical Interpretation

The acoustic signal captures energy released during bubble formation, growth, and collapse within the cryogenic liquid. When liquid near the heated surface becomes superheated, vapor bubbles form and grow rapidly before collapsing or detaching. These events emit acoustic energy that travels through the tank structure and appears in the signal as high-amplitude peaks.

Different boiling regimes exhibit distinct acoustic behaviors. For example, quasi-homogeneous and heterogeneous nucleation patterns may differ in terms of timing, peak magnitude, and frequency content. In environments that simulate microgravity, where convection is greatly reduced, superheating is more pronounced. This can lead to more energetic boiling activity, producing sharper and more irregular peaks.

These acoustic characteristics provide information about the temporal structure of nucleation events. In this work, rhythmic patterns extracted from these signals are used to evaluate whether the presence of one boiling source affects the behavior of another. This analysis enables a deeper understanding of how boiling sources interact in cryogenic systems.

D. Hand Labeling Dashboard

Due to high variability in the accuracy of existing peak detection algorithms, a Python Dash applet was created for manual labeling. This Python dashboard allows researchers to efficiently label experimental runs with high precision. A full image of the dashboard along with an explanation of its capabilities can be found in Appendix 5.

Additionally, example labeled runs denoting the functionality of the applet are presented in Appendix 6. Hand labeled runs were utilized despite the time consuming nature to ensure ample precision in the methodologies below.

III. Methods

A. Exploratory Assessment of Rhythmic Variation

An initial visual inspection of inter-nucleation interval variability was conducted to explore whether rhythmic patterns differed across boiling configurations. Kernel density estimation and violin plots were generated to compare the distributions of standard deviations across groups. These exploratory visualizations revealed apparent differences in spread between configurations, motivating the use of formal statistical tests to assess whether the presence of a secondary boiling signal significantly affects rhythmic regularity.

In dual nucleation experiments, the *Dominant Signal* is defined as the signal with the higher mean peak amplitude, and the *Lesser Signal* refers to the one with a lower mean peak amplitude. This classification enables direct comparison between rhythmic signals in isolated conditions and those occurring in the presence of other active sources.

The following rhythm groups were defined for analysis:

- **Dominant Rhythm**: A consistently rhythmic nucleation site identified in experiments containing two active signals, characterized by a higher mean peak amplitude relative to the secondary source.
- **Lesser Rhythm**: The secondary nucleation site present in dual-signal experiments, exhibiting a lower mean peak amplitude and less pronounced acoustic activity.
- **Single Rhythm**: A rhythmic nucleation pattern observed in experiments with only one active boiling source, serving as a baseline for comparisons.
- **Rhythm with Random Interference**: A rhythmic signal present in the same experiment as a randomly timed, less structured nucleation pattern. This configuration is used to assess the influence of stochastic boiling on rhythmic regularity.

B. Statistical Analysis

To formally assess whether boiling signal interactions affect rhythmic consistency, several statistical tests were performed on the standard deviations of inter-nucleation intervals across the defined rhythm groups.

The **Shapiro-Wilk test** was used to evaluate the normality of each group's distribution. Based on the outcomes, group variances were compared using the **Levene's test** for homogeneity of variance. Because many groups did not exhibit normality or equal variances, **Welch's t-test** was abandoned in father of Group means were compared using the **Welch's t-test** the non-parametric **Mann–Whitney U test** in assessing differences in distributions. The **Mann–Whitney U test** is a nonparametric test with no prior assumptions, normality and equal variance are not required for accurate results. A significance threshold of $\alpha = 0.05$ was used throughout the analysis.

IV. Results

A. Visual Inspection

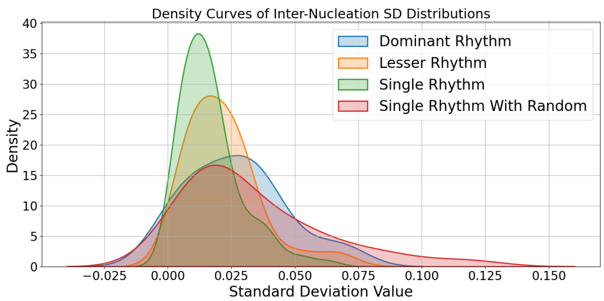

Fig. 3. Kernel Density Plot Showcasing respective SD distributions for Inter-Nucleation Time Differences.

As seen in Figure 3, looking at the respective Inter-Nucleation SDs reveals four distinct distributions. The density plot illustrates the spread and concentration of standard deviations across the different groups. Notably, the distributions for *Dominant Rhythm* and *Rhythm with Random Interference* appear to be relatively wide, indicating greater variability in inter-nucleation times within these groups. In contrast, the *Single Rhythm* group shows a more concentrated peak, suggesting a tighter distribution with lower variability. The *Lesser Rhythm* group demonstrates a moderate spread, with a slight skew indicating a blend of behaviors within this category. This visual highlights the deviations in inter-nucleation timings between different rhythm patterns.

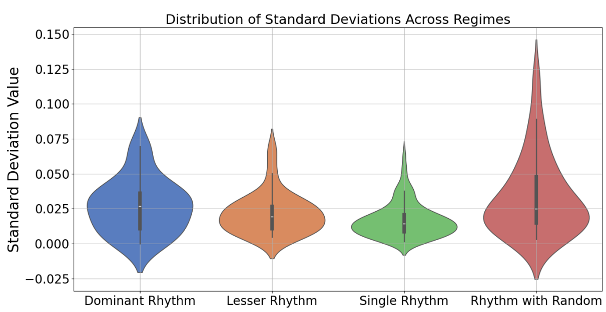

Fig. 4. Violin Plot Showcasing respective SD distributions for Inter-Nucleation Time Differences.

As seen in Figure 4, the violin plot further illustrates the distribution of standard deviations across the different groups. The plot highlights the varying spread and concentration of inter-nucleation time differences. Notably, the distributions for *Dominant Rhythm* and *Rhythm with Random Interference* exhibit less concentrated shapes, indicating a higher degree of variability in inter-nucleation times within these groups. Conversely, the *Single Rhythm* group has a more concentrated shape, suggesting a tighter distribution with lower variability. The *Lesser Rhythm* group shows a moderately wide shape, with a slight skew, indicating a mixture of behaviors within this category. These visual differences further emphasize the potential variability in the inter-nucleation time differences.

B. Statistical Tests

1) Normality Tests: The Shapiro-Wilk test was performed to assess the normality of the standard deviation distributions for each group. The null hypothesis (H_0) of the Shapiro-Wilk test is that the data follows a normal distribution, while the alternative hypothesis (H_A) suggests that the data deviates from normality.

Group	Statistic	p-value
Dominant Rhythm	0.945	0.215
Lesser Rhythm	0.871	0.005
Single Rhythm	0.887	4.08×10^{-7}
Rhythm with Random	0.851	9.87×10^{-4}

TABLE I
Shapiro-Wilk Test Results for Normality

As shown in Table I, *Dominant Rhythm* is the only group where the normality assumption is not rejected ($p = 0.215$). For all other groups, the p-values are less than 0.01, indicating significant deviations from normality.

2) Levene's Test for Equal Variances: Levene's test was conducted to assess the homogeneity of variances across the groups. The null hypothesis (H_0) for Levene's test is that the variances of the groups are equal, while the alternative hypothesis (H_A) suggests that at least one group has a different variance.

Group Comparison	Statistic	p-value
Dominant Rhythm vs *Lesser Rhythm*	2.49	0.122
Dominant Rhythm vs *Single Rhythm*	9.84	0.002
Dominant Rhythm vs *Rhythm with Random*	0.87	0.357

TABLE II
Levene's Test for Equality of Variances

From Table II, we see that *Dominant Rhythm* and *Single Rhythm* exhibit significantly different variances ($p = 0.002$), suggesting that their variability in inter-nucleation times differs.

3) Mann-Whitney U Test: The Mann-Whitney U test was conducted for non-normally distributed groups to assess if one group tends to have larger values than the other. The null hypothesis (H_0) for the Mann-Whitney U test is that the distributions of the two groups are the same, while the alternative hypothesis (H_A) suggests that the second comparison group has a higher central tendency than the first comparison group.

Group Comparison	Statistic	p-value
Single Rhythm vs *Dominant Rhythm*	809	0.008*
Single Rhythm vs *Rhythm with Random*	835	0.001*
Single Rhythm vs *Lesser Rhythm*	918	0.043*
Dominant Rhythm vs *Lesser Rhythm*	234	0.135
Lesser Rhythm vs *Rhythm with Random*	263	0.092

TABLE III

MANN–WHITNEY U TEST RESULTS COMPARING THE SPREAD OF INTER-PEAK INTERVALS ACROSS ACOUSTIC BOILING REGIMES. COMPARISONS WITH $p < 0.05$ ARE MARKED WITH AN ASTERISK (*) TO INDICATE STATISTICAL SIGNIFICANCE.

Table III presents the results of the Mann–Whitney U tests conducted to compare the variability of inter-peak intervals across different boiling regimes. Significant differences were observed between *Single Rhythm* and both *Dominant Rhythm* ($p = 0.008$) and *Rhythm with Random* ($p = 0.001$), indicating that *Single Rhythm* tends to exhibit lower standard deviations. Additionally, the comparison between *Single Rhythm* and *Lesser Rhythm* was also significant ($p = 0.043$), though marginally. In contrast, comparisons between *Dominant Rhythm* and *Lesser Rhythm* ($p = 0.135$), and between *Lesser Rhythm* and *Rhythm with Random* ($p = 0.092$), did not yield statistically significant differences.

4) Interpretation of p-values: For all statistical tests, p-values are interpreted using the standard threshold of $\alpha = 0.05$. If $p \leq 0.05$, the null hypothesis is rejected, suggesting a statistically significant difference between groups. If $p > 0.05$, the null hypothesis is not rejected, indicating no statistically significant difference.

In this context, the results imply that the presence of additional or interfering rhythms (*Dominant Rhythm*, *Rhythm with Random*) is associated with greater variability in boiling behavior when compared to *Single Rhythm*. These findings support the hypothesis that acoustic interference from multiple boiling sources disrupts rhythmic consistency, increasing the standard deviation of peak-to-peak intervals. The non-significant differences involving *Lesser Rhythm* suggest its variability characteristics are more similar to other regimes, potentially due to weaker rhythmic influence or measurement noise.

V. DISCUSSION

The results show that having more than one boiling source affects the consistency of when bubbles form. The Dominant Rhythm and Rhythm with Random groups had greater variation in the timing between nucleation events compared to the Single Rhythm group. This suggests that when two boiling signals occur in the same experiment, they may interfere with each other and make the timing of bubble formation less predictable.

The Single Rhythm group had the lowest variation. This supports the idea that when only one boiling source is active, it creates a more stable and repeatable pattern. In contrast, the presence of a second signal appears to introduce changes that reduce the stability of the rhythm.

The Lesser Rhythm group showed a moderate level of variation. It was more variable than Single Rhythm but less variable than the Dominant and Random groups. This could mean that weaker signals are still affected by other sources, but not as strongly.

These results may help improve monitoring systems for cryogenic tanks. By measuring how consistent the bubble timing is, it may be possible to detect when multiple boiling sources are active. This can help identify conditions that could lead to instability in space or low-gravity environments.

VI. CONCLUSION

This study examined whether boiling signals from different locations affect each other during cryogenic tank experiments. The timing between bubble events was measured using acoustic data, and the amount of variation was compared across different boiling setups.

The results show that when a second boiling source is present, the variation in timing increases. The Single Rhythm group had the most consistent behavior, while the Dominant Rhythm and Rhythm with Random groups had more variation. The Lesser Rhythm group had a level of variation between the others.

These results support the idea that overlapping boiling activity can change the behavior of bubble formation. Understanding this effect can help improve future acoustic monitoring tools. It may also help in the design of safer systems for storing and handling cryogenic fuels in space environments.

REFERENCES

[1] C. Dunlap, H. Pandey, E. Weems, and H. Hu, “Nonintrusive heat flux quantification using acoustic emissions during pool boiling,” *Applied Thermal Engineering*, vol. 228, 2023, Art. no. 120558.

[2] S. Barathula and K. Srinivasan, “Review on research progress in boiling acoustics,” *International Communications in Heat and Mass Transfer*, vol. 139, 2022, Art. no. 106465.

[3] J. Tang, G. Xie, J. Bao, Z. Mo, H. Liu, and M. Du, “Experimental study of sound emission in subcooled pool boiling on a small heating surface,” *Chemical Engineering Science*, vol. 188, pp. 179–191, 2018.

[4] B. M. Dorofeev and V. I. Volkova, “An acoustic method of investigation of the process of boiling,” *High Temperature*, vol. 43, no. 4, pp. 620–627, 2005.

[5] B. M. Dorofeev and V. I. Volkova, “The effect of evaporation and condensation in vapor bubbles on the hydrodynamic sound generation in a subcooled boiling liquid,” *Acoustical Physics*, vol. 52, no. 2, pp. 173–179, 2006.

[6] Y. Ueki and K. Ara, “Proof of concept of acoustic detection of boiling inception and state transition using deep neural network,” *International Communications in Heat and Mass Transfer*, vol. 129, 2021, Art. no. 105675.

[7] V. K. Dhir, “Boiling under microgravity conditions,” in *Proc. 12th Int. Heat Transfer Conf.*, Grenoble, France, 2002.

[8] C. B. Muratov, V. V. Osipov, and V. N. Smelyanskiy, “Issues of long-term cryogenic propellant storage in microgravity,” NASA Technical Memorandum TM-2011-215988, ARC-E-DAA-TN4295, 2011.

[9] M. Hasan and R. Balasubramaniam, “Analysis of the pressure rise in a partially filled liquid tank in microgravity with low wall heat flux and simultaneous boiling and condensation,” in *50th AIAA Aerospace Sciences Meeting*, 2012.

APPENDIX A
APPLET PICTURES

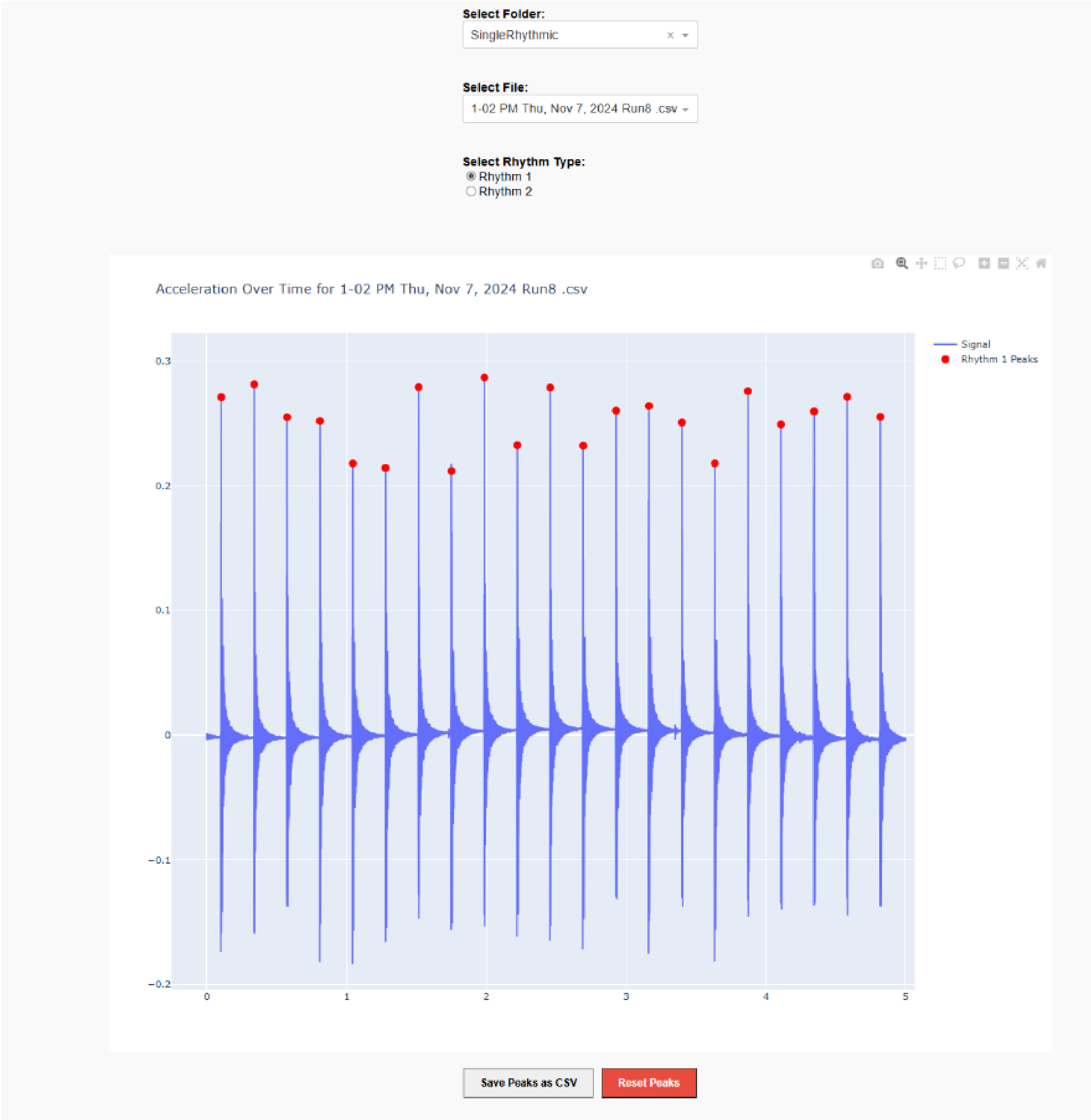

Fig. 5. Full landing page of Python Dash applet created to manually label runs.

The Python Dash applet created has capabilities of dynamically loading folders and runs uploaded to its repository. Meaning, researchers can easily upload folders containing labeled runs, label peaks within the runs by rhythm, and finally save the time stamps and amplitude values of the labeled peaks to a CSV. The saved CSVs are stored in a designated folder and preserve the original title of the experimental run along with the folder structure of the initially submitted runs, enabling easy comparison.

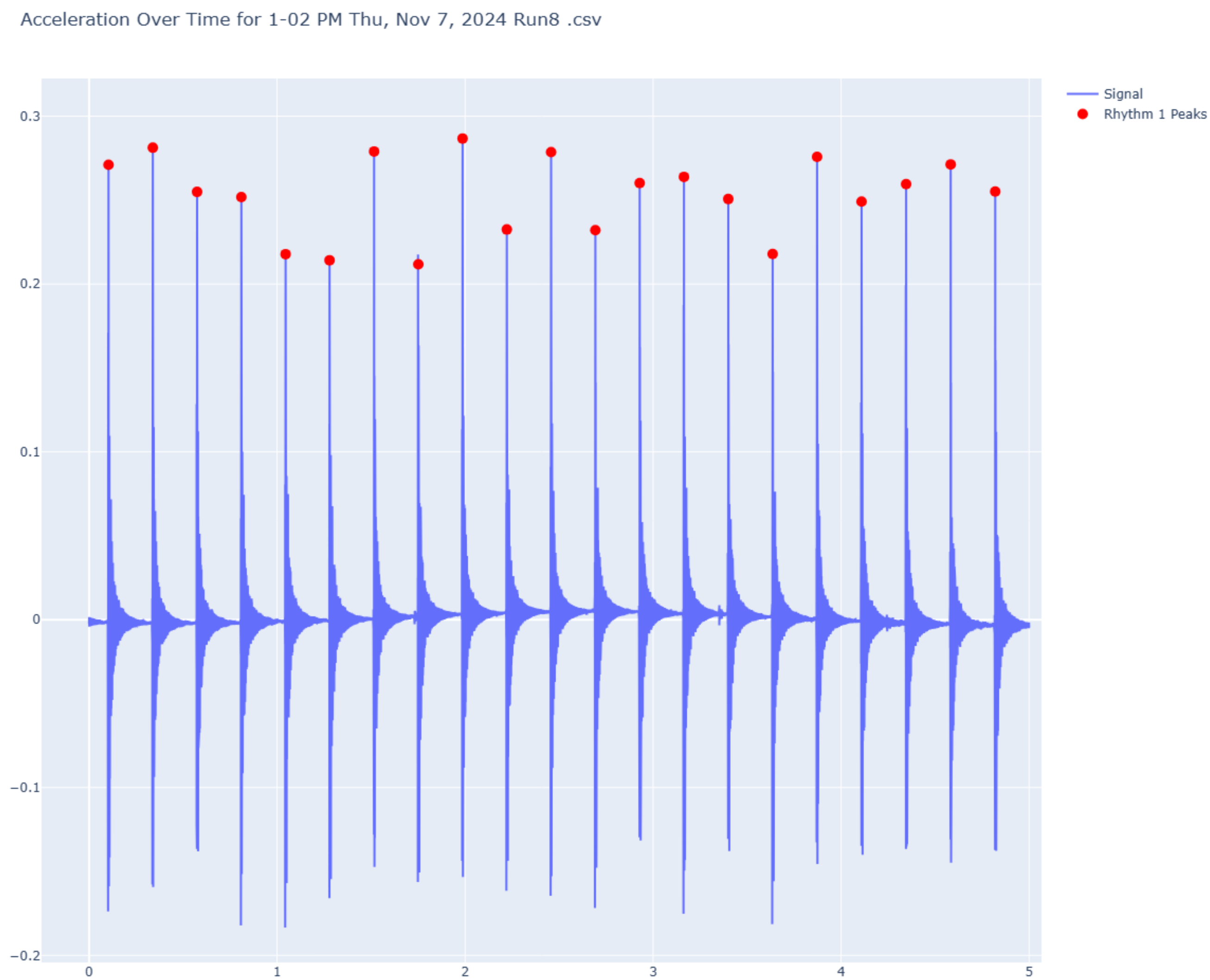

Fig. 6. Example of a manually labeled acoustic run using the custom Dash labeling interface. Peaks are identified and validated based on visual inspection and contextual features.