PROBLEM DESCRIPTION

Detecting internal cracks in metallic structures is a critical challenge across industries such as aerospace, construction, and manufacturing. Cracks can compromise structural integrity, leading to catastrophic failures if undetected. Traditional methods like ultrasonic testing and X-ray inspection are effective but expensive, complex, and impractical for on-site or continuous monitoring. This project proposes a low-cost, portable crack detection system using piezoelectric discs and an ESP32 or STM32 microcontroller. The system will send high-frequency vibrations through a metal object and analyze the received signal to detect amplitude drops or phase shifts caused by internal defects.

Research Objectives:

1. To design a vibration-based crack detection system using piezoelectric discs.
2. To implement real-time signal acquisition and analysis using an ESP32/STM32 microcontroller.
3. To visualize waveform data and identify anomalies through amplitude changes and frequency distortions.
4. To develop an algorithm using Fast Fourier Transform (FFT) for frequency spectrum analysis.

Our goal is to **detect cracks in metallic solid objects** by generating **ultrasonic vibrations (40 kHz)** on one side and capturing the transmitted signal on the other side. A change in the received signal will indicate the presence of a crack. This project aims to solve that gap by utilizing piezoelectric sensors to measure impact forces, process data with an ESP32 microcontroller, and visualize results on a web platform.

Key Challenges:

- To develop a low-cost, portable force measurement system using piezoelectric sensors.
- To process sensor data in real-time using ESP32 and display results on a web interface.
- To validate the accuracy of piezoelectric sensors compared to traditional force measurement systems.

SOLUTION

The proposed solution uses piezoelectric discs to detect internal cracks in metallic structures by analyzing vibration signals. A 27mm piezo disc transmits a 40 kHz signal through the object, while another disc receives the vibrations on the opposite side. The ESP32 or STM32 microcontroller samples the received signal using its ADC (12-bit resolution), converting it into digital values. These values are processed through signal filtering and Fast Fourier Transform (FFT) to identify changes in amplitude or phase caused by structural defects. Machine learning models, including Random Forest and Decision Tree algorithms, are trained on signal features to classify healthy versus cracked regions with high accuracy. The results are visualized as waveforms, making crack detection intuitive and precise. This system offers a cost-effective, portable, and real-time structural health monitoring solution, bridging the gap between advanced diagnostics and accessible technology.

RESEARCH METHODOLOGY

Literature Review:

We reviewed existing non-destructive testing (NDT) techniques, including ultrasonic and acoustic emission methods, to understand their limitations. Research on piezoelectric materials and vibration propagation in metals informed the design of the sensor system.

System Design:

A 27mm piezoelectric disc acts as a vibration transmitter, generating a 40 kHz signal via PWM output from the microcontroller. A second piezo disc serves as the receiver, placed on the opposite side of the test object. The receiver converts mechanical vibrations into analog voltage, sampled by the ADC (Analog-to-Digital Converter) of the microcontroller (12-bit resolution, values from 0–4095).

Data Acquisition and Signal Processing:

The microcontroller samples the received signal at high speed. A rolling buffer stores ADC readings, which are then processed to generate a real-time waveform. The system detects amplitude drops and phase shifts — indicators of cracks disrupting wave propagation.

Frequency Analysis with FFT:

FFT is applied to transform the time-domain signal into the frequency domain. By analyzing the frequency spectrum, the system distinguishes healthy structures (consistent signal) from damaged ones (distorted or weakened frequencies).

Prototyping and Testing:

The prototype is tested with metal plates of varying thicknesses and controlled defects. Known crack sizes and positions help validate system accuracy. We compare the system's readings to manual measurements and visual inspections to refine calibration.

Visualization and Interpretation:

Waveform data is visualized on a web interface or serial plotter. Clear visual markers (like signal dips or phase shifts) highlight possible crack locations. The FFT results are plotted to show frequency changes, aiding in identifying crack characteristics.

Research Methodology Conclusion:

Detecting internal cracks in metallic structures is a crucial aspect of structural health monitoring, with significant implications for safety and longevity in industries such as aerospace, automotive manufacturing, and civil engineering. Research has shown that non-destructive testing (NDT) methods, like ultrasonic inspection and acoustic emission analysis, are effective but often cost-prohibitive and impractical for real-time or in-field applications. Studies on piezoelectric materials have highlighted their potential for low-cost, portable sensing solutions, as they can act as both vibration transmitters and receivers, converting mechanical energy into electrical signals. Literature suggests that piezoelectric discs can propagate high-frequency vibrations through metal objects, and by capturing the transmitted signal on the opposite side, amplitude drops and phase shifts caused by internal defects can be identified. The use of microcontrollers, such as ESP32 and STM32, with integrated ADCs and PWM outputs, enables real-time signal sampling and waveform visualization, while Fast Fourier Transform (FFT) techniques allow frequency domain analysis to distinguish clean, consistent signals from distorted ones caused by structural anomalies. Experimental research indicates that larger cracks cause noticeable amplitude reductions, while smaller, internal fractures disrupt specific frequency components, aligning with findings in previous studies on vibrational wave scattering. This system, inspired by established principles of ultrasonic tomography and guided wave testing, offers a scalable, affordable alternative for early-stage crack detection, with opportunities for enhancement through multi-sensor arrays, signal conditioning circuits, and machine learning algorithms for advanced defect classification. By bridging insights from materials science, signal processing, and embedded systems, this project aims to contribute to the growing body of research on accessible, real-time monitoring solutions for structural integrity assessment.

How ST-AIoT Craft Helped us Execute the project efficiently

The **ST AIoT Craft tool**, combined with the **SensorTile.box PRO**, was instrumental in efficiently executing our crack detection project. It provided an intuitive platform to configure sensors, collect high-frequency vibration data, and seamlessly integrate machine learning models — drastically reducing development complexity and time. Using **Expert Mode**, we configured the onboard **LSM6DSV16X 6-axis IMU** to capture vibration signals at precise sampling rates. This data was processed in real-time with the built-in **FFT (Fast Fourier Transform) function**, allowing us to analyze the frequency spectrum and detect anomalies like amplitude drops and phase shifts caused by cracks.

The ST AIoT Craft tool made it easy to train and deploy **Decision Tree** and **Random Forest** algorithms directly on the SensorTile.box, without needing external computational resources. By labeling data from intact and defective structures, we trained models to classify signals with high accuracy. The tool’s support for **Bluetooth Low Energy (BLE)** streaming enabled us to visualize live waveform and frequency data on the ST BLE Sensor app, simplifying real-time analysis and debugging.

Additionally, the **STM32U585AI microcontroller**'s efficient data handling capabilities, combined with the SensorTile.box's built-in wireless connectivity and microSD card storage, allowed us to test and refine our models quickly in various scenarios. This accelerated iterative improvements, helping us fine-tune the system for better sensitivity and robustness. Overall, the ST AIoT Craft tool served as a complete development ecosystem, empowering us to build an advanced, portable, and cost-effective structural health monitoring solution without the need for extensive hardware modifications or external signal processing units.

DETAILED SOLUTION

The proposed system uses **piezoelectric discs** to detect internal cracks in metallic objects by analyzing vibration signals. A **SensorTile.box PRO** collects vibration data, processes it using Fast Fourier Transform (FFT), and classifies the signal with machine learning models trained using the **ST AIoT Craft tool**. The results are visualized in real time, providing a cost-effective, portable, and accurate crack detection solution.

System Architecture:

1. **Vibration Transmission:**
   A **27mm piezoelectric disc** generates ultrasonic vibrations at **40 kHz**. The **SensorTile.box PRO** produces this signal via **PWM output** from its onboard **STM32U585AI microcontroller**, which drives the piezo disc through a **MOSFET driver** for signal amplification.
2. **Signal Reception:**
   A second **piezo disc**, placed on the opposite side of the metal object, receives the transmitted vibrations. When a crack is present, the signal is disrupted — causing amplitude drops, phase shifts, or frequency distortions.
3. **Signal Acquisition:**
   The weak analog signal from the receiving piezo disc is:

- **Amplified** using the **AD620 instrumentation amplifier**.
- **Converted to digital** using the **12-bit ADC** in the SensorTile.box.

4. **Signal Processing:**
   The digital data is:

- **Filtered** to remove noise.
- **Transformed to frequency domain** using **FFT** to detect anomalies in specific frequency components.

5. **AI-Based Crack Detection:**
   Using the **ST AIoT Craft tool**, we trained **Random Forest** and **Decision Tree** models on labeled vibration data (healthy vs cracked samples). The trained models run locally on the **STM32U585AI**, classifying real-time data to determine crack presence.
6. **Data Visualization & Output:**
   The results are streamed via **Bluetooth Low Energy (BLE)** to the **ST BLE Sensor app**. The app visualizes the signal as waveforms and shows the classification result

(crack/no crack). Alternatively, the data can be stored on a **microSD card** for later analysis.

FLOW CHART