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FRUGAL INNOVATION FOR SUSTAINABLE MANUFACTURING: RETROFITTING LEGACY STAMPING PRESSES WITH COTS SENSORS

Small and Medium-sized Enterprises operating legacy stamping presses often lack affordable diagnostics, risking undetected tool damage. This study proposes a frugal vibroacoustic retrofitting methodology using a low-cost piezoelectric sensor and edge processing. Experiments compared normal blanking (0.5 mm brass) with simulated double-hits (0.1 mm spacer). Analyses revealed that abnormal events generate distinct, highly impulsive transients with shorter post-impact signal persistence and elevated broadband energy including mid- and high-frequency components. Unsupervised clustering confirmed reliable detection using simple features despite partial signal overlap. The approach enables cost-effective tool protection and sustainable asset life-extension, supporting Zero-Defect Manufacturing in resource-constrained environments.

1. INTRODUCTION

Manufacturing industries face increasing pressure to reduce material waste, energy consumption, and environmental impact while maintaining high productivity and quality standards [1]. Sustainable manufacturing refers to the production of goods through processes that minimize negative environmental impacts, reduce the consumption of energy and natural resources, ensure safety for workers, communities, and end users, and remain economically viable. This concept extends beyond product design to encompass manufacturing processes and production systems throughout the entire lifecycle, requiring a holistic consideration of environmental, economic, and social dimensions in accordance with the triple bottom line framework [2]. Within the Circular Economy paradigm, extending the operational lifetime of existing production assets is recognized as one of the most effective strategies for reducing embodied carbon and avoiding premature capital replacement. Rather than focusing exclusively on recycling or end-of-life recovery, Circular Economy frameworks emphasize slowing resource loops by prolonging the useful life of machines, tools, and production systems [3].

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Empirical evidence from industry suggests that despite the rapid development of Industry 4.0 technologies, many Small and Medium-sized Enterprises (SMEs) continue to operate legacy metal stamping presses that lack integrated sensing and diagnostic capabilities. Full machine replacement or high-end digital retrofitting is often economically infeasible for such companies, leading to reactive maintenance strategies and limited process visibility. As a consequence, critical process anomalies may remain undetected until significant material scrap, tool damage, or unplanned downtime occurs.

In progressive stamping operations, slug-related anomalies – such as slug pulling, stacking, or abnormal double-hits – represent a particularly critical failure mode [4]. These events introduce unintended contact conditions during tool closure, generating localized overloads that can rapidly escalate into catastrophic tool failure. Beyond direct tooling costs, undetected anomalies result in wasted material, unnecessary energy consumption, and premature degradation of tooling components manufactured from resource-intensive materials such as tool steels and carbides. Moreover, they generate additional organizational losses in the form of increased workload of operators and maintenance staff related to interventions, diagnostics, changeovers and unplanned machine downtime.

Condition-based maintenance (CBM) has long been proposed as an effective approach for reducing unplanned failures by linking maintenance decisions to machine condition rather than fixed schedules. Classical CBM frameworks consist of data acquisition, signal processing, and maintenance decision-making stages [5]. However, in the context of sheet metal stamping, practical CBM implementation remains limited due to the complexity of the process and the cost and invasiveness of traditional sensing solutions, such as embedded force or displacement sensors [6].

Acoustic emission (AE) and vibroacoustic sensing offer an alternative pathway for process supervision in forming operations. AE techniques are capable of capturing transient elastic waves generated by friction, impact, and material deformation, often before macroscopic damage becomes visible. Importantly, such sensing can be implemented externally, without direct modification of tooling geometry, making it attractive for retrofitting legacy equipment. This paper addresses the identified gap by proposing a frugal retrofitting methodology for legacy stamping presses based on low-cost vibroacoustic sensing and edge-level signal processing. The objective is not to replicate complex Industry 4.0 architectures, but to demonstrate that early detection of slug-related anomalies can be achieved using commercially available sensors and minimal computational infrastructure. By enabling early intervention, the proposed approach supports Zero-Defect Manufacturing strategies while contributing to sustainability through tool life extension, scrap reduction, and avoidance of premature equipment replacement.

2. LITERATURE REVIEW

2.1. ACOUSTIC EMISSION IN SHEET METAL FORMING

Acoustic emission techniques have been investigated for several decades as a means of monitoring forming processes, including blanking, drawing, and stamping. Early reviews established that AE signals generated during metal forming contain information related to friction, plastic deformation, and tool–workpiece interaction, positioning AE as a viable in-process monitoring technique [7].

Subsequent experimental studies demonstrated that AE energy and amplitude are closely related to mechanical energy dissipation at the contact interface. Investigations in stamping environments showed that increases in friction, galling, and tool wear are accompanied by measurable changes in AE signal characteristics [8]. These findings established a physical basis for interpreting AE not as incidental noise, but as a process-relevant signal reflecting contact phenomena.

More detailed tribological investigations further revealed that different wear mechanisms generate distinct AE signatures. Adhesive wear and severe contact events were shown to produce high-frequency AE components, while milder abrasive mechanisms tend to be associated with lower-frequency [9]. This mechanistic understanding is particularly relevant for detecting abnormal impact events, such as slug-induced double-hits, which involve localized adhesive and impact-dominated contact conditions.

2.2. AE-BASED DETECTION OF DEFECTS AND TOOL DEGRADATION IN STAMPING

Several studies have demonstrated the applicability of AE sensing for detecting defects and degradation in industrial stamping environments. Real-time AE-based crack detection systems have been successfully implemented in automotive stamping lines, using frequency-band filtering and amplitude-based features to distinguish normal and defective states under production [7]. These results confirm that meaningful diagnostic information can be extracted without complex sensor fusion or high-resolution force measurements.

AE has also been applied to the monitoring of surface damage mechanisms such as galling, a dominant wear mode in sheet metal forming. Experimental investigations identified a staged evolution of AE activity corresponding to elastic–plastic deformation, material transfer, and catastrophic rupture [4]. Importantly, AE activity was observed to increase before severe surface damage became visible, highlighting the potential for early intervention.

Time-series analyses of AE signals during stamping have further shown that signal features evolve systematically with tool wear progression, despite the non-stationary nature of the process [10]. While many studies focus on long-term wear monitoring, these findings support the feasibility of detecting transient anomalies associated with abnormal contact events.

2.3. CONDITION-BASED MAINTENANCE IN STAMPING PROCESSES

Condition-based maintenance frameworks provide the conceptual foundation for linking process monitoring to maintenance decisions. Comprehensive reviews of CBM highlight the importance of early fault detection and diagnostic reliability, emphasizing that even simple threshold-based approaches can yield significant benefits when appropriately implemented [11].

In the specific context of sheet metal blanking and stamping, CBM research remains comparatively limited. Existing approaches predominantly rely on force–displacement monitoring to infer tool condition and wear progression [12]. While effective, such methods typically require dedicated sensors integrated into the press structure or tooling, which increases cost and limits retrofitting potential for legacy machines.

The complexity and investment requirements associated with these solutions have hindered widespread adoption in SMEs. This gap motivates the exploration of alternative sensing modalities that can support CBM objectives with reduced system complexity.

2.4. SUSTAINABILITY PERSPECTIVE AND RESEARCH GAP

From a sustainability standpoint, preventing catastrophic tool failure and excessive scrap generation directly contributes to extending asset lifetimes and reducing resource consumption. Circular Economy frameworks explicitly identify life extension and maintenance-driven strategies as higher-value interventions than material recycling alone.

Despite extensive research on AE-based diagnostics and condition-based maintenance, including advanced cyber-physical monitoring and control architectures developed for Industry 4.0 machining systems [13, 14], limited attention has been paid to low-cost, frugal implementations tailored to legacy stamping equipment operating in resource-constrained environments [10]. Recent reviews on acoustic anomaly detection highlight that, although AE remains a dominant sensing modality, practical deployment in noisy industrial settings – particularly with minimal hardware – remains an open challenge [6].

This study addresses this gap by combining vibroacoustic sensing, non-destructive surrogate fault injection, and edge-level processing into a frugal retrofitting methodology aimed at sustainable operation of legacy stamping presses. The focus is placed on early anomaly detection rather than comprehensive wear modelling, aligning technical feasibility with sustainability objectives relevant to SMEs.

3. METHODOLOGY

3.1. CONCEPT OF FRUGAL INNOVATION IN MANUFACTURING DIAGNOSTICS

Frugal innovation focuses on delivering essential functionality through simplified and cost-efficient solutions, making advanced technologies accessible to organizations with limited financial and technical resources [15]. In the context of manufacturing diagnostics, this approach prioritizes early anomaly detection rather than comprehensive machine modelling or high-resolution monitoring.

The proposed methodology operationalises frugal innovation as a research and implementation strategy for diagnostics in stamping environments where resources are limited. Instead of pursuing high-end multi-sensor architectures or invasive instrumentation, the approach deliberately prioritises minimal hardware complexity, non-intrusive installation, and physically interpretable features that can be computed at the edge. As conceptually illustrated in Fig. 1, a single automotive-grade piezoelectric sensor is used as the primary transducer to capture impact-driven vibroacoustic responses during tool closure. The sensor signal is acquired using low-cost consumer electronics and processed locally (edge layer) to extract stroke-level descriptors within brief post-impact windows.

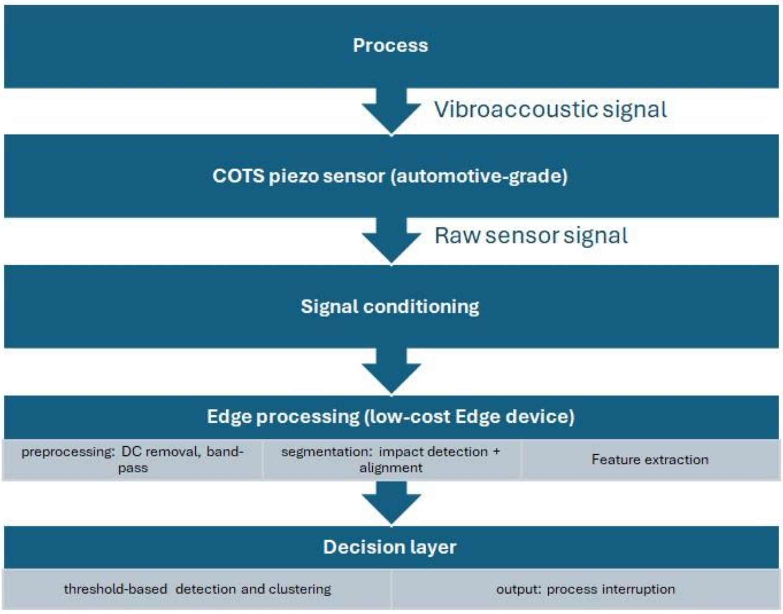

Fig. 1. Conceptual schematic of the proposed frugal vibroacoustic monitoring methodology

This enables detection after a single stroke without reliance on cloud infrastructure or large labelled datasets. The validation design employs a controlled comparative framework comprising three repeatable process states (no material condition, stable blanking, and surrogate abnormal contact). The introduction of the abnormal state is achieved via non-destructive fault injection (copper spacer) to reproduce impact-like contact conditions, while ensuring asset protection and experimental repeatability. The design is intended to isolate the diagnostic signature of abnormal contact from confounding factors, thereby enabling the feasibility of threshold-based detection and unsupervised structure discovery to be evaluated under realistic constraints representative of SME retrofitting scenarios.

3.2. EXPERIMENTAL SETUP AND VALIDATION STRATEGY

Experimental validation was conducted using a laboratory test based on a pneumatic press. While simplified relative to industrial stamping presses, this setup enables controlled reproduction of impact events and repeatable experimentation under safe conditions.

The piezoelectric sensor was mounted in direct mechanical contact with the base plate to maximize sensitivity to transient vibroacoustic phenomena generated during tool closure. The experimental setup, including sensor placement, signal acquisition chain, and edge-processing architecture, is schematically illustrated in Fig. 2.

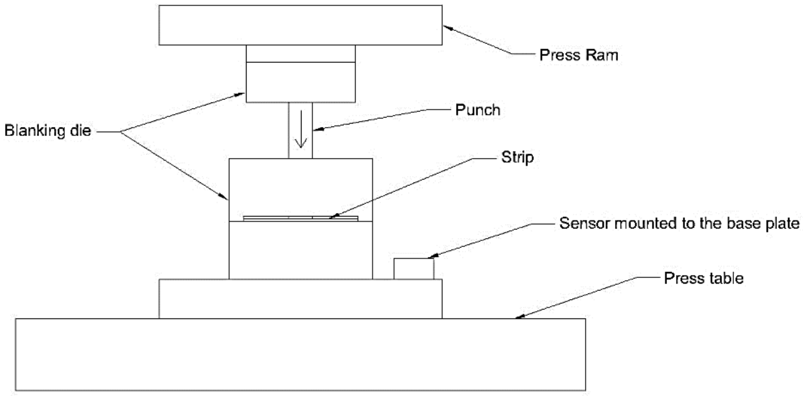

Fig. 2. Schematic representation of the experimental workstation. The setup consists of a pneumatic press equipped with a blanking die and a strip material, with a piezoelectric sensor mounted on the base plate. The sensor captures vibroacoustic signals generated during punch–die interaction under different operating conditions

Three experimental conditions were investigated in order to evaluate the feasibility of vibroacoustic-based detection of abnormal contact events in a stamping process. All tests were performed on a pneumatic press using the same tooling configuration and sensor placement. The base material for blanking experiments was CuZn37 brass strip with a thickness of 0.5 mm. The following test cases were defined to evaluate detection feasibility: (1) No material condition (10 strokes) without material, representing baseline dynamics; (2) Normal blanking condition (10 strokes) processing 0.5 mm CuZn37 brass strip; and (3) Simulated double-hit condition (10 strokes) with a 0.1 mm copper spacer inserted at the tool interface to reproduce abnormal contact forces while ensuring asset protection.

This experimental design enabled controlled comparison between reference conditions and fault-like events while ensuring repeatability and asset protection. Direct experimentation involving real slug pulling events poses a substantial risk of irreversible tool damage. To ensure asset protection and experimental repeatability, a non-destructive surrogate fault injection method was developed. To validate detection capability safely, a thin copper spacer with a thickness of 0.1 mm was introduced into the tool interface to simulate the presence of a foreign body during press closure. This surrogate fault reproduces abnormal impact conditions analogous to early-stage slug-related anomalies without damaging tooling components. Furthermore, successfully detecting such a thin inclusion (0.1 mm) confirms the system’s high sensitivity, implying that full-thickness double hits (e.g., 0.5 mm) would be detected with an even greater margin of confidence.

The method enables systematic comparison between normal and anomalous strokes while adhering to sustainable research practices.

4. RESULTS

4.1. TIME-DOMAIN ANALYSIS

Time-domain analysis was conducted on vibroacoustic recordings acquired under three experimental conditions (no material condition, normal blanking, and simulated double-hit using a copper spacer). Each recording was processed by removing DC offset, resampling to 48 kHz for strict comparability, and applying a consistent band-pass filter (300–18,000 Hz) to emphasize impact-related content. Individual press strokes were segmented by detecting peaks in a smoothed absolute amplitude envelope (moving-average of |signal|) with a robust median–MAD threshold and a minimum inter-stroke separation. Detected impacts were further refined by aligning each event to the local maximum of |signal| within ±2 ms. For each stroke, threshold-based persistence metrics were computed within a 0–50 ms post-impact window - the cumulative time above a given fraction of the peak amplitude. Accordingly, the time axis in Fig. 3 includes a short pre-impact interval represented by negative time values, where t = 0 corresponds to the aligned impact peak. Figure 3 compares the mean absolute vibroacoustic waveforms recorded under no material, normal blanking, and simulated double-hit conditions. Clear differences in post-impact signal persistence can be observed, particularly for the double-hit condition, which exhibits a shorter and more impulsive transient response.

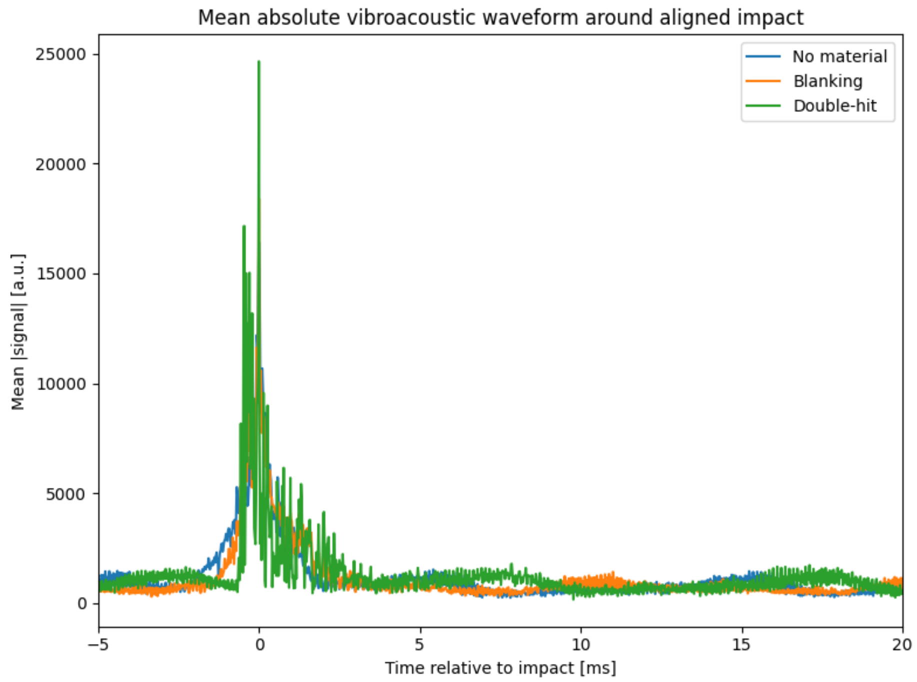

Fig. 3. Mean absolute vibroacoustic waveform (|signal|) around the aligned impact, averaged over 10 strokes for each experimental condition. The signals are aligned such that t = 0 corresponds to the impact peak; negative time values represent the pre-impact interval. Amplitudes are shown in arbitrary units (a.u.)

For the no material condition, the mean transient duration amounted to 7.173 ± 6.411 ms. Although no material shearing occurs in this case, the press closure and structural excitation generate repeatable impact responses with moderate post-impact persistence times. The relatively large standard deviation reflects variability in structural vibration modes excited during unloaded strokes.

In the normal blanking condition, a comparable mean duration of 5.123 ± 3.840 ms was observed. The similarity between no material and blanking conditions indicates that peak-based duration alone is insufficient to distinguish stable blanking from unloaded strokes.

Nevertheless, the presence of material shearing introduces additional frictional and plastic deformation mechanisms, contributing to sustained vibroacoustic activity and a broad interquartile range, as illustrated in Fig. 4.

In contrast, the simulated double-hit condition exhibited a distinctly shorter mean transient duration of 3.373 ± 1.886 ms. This reduction indicates a more impulsive response with shorter post-impact signal persistence and suggests a contact condition potentially associated with higher effective contact stiffness and reduced energy dissipation time associated with abnormal contact caused by the copper spacer. While individual stroke variability remains high, the downward shift in central tendency is clearly visible in both mean and median values.

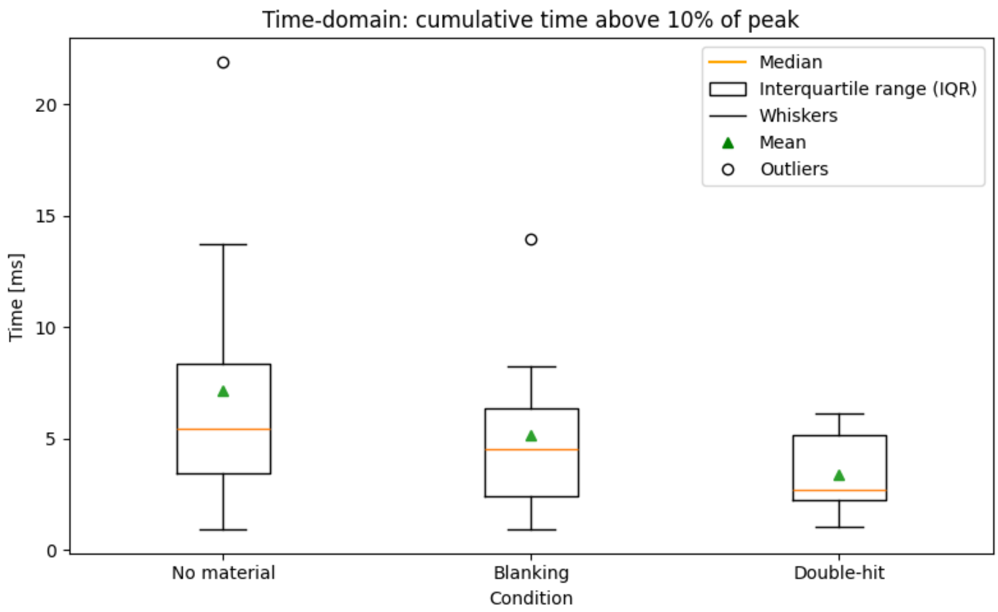

Fig. 4. Boxplots of the cumulative time above 10% of the peak amplitude calculated for individual strokes under no material, blanking, and double-hit conditions. Each box represents ten strokes per condition; the central line indicates the median, the box denotes the interquartile range (IQR), the whiskers represent the data range excluding outliers, the triangle marker indicates the mean value, and dots represent outliers

Overall, the results demonstrate that double-hit events tend to produce shorter-lived but more impulsive vibroacoustic transients, whereas no material and normal blanking strokes exhibit longer and more variable signal persistence. Although partial overlap between conditions exists due to structural dynamics and the limited dataset size, the transient duration above 10% of peak amplitude provides a robust, low-complexity time-domain indicator capable of contributing to early abnormal event detection.

4.2. FREQUENCY-DOMAIN ANALYSIS

Frequency-domain analysis was performed using Welch's method on the filtered recordings (300–18,000 Hz) to estimate the power spectral density (PSD) under the three experimental conditions. The analysis was conducted on the full-length recordings using overlapping windowed segments, and averaged PSD spectra were computed for each condition to ensure robust spectral estimation. Figure 5 shows the averaged PSD spectra for the three investigated process conditions.

The no material condition established the baseline spectral profile. Contrary to an idealized quiet baseline, the spectrum exhibited measurable energy extending into the high-frequency range, dominated by structural resonances (e.g., narrowband peaks around 8.6 kHz) associated with the press actuation mechanism.

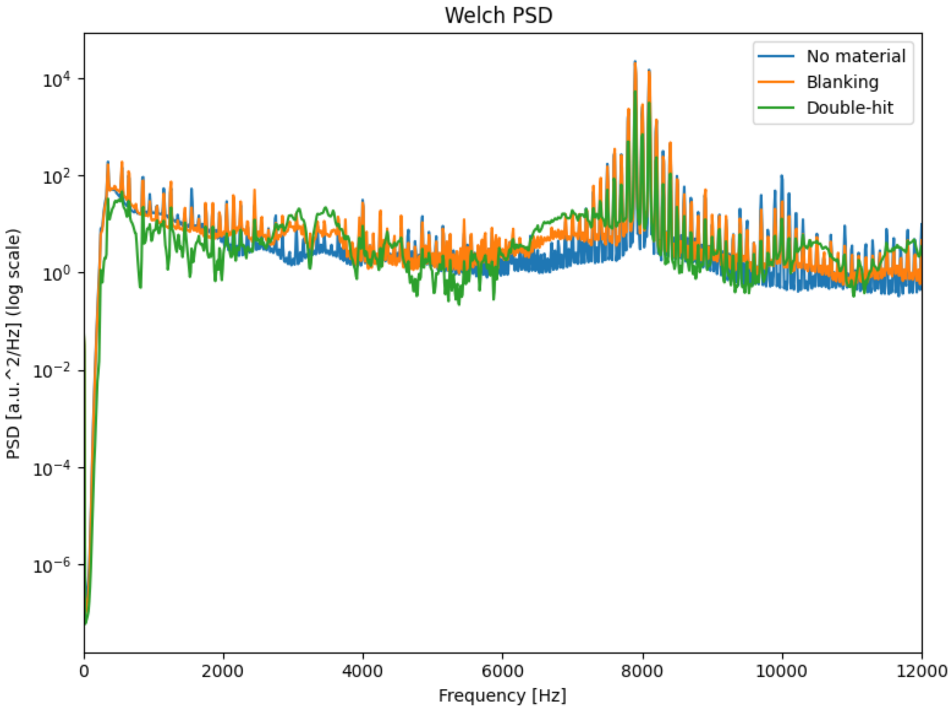

Fig. 5. Averaged power spectral density (PSD) spectra of vibroacoustic signals recorded under no-material, normal blanking (0.5 mm CuZn37), and simulated double-hit (0.1 mm spacer) conditions

During normal blanking, a moderate increase in low- to mid-frequency spectral energy (1–6 kHz) was observed compared to the no material condition, as confirmed by the increased band power in this range. This behavior is consistent with stable material shearing, where part of the mechanical energy is dissipated through the blanking process, resulting in a redistribution of spectral energy toward lower frequencies while maintaining a spectral shape comparable to the baseline in the higher-frequency range.

In contrast, the simulated double-hit condition generated a distinct spectral signature characterized by a redistribution of broadband spectral energy. While the structural resonance peaks (7–9 kHz) remained present across all conditions, the double-hit event produced a consistent elevation of spectral amplitudes, particularly in the 1–6 kHz band. This indicates that the impact-dominated contact phenomena associated with the copper spacer excite the machine structure more intensely, primarily through elevated mid-band energy (1–6 kHz) and localized high-frequency enhancement in the 7–9 kHz range.

A consistent local enhancement of spectral energy was observed in the 6–7 kHz band across all process conditions. While normal blanking causes a slight amplification of this resonance, the double-hit condition results in a more pronounced and variable increase, indicating intensified excitation of the same structural mode during impulsive contact events rather than the emergence of new high-frequency components.

The observed spectral differences indicate that abnormal contact events produce measurable energy shifts that can be detected using low-cost piezoelectric sensors. Importantly, this distinction is achieved by monitoring the broadband energy distribution rather than relying solely on specific high-frequency peaks, supporting the feasibility of threshold-based anomaly detection for real-time protection of stamping tools.

4.3. FEATURE-BASED AND MULTIVARIATE ANALYSIS

To complement the time- and frequency-domain investigations, a feature-based multivariate analysis was conducted to assess whether a limited set of physically meaningful features is sufficient to differentiate normal and abnormal contact events. Rather than focusing on detailed signal morphology, this analysis aims to evaluate the discriminative potential of simple stroke-level descriptors suitable for low-cost, real-time implementation.

For each press stroke, a small number of scalar features was extracted from the vibroacoustic signal within a short post-impact time window (0–10 ms). This window was selected to capture the transient response associated with tool–material interaction while minimizing the influence of background vibrations and subsequent structural ringing. The extracted features included RMS value, total signal energy, and energy content within the high-frequency range identified in Section 4.2 as characteristic of impact-dominated contact phenomena. Based on their discriminative behavior and robustness, a reduced subset of features focusing on peak amplitude and narrowband spectral energy in the 6–7 kHz range was selected for the clustering analysis.

The resulting feature vectors provide a compact representation of each stroke, enabling direct comparison between process conditions without relying on complex signal transformations or large training datasets. Inspection of the feature distributions indicates that no material and normal blanking strokes exhibit partially overlapping characteristics, reflecting stable and repeatable process dynamics. In contrast, strokes recorded under the simulated double-hit condition tend to exhibit increased energy-related features and more impulsive (shorter-persistence) transient responses.

Although complete separation between all three conditions is not observed at this stage, the feature space reveals a consistent tendency for simulated double-hit strokes to deviate from normal blanking behaviour. This suggests that thickness-related abnormal contacts introduce systematic changes in the vibroacoustic response that are captured by simple, physically interpretable features.

4.4. UNSUPERVISED CLUSTERING OF STROKE-LEVEL FEATURES

To assess whether the extracted features reveal structure in the data without prior labelling, an unsupervised k-means clustering analysis was performed. Each press stroke was represented by a low-dimensional feature vector composed of physically interpretable descriptors, including the band power in the 6–7 kHz range and absolute peak value, computed within the 0–10 ms post-impact window described in Section 4.3. All features were normalized prior to clustering. Figure 6 shows the distribution of stroke-level features in the PCA space with k-means clustering ($k = 3$). The PCA coordinates shown in Fig. 6 represent transformed and centred feature values and may therefore take both positive and negative values.

Clustering assuming three clusters did not yield a strict one-to-one correspondence with the experimental conditions. Nevertheless, a consistent tendency was observed: strokes recorded under the simulated double-hit condition more frequently grouped together and occupied a distinct region of the feature space characterized by increased energy and more impulsive transient response. In contrast, no material and normal blanking strokes exhibited greater similarity, reflecting their stable and repeatable contact conditions.

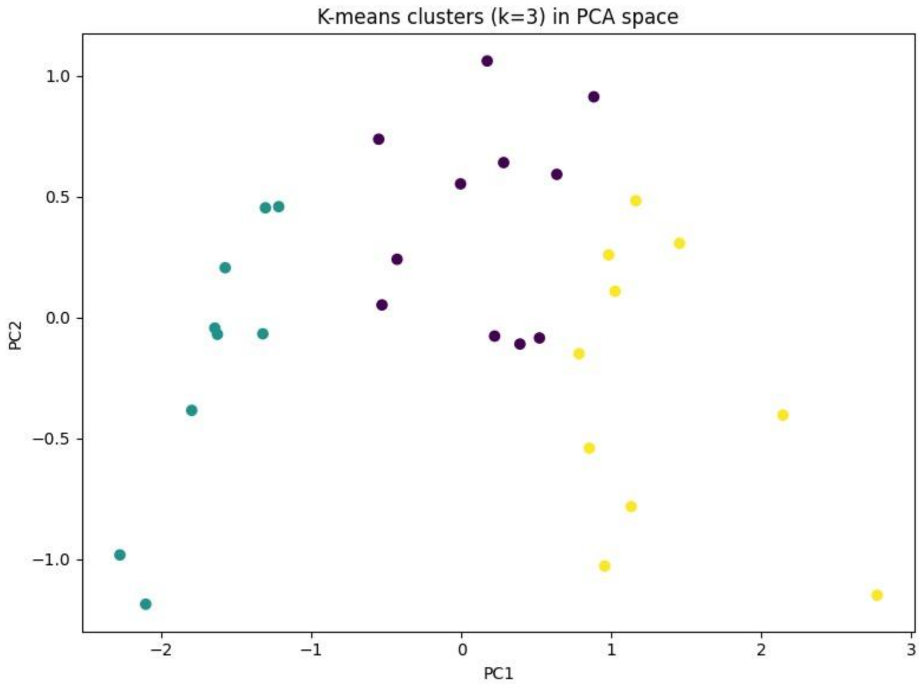

Fig. 6. Projection of stroke-level vibroacoustic features into a two-dimensional PCA space with k-means clustering (k = 3). Each point represents a single press stroke described by physically interpretable features (peak amplitude and narrowband spectral energy in the 6–7 kHz range). Colours indicate cluster membership assigned by the unsupervised algorithm

To evaluate practical applicability, a second clustering experiment using two clusters was conducted to represent normal operation and abnormal contact events. In this configuration, all simulated double-hit strokes were consistently assigned to the same cluster in this configuration with the majority of normal blanking strokes (8 out of 10) while all no material strokes and minority of normal blanking strokes (2 out of 10) grouped together. Although partial overlap remained, particularly between normal process states, the unsupervised algorithm identified a dominant abnormal cluster driven by the injected spacer events.

For three clusters, strokes associated with the simulated double-hit condition again exhibited a dominant clustering tendency (7 out of 10), whereas no material and blanking strokes showed greater dispersion across clusters, reflecting their similar and stable process dynamics.

Overall, the clustering results indicate that a small set of simple, physically interpretable features is sufficient to expose latent structure in the data and to distinguish abnormal contact events from normal operation to a large extent. Given the limited dataset size and the physical similarity between normal process conditions, complete separation was not expected. Nevertheless, the results support the use of the proposed features as a basis for threshold-based monitoring and future supervised learning approaches once larger datasets become available.

5. DISCUSSION

The observed vibroacoustic characteristics are consistent with previous acoustic emission studies in metal forming processes. It has been shown that AE signals are directly related to energy dissipation mechanisms at the contact interface, including friction, plastic deformation, and wear-related phenomena [8, 9].

In particular, increased signal energy and impulsive transient responses have been associated with adhesive interactions, galling, and impact-dominated contact conditions [4, 8]. Experimental studies have also demonstrated that AE activity is closely related to the mechanical energy dissipated between contacting surfaces, providing a physical basis for interpreting signal amplitude and spectral energy distribution [7, 8].

Furthermore, different wear and contact mechanisms generate distinct frequency-domain signatures, with severe contact events producing elevated high-frequency components and broadband energy increases [9]. The results obtained in this study – particularly the increased mid-frequency energy and more impulsive time-domain response observed for simulated double-hit conditions – are consistent with these findings and indicate that abnormal contact events introduce measurable changes in energy dissipation and structural excitation of the system.

Beyond the detection of double-hit events, acoustic emission and vibroacoustic sensing are not limited to a single failure mode. Previous studies have demonstrated that AE signals can be used to identify a wide range of process anomalies in sheet metal forming, including tool wear, galling, cracking, and lubrication-related issues [4]. In particular, AE has been shown to provide early indication of surface damage mechanisms and changes in friction conditions before visible defects occur, enabling proactive intervention. This suggests that the proposed methodology may be extended to other fault types, provided that they generate distinguishable changes in vibroacoustic response [4, 7].

Slug-related anomalies and double-hit events represent a critical threat to tooling integrity in stamping operations, particularly in legacy presses where in-process diagnostics are limited. The results presented in Sections 4.1–4.4 demonstrate that abnormal contact events generate repeatable vibroacoustic signatures that can be detected at the stroke level, enabling intervention immediately after the first affected event using low-cost sensing and simple features. From a sustainability perspective, this capability is significant because it enables early process interruption before cumulative damage occurs [16].

Preventing repeated abnormal impacts directly contributes to tool life extension, reducing the frequency of tool repair, refurbishment, or replacement. Given that stamping tools are typically manufactured from high-alloy steels or cemented carbides with high embodied energy, extending their service life aligns with Circular Economy strategies focused on asset retention and life extension rather than replacement [17]. Even incremental improvements in early fault detection can therefore translate into disproportionate environmental benefits over the tool lifecycle.

In conventional stamping operations without real-time anomaly detection, slug-related faults may remain undetected for extended periods, resulting in the production of large batches of defective parts and unnecessary energy consumption. The proposed approach enables detection of abnormal contact events after the first affected stroke, limiting scrap generation to a single part and avoiding continued energy use associated with defective production.

Although the present study does not quantify absolute energy or material savings, the experimental results indicate a clear pathway toward Zero-Defect Manufacturing principles [18], where defects are prevented rather than inspected out after production. By minimizing scrap and reducing rework and downtime, the methodology supports improved material efficiency and lower energy consumption per conforming component, contributing to reduced manufacturing-related environmental impact.

A central contribution of this work lies in demonstrating that meaningful diagnostic information can be obtained using a frugal retrofitting approach based on commercial off-the-shelf components. Unlike force-based or embedded sensor solutions, the proposed vibroacoustic monitoring system requires no modification of tooling geometry and minimal integration effort, making it suitable for legacy presses commonly used in Small and Medium-sized Enterprises.

From a sustainability perspective, this accessibility is critical. High investment requirements often prevent SMEs from adopting advanced monitoring technologies, indirectly encouraging premature machine replacement. By lowering technical and financial barriers, the proposed methodology enables SMEs to improve process reliability and product quality while extending the useful life of existing equipment. This democratization of diagnostic capability supports sustainable industrial development by aligning environmental objectives with realistic economic constraints. The total hardware cost of the prototype system, including the single-board computer and conditioning electronics, was approximately 100 EUR. This represents a negligible fraction of the investment required for dedicated industrial monitoring solutions, which often exceed several thousand euros.

A key challenge for the practical implementation of acoustic-based monitoring systems is the presence of significant background noise in industrial environments. Previous studies have shown that signals generated by surrounding machinery and tooling may exhibit higher amplitudes than those originating from the forming process itself, complicating signal interpretation [10].

In the present study, this limitation was partially addressed through consistent band-pass filtering and the use of short post-impact analysis windows, which reduce the influence of background vibrations and structural ringing. Furthermore, the use of physically interpretable features focused on transient responses improves robustness to non-stationary noise conditions.

Nevertheless, validation under industrial production conditions remains an important direction for future work. In particular, the robustness of the proposed approach to varying noise levels, machine configurations, and process disturbances will be critical for practical deployment.

6. CONCLUSIONS AND FUTURE WORK

This study presented a frugal vibroacoustic monitoring methodology for the detection of abnormal contact events in a stamping process, with a particular focus on simulated double-hit conditions representative of slug-related anomalies. The proposed approach targets legacy stamping presses commonly used in Small and Medium-sized Enterprises, where advanced in-process diagnostics are often unavailable.

Experimental validation was conducted on a pneumatic press using three controlled test conditions: no material, normal blanking of 0.5 mm CuZn37 material, and simulated double-hit events introduced via a 0.1 mm copper spacer. Vibroacoustic signals were recorded and analysed using simple time-domain, frequency-domain, and feature-based methods. The results demonstrated that simulated double-hit events generate distinctive and repeatable signatures, characterized by more impulsive transients with shorter post-impact signal persistence in the time domain and broadband energy amplification (particularly in the 1–6 kHz range) in the frequency domain.

Feature-based analysis confirmed that a small set of physically interpretable indicators – namely RMS value, signal energy, and transient persistence – captures systematic differences between normal blanking and abnormal contact events. Unsupervised clustering further revealed that strokes associated with simulated double-hits tend to group together without prior labelling, despite partial overlap with normal operating conditions. This confirms that meaningful structure is present in the data even when using a minimal feature set and simple analysis techniques.

From a sustainability perspective, the proposed methodology enables early process interruption after a single abnormal stroke, supporting tool protection, scrap reduction, and energy efficiency improvements. By relying on low-cost commercial components and non-intrusive installation, the approach offers a practical pathway for extending the useful life of existing equipment and aligns with Circular Economy principles emphasizing asset life extension over replacement.

The presented work constitutes a proof of concept and, as such, has limitations related to the small dataset size and laboratory-scale experimental setup. Future work will focus on validation under industrial production conditions, expansion of the dataset to cover a wider range of materials and fault severities, and refinement of decision thresholds for real-time implementation. The methodology also provides a foundation for subsequent supervised learning approaches once sufficient data become available, while preserving the frugal and sustainable character of the proposed system.

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