Development of a Sound Analysis Tool for Pre-Diagnosis of Mechanical Failure

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Abstract - Early detection of mechanical faults in rotating machinery prevents unplanned downtime and reduces maintenance costs. Traditional vibration analysis remains the reference method, but it requires dedicated sensors and data acquisition systems that are not always available in the field. This paper presents a smartphone-based sound analysis method for pre-diagnosis of faults, focusing on audible acoustics (20 Hz–20 kHz) as a practical, low-cost complement to vibration analysis. We describe an end-to-end workflow - acquisition, preprocessing, feature extraction, fault indicators, and decision logic - implemented in Python. Two case studies are included: (i) a wind-turbine pitch drive with suspected planetary stage issues, and (ii) an electric motor with bearing tones consistent with BPFO/BPFI. Results show that sound spectra, envelopes, and time–frequency maps can reveal consistent spectral components associated with gear mesh and rolling bearing kinematics, enabling consistent field triage and decision-making when vibration tools are unavailable. We discuss the advantages and limitations. The proposed approach does not replace vibration analysis; instead, it bridges the gap between qualitative listening and instrumented diagnostics, accelerating triage and decision-making in the field.

Index Terms — Acoustic analysis, smartphone sensing, condition monitoring, bearings, gear mesh, wind turbine, electric motors, predictive maintenance.

I. INTRODUCTION

Sound analysis has long been utilized in industrial environments as an intuitive method for assessing machine condition. Although a wide range of acoustic technologies exists, this work focuses specifically on audible-range airborne sound acquired with smartphones, distinguishing it from ultrasonic or structure-borne techniques. Traditional sound-based assessments are typically quantitative, focusing on global noise levels or compliance with acoustic limits, which provides limited diagnostic insight into the mechanical sources of a fault. In contrast, faults in rotating machinery—such as bearing defects, gear-mesh irregularities, looseness, and impacts—manifest through distinct spectral signatures that can be revealed when sound is analyzed in the frequency domain.

Although audio-frequency vibration phenomena can be captured with microphones, many commercial smartphone applications focus on sound-level measurements require licensing fees or provide only limited access to raw spectral data. Considering the large number of field technicians typically involved in maintenance operations, equipping every individual with paid applications becomes impractical. Moreover, these apps rarely integrate contextual information, such as camera orientation or distance to the component, which is essential for reliable interpretation in the field.

The key innovation of this work lies not in the concept of sound analysis itself, but in the use of an ordinary smartphone as a synchronized audio–video acquisition device. By recording short video clips instead of audio alone, the technician captures both the sound spectrum and the physical context of the measurement—camera angle, approximate distance to the component, and intentional spatial scanning. This produces a traceable field record that improves procedural consistency across technicians. Metrological repeatability is not established nor intended within the scope of this method; rather, the objective is to standardize acquisition practices and enhance traceability for pre-diagnosis, while quantitative assessments remain the role of calibrated vibration or ultrasonic instrumentation.

This paper introduces a smartphone-based acoustic workflow for rapid pre-diagnosis in rotating machinery, providing a lightweight complement to conventional vibration analysis.

II. LITERATURE REVIEW

Sound-based assessment of machinery has evolved significantly over the past century. The earliest forms of acoustic evaluation were entirely qualitative, relying on the human ear as the primary diagnostic instrument. Operators, mechanics, and engineers interpreted abnormal tones, rattles, or pulsations as indications of mechanical problems. This informal practice was widespread long before the development of modern condition-monitoring technologies [1].

More structured acoustic monitoring began to take shape in the mid-20th century, driven initially by advances in sound recording technology developed for military, broadcast, and scientific applications. Improvements in microphones, portable recorders, and early analog spectrum analyzers enabled the first attempts to document and analyze machine sounds more systematically. Throughout the 1960s and 1970s, sound analysis increasingly incorporated frequency-domain methods, as digital and analog instruments became capable of identifying tonal components in recorded audio [1].

A major milestone occurred with the emergence of Acoustic Emission (AE) technology in the late 1960s, marking the first formal application of acoustic techniques to rotating machinery. AE research expanded rapidly in the subsequent decades, demonstrating that transient elastic waves generated by impacts, crack growth, friction, and material deformation could be used to detect early-stage mechanical faults in bearings, gearboxes, pumps, and engines. AE techniques were originally developed for structural testing but were soon adapted to machine diagnostics due to their high sensitivity and ability to detect microscopic damage earlier than vibration analysis [2].

While AE dealt mostly with ultrasonic signals, a parallel branch of research focused on audible-range acoustic monitoring. With the spread of digital recording technologies in the late 20th and early 21st centuries, audible-sound - based methods became more accessible. Research in this period examined the use of microphones and airborne sensors as contact-free alternatives to vibration sensors, noting that acoustic signals can capture mechanical information when structural coupling is weak or when sensor placement is constrained [3].

Advances in mobile technology have made smartphones practical acoustic sensors for industrial monitoring. Their built-in microphones, sufficient sampling rates, and widespread availability enable low-cost sound-analysis workflows, as shown in Figure 1, have been increasingly recognized as viable tools for quick, low-cost condition monitoring due to their portability, ease of use, and widespread availability [1], [4].

Fig. 1 Example of noise measurement by smartphone.

Today, acoustic analysis in machinery spans a continuum - from human listening to professional sound-level meters, to ultrasonic AE systems, to modern digital and AI-enhanced techniques. Contemporary research emphasizes machine learning, anomalous sound detection, and acoustic scene analysis, expanding the diagnostic capabilities far beyond the qualitative methods of the past. Despite technological advancements, the underlying principle remains the same: machines produce characteristic acoustic signatures, and deviations from these patterns can reveal early signs of degradation [3].

This distinction is important because these three technologies evolved along different historical paths within acoustic diagnostics and serve fundamentally different purposes in practice.

AE, maintenance ultrasound, and smartphone-based audible sound analysis form three distinct branches of acoustic diagnostics. AE is a structure-borne nondestructive testing method based on transient elastic waves; maintenance ultrasound uses specialized airborne/structure-borne sensors in the 20–100 kHz range as defined in ISO 29821 [5], [6]; and the present work deals exclusively with audible-range airborne sound acquired by smartphones for field triage. These approaches differ in sensors, physical principles, signal characteristics, and diagnostic objectives.

III. METHODOLOGY

Starting from a smartphone-recorded video and ending with the extraction of fault-related spectral features. The methodology consists of four main stages: video acquisition, audio extraction, signal preprocessing, and fault-oriented spectral analysis.

A. Audio - Video Acquisition Using Smartphones

The diagnostic process begins with the recording of a short video (typically 5 - 15 seconds) using a standard smartphone. Video recording is preferred over a standalone audio recording because it provides:

- Visual context (camera distance, orientation, component being measured);
- The ability to verify operator movement and the position of the microphone during acquisition;
- Evidence for spatial variation of sound, allowing identification of localized noise sources;
- A fully traceable and replayable record for remote engineering analysis.

Typical smartphone microphones record at 44.1 kHz [7] or 48 kHz [8], which is sufficient to capture the audible spectrum relevant for mechanical fault signatures.

Recommended placement guideline. To minimize flow-induced noise, avoid placing the microphone directly in the path of cooling-fan airflow (or any directed airstream) [9].

B. Audio Extraction and Pre-Processing

The video is imported, and the audio track is extracted to WAV/PCM 16-bit. The signal is then conditioned to improve diagnostic content and comparability:

- DC offset removal
- Band-pass filtering (e.g., 20 Hz - 20 kHz) to eliminate irrelevant frequency content
- Resampling (if necessary) to a unified sampling rate
- Windowing and segmentation (1s segments, 50% overlap, Hann window)
- Normalization to equalize amplitude across recordings

These steps prepare the signal for high-resolution spectral analysis and ensure consistency across recordings obtained by different technicians.

C. Audio Signal Processing and Diagnostic Features

With the collected audio data, it becomes possible to perform a wide range of analyses, similar to what is commonly done with vibration signals. In this work, we opted for a focused set of techniques that provide consistent and interpretable pre-diagnostic value:

- Time-domain waveform analysis: inspection of periodicity, impacts, modulation, and general signal behavior.
- Frequency-domain (FFT): identification of salient tonal components and basic orders (1×, harmonics/sidebands).
- Envelope analysis: enhances impact events and bearing-related frequencies that may be hidden in the standard vibration spectrum.
- Waterfall plots: visualization of spectral evolution across time segments, see Figure 2, highlighting non-stationary behavior during start-ups, load changes, or transient events.

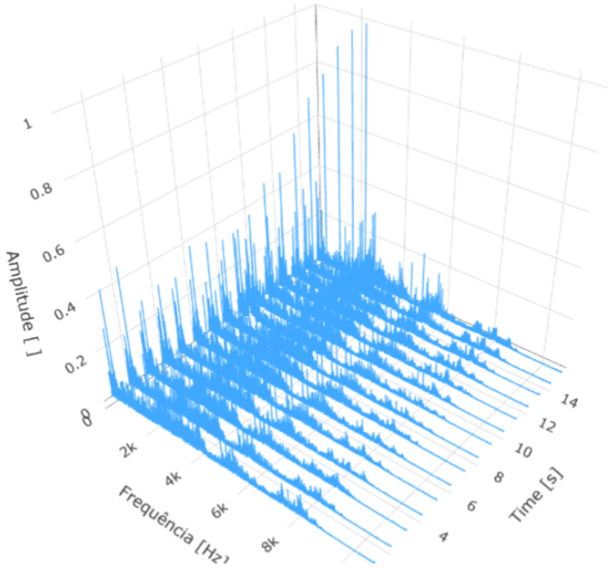

Fig. 2 Waterfall plot acquired by sound analysis.

IV. CASE STUDY

A. Wind Turbine Pitch Drive (Planetary Stage)

1) *Context and Operating Conditions:* A recording was made during pitch actuation of blade 1 from a prototype wind turbine (model AGW 4.2, see Figure 3). The rotor was stationary, and the motion was driven solely by the pitch system. Field personnel reported an abnormal mechanical sound, prompting additional investigation via smartphone video.

2) *Data Acquisition:* Audio recordings were captured using a smartphone during pitch actuation of blades 1, 2, and 3. The rotor was stationary during all acquisitions. Two short clips were taken per blade: (i) a steady clip near the pitch gearbox housing and (ii) a slow panning clip across the gearbox–motor interface to sample positional variation and directionality.

3) *Signal Processing and Acoustic Features:* After audio extraction and preprocessing, narrowband FFT analysis revealed modulations around ≈ 12.5 Hz, correlating with half the sun-gear speed (≈ 25 Hz) under the tested actuation (see Figure 4). Such half-order content is often associated with mechanical looseness/backlash in planetary stages. Time–frequency maps (waterfall) confirmed the persistence of these components over the actuation interval.

Fig. 3 Waterfall plot acquired by sound analysis.

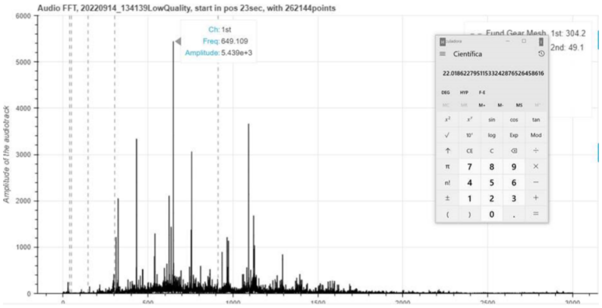

Fig. 4 Spectrum of noise measure at pitch drive 1.

4) *Comparative Analysis:* Across the three blades, blade 1 exhibited higher amplitudes and more pronounced harmonic content at the first planetary stage gear-mesh region than blades 2 and 3. The comparative behavior suggests a localized condition on blade 1 (e.g., periodic internal impacts or backlash asymmetry).

5) *Hypothesis:* The suspected fault was localized to the sun gear on the first planetary stage.

6) *Finding:* The motor was subjected to an excessive axial load, which caused the shaft to be displaced downward and generated abnormal noise in the gear assembly.

Fig. 5 Motor responsible for pitch system.

B. Induction Motor (Bearing BPFO / BPFI Case)

1) *Context and Operating Conditions:* A newly installed induction motor exhibited an unusual audible tone during the first hours of operation at the customer site. No vibration analyzer was available, and the first diagnostic request reached the engineering team in the form of a short smartphone video recorded by the commissioning technician.

2) *Audio–Video Acquisition:* The technician positioned the smartphone approximately 25–30 cm from the drive-end bearing housing and performed a horizontal sweep across the motor. Ambient noise was moderate, but airflow did not impact the microphone directly, allowing a clean signal.

3) *Signal Processing and Acoustic Features:* After extraction and preprocessing:

- Envelope spectrum: Sharp and repeatable peaks were observed at frequencies compatible with BPFO expected for the bearing installed in the motor.
- Harmonic structure: The envelope spectrum also showed the first harmonic of BPFO and a smaller, but detectable, second harmonic.
- Waveform analysis: The time-domain signal exhibited low-frequency modulation consistent with periodic rolling-element impacts.

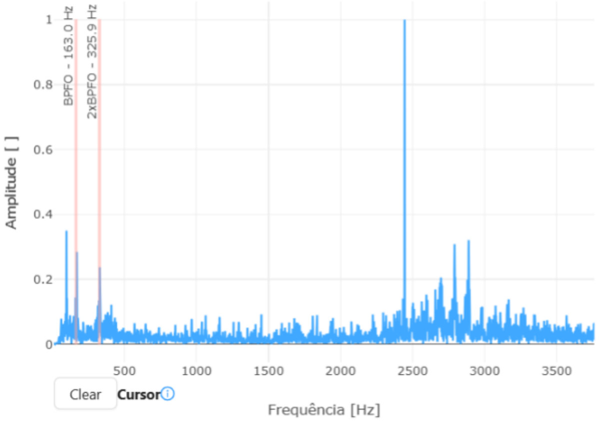

Fig. 6 Detection of BPFO by sound spectrum.

4) *Interpretation:* The spectral findings suggested a potential outer-race defect. Based on this preliminary diagnosis from the acoustic data, the team recommended opening the bearing housing for inspection. During the field inspection, however, only the inner race could be accessed and visually evaluated. The observed damage was consistent with deterioration of the inner race, thereby validating the capability of the smartphone-based method for early detection, while also highlighting the practical inspection limitations encountered on site.

5) *Finding:* The bearing damage was caused during transportation. Handling and transport-induced shocks likely generated the inner-race deterioration observed during inspection.

Fig. 7 During inspection, identified BPFI.

V. DISCUSSION

The case studies show that smartphone-based sound analysis can reveal meaningful diagnostic patterns even when recordings are obtained informally in the field. Extracting tonal components, harmonic structures, and modulation features directly from video files provides a structured interpretation of what technicians often perceive only intuitively. This transforms an accessible sensing modality into a practical early-warning tool.

A central advantage of the method is its accessibility: it uses devices that technicians already carry, without requiring sensors, cabling, or acquisition hardware. This lowers the operational threshold for initiating a diagnostic assessment, particularly in remote locations or during initial troubleshooting steps. The approach also complements established monitoring routines by helping identify which machines warrant detailed vibration measurements, thus improving prioritization and reducing unnecessary interventions.

The acoustic signatures captured in both case studies aligned with the mechanical behaviors later examined through vibration analysis, demonstrating that smartphone audio can highlight fault-related patterns sufficiently well for triage. While not a replacement for calibrated sensors, audio analysis provides an alternative view of machine dynamics—especially useful in situations where structural coupling or limited access can constrain accelerometer performance.

The method does have inherent limitations: consumer microphones introduce variability in frequency response and gain control, and the recordings are susceptible to environmental noise. Consequently, absolute amplitudes should not be interpreted quantitatively. Even so, the relative spectral content and the repeatability of features across recordings proved reliable enough to support preliminary assessments.

Looking forward, integrating audio data with maintenance records and existing monitoring platforms may expand its utility. Lightweight machine-learning models trained on real field recordings could increase consistency and automate the recognition of recurrent patterns. Such developments would preserve the low-cost nature of the method while increasing diagnostic confidence.

Overall, the findings position smartphone-based sound analysis as a practical and scalable early-diagnostic layer that strengthens modern condition-monitoring workflows.

VI. CONCLUSION

This work presented a smartphone-based sound analysis methodology for early detection of mechanical issues in rotating machinery. By extracting spectral and envelope-domain features from ordinary video recordings, the method offers an accessible and low-cost complement to traditional vibration analysis.

The industrial case studies illustrated the approach's ability to reveal characteristic signatures of looseness, gear-mesh anomalies, and rolling-element bearing defects. These insights supported decision-making in field scenarios where conventional instrumentation was not initially available.

Although not intended to replace vibration sensors, the method provides rapid triage capabilities and helps direct maintenance resources more efficiently. Its minimal setup requirements and reliance on ubiquitous devices make it particularly suitable for early troubleshooting and for environments where sensor installation is constrained.

Future work includes expanding the signal-processing toolbox, exploring automated pattern recognition, and validating the approach across a broader range of machines and operating conditions. Integrating smartphone-based audio with predictive-maintenance platforms may further enhance early-fault detection and reduce unplanned downtime.

Sound analysis from smartphone video recordings therefore represents a practical and scalable addition to contemporary condition-monitoring strategies.

VII. ACKNOWLEDGMENT

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IX. VITA

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