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EDUCATIONAL ARDUINO-BASED DAMAGE MONITORING SYSTEM: A BOLTED CFR-PLATE SETUP

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Abstract:

Wind blade damage is one of the biggest challenges in the wind industry, and early detection of minor damages before they escalate into major issues is crucial for maintaining efficiency and reducing repair costs. This work presents an Arduino-based educational setup for real-time monitoring of two bolted CFR plates, designed to simulate wind blade monitoring in a classroom setting. The system includes a vibromotor at one end of the plates and an accelerometer at the other. The vibromotor generates vibrations that travel through the plates, which are detected by the accelerometer. If mechanical damage occurs, simulated by inserting a paper clip between the plates, the vibration strength decreases, signaling a site where minor damage might grow into a larger issue. This setup provides hands-on experience in preventive maintenance and damage detection, helping students understand the importance of structural health monitoring in the wind energy sector.

1. INTRODUCTION

Blade failures can disrupt energy production for prolonged periods, as their repair is both extensive and technically demanding (Lim, 2015). To address this, several monitoring methods have been developed. Acoustic emission sensors detect high-frequency microsounds generated during crack initiation (Acuren, 2022). Thermography employs infrared imaging to identify internal defects such as moisture ingress or delamination (InfraTec, 2020). Fiber optic sensors measure strain and temperature within the blade structure (Yang et al., 2023), though their integration increases manufacturing costs. Vibration monitoring, such as the system developed by Broadland Care (Tcherniak & Mølgaard, 2017), utilizes accelerometers to track changes in dynamic behavior and detect early-stage damage in real time. This method is suitable for in-situ application, enabling continuous assessment of structural integrity and localization of microdamage initiation sites.

Based on the method proposed by Broadland Care, we developed a cost-effective, Arduino-based educational model. The system integrates a mechanical actuator (vibromotor) and vibration sensors (accelerometers) to demonstrate how incipient faults can be detected through dynamic response analysis before progressing into critical blade damage.

2. THEORETICAL BASIS

The proposed system is designed as an educational setup to teach wind turbine health monitoring in the classroom. It consists of an actuator (vibromotor) and an accelerometer, both mounted on a simulated version of a wind turbine blade, and controlled within an Arduino environment (**Fig. 1**). The actuator generates vibrational pulses, while the accelerometer, positioned at a distance from the actuator, detects these vibrations. As a crack develops in the blade, the vibrational characteristics of the mechanical system change, resulting in a noticeable reduction in the signal amplitude recorded by the accelerometer. This setup provides students with a hands-on experience in detecting early-stage blade damage through vibration analysis, demonstrating the principles of structural health monitoring in a cost-effective, real-time manner.

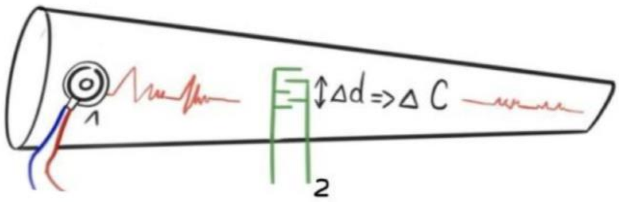

Fig. 1 A method utilizing Arduino for monitoring the initiation of damage on a wind turbine blade involves the following components: (1) a vibromotor, which acts as the system's actuator, generating vibrational impulses, and (2) an accelerometer, which captures and records these vibrational signals.

3. METHODOLOGY

Using a Mobile Phone

A hands-on approach is very helpful in the classroom, especially when using simple experiments, based on real-life situations. In this case, we first tested the damage detection method using a mobile phone. With the phone in its protective case, we used the Vibrana app to create vibration pulses and measured their strength using the PhyPhox app and the phone's built-in accelerometer. Then we removed the case and repeated the test to see how the vibration changed, as shown in **Fig. 2**. The vibrational monitoring results, measured by the built-in accelerometers of the smartphone are displayed in **Fig. 3**: the upper vibrational pulses relate to the smartphone, mechanically shielded by its protective case, while the lower vibrational pulses, with smaller amplitude than the upper ones, reveal the attenuation of the vibrational signal propagation due to a better mechanical coupling between the smartphone and the table underneath after removal of the protective case.

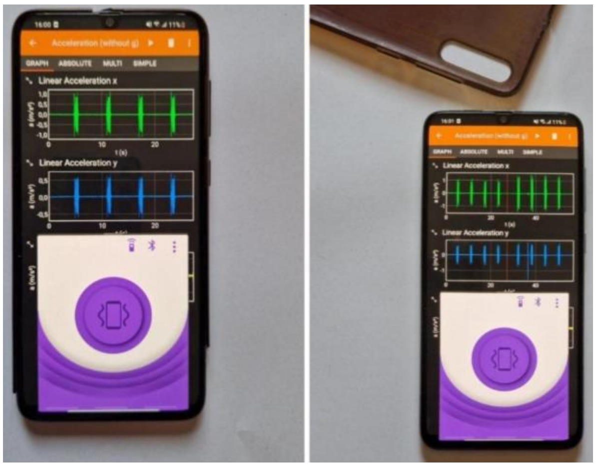

Fig. 2 Demonstration of a vibrational experiment in a real-world environment: (the left image) illustrates the experiment with the protective case placed on the mobile device, while (the right image) shows the experiment with the protective case removed from the phone.

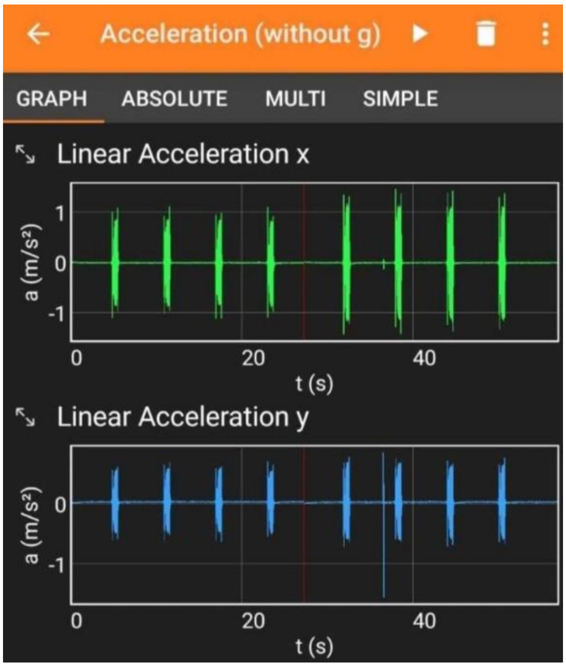

Fig.3 Testing of vibration detection using a mobile phone. The first four pulses were recorded by the phone's accelerometer without the protective case, while the remaining four pulses were recorded with the case in place. The recording application, Phyphox, was paused between the two experiments.

Using an Arduino-based Environment

Fig. 4 shows the electrical schematic of the proposed vibration monitoring system. The vibromotor is connected to the Arduino board as follows: one terminal of the motor is linked to the Arduino's 5V pin through a 1 kΩ resistor, which limits the current and protects the microcontroller. The other terminal of the motor connects to the collector (C) of an NPN transistor.

The base (B) of the transistor is connected to digital pin 3 of the Arduino via another 1 kΩ resistor. This setup allows the Arduino to control the transistor using a digital signal. The emitter (E) of the transistor is connected to the Arduino's GND pin, providing the return path for the current.

When the Arduino sends a HIGH signal (e. g., 5 V) to digital pin 3, the transistor turns on, allowing current to flow through the motor and generate vibrations. When a LOW signal (0 V) is sent, the transistor turns off, stopping the motor. This way, the Arduino can control the motor's vibrations through simple digital commands.

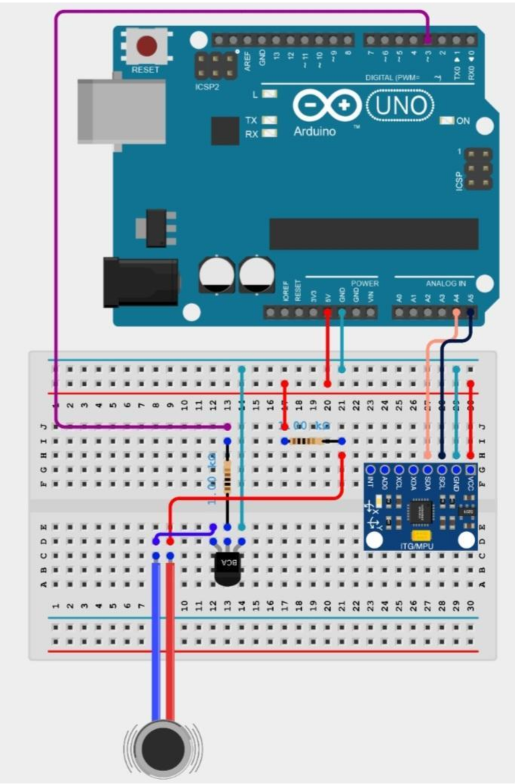

Fig. 4 Electrical schematic diagram of a vibrational damage detection system in an Arduino-based environment.

Next, the MPU6050 accelerometer was connected to the Arduino. Its ground (GND) pin was connected to the Arduino Uno's GND to establish a shared ground reference. The VCC (power) pin of the accelerometer was connected to the 5 V output of the Arduino to supply power.

Since serial communication over I²C requires two main lines — SDA (Serial Data) and SCL (Serial Clock) — these were connected accordingly: the SDA pin of the MPU6050 was wired to pin A4 on the Arduino Uno, and the SCL pin was connected to pin A5. These connections allow data transmission and clock synchronization between the devices.

The Arduino code for the proposed monitoring system is provided below.

```
#include <Adafruit_MPU6050.h>
#include <Adafruit_Sensor.h>
#include <Wire.h>

Adafruit_MPU6050 mpu;
int motorPin = 3;
float vibrationThreshold = 1.5; // in m/s^2
void setup() {
  Serial.begin(9600);
  pinMode(motorPin, OUTPUT);
  if (!mpu.begin()) {
    Serial.println("Failed to find MPU6050 chip");
    while (1) {
      delay(10);
    }
  }
  Serial.println("MPU6050 Found!");
  mpu.setAccelerometerRange(MPU6050_RANGE_8_G);
  mpu.setGyroRange(MPU6050_RANGE_500_DEG);
  mpu.setFilterBandwidth(MPU6050_BAND_21_HZ);
  delay(100);
}
void loop() {
  // Get new sensor events with the readings
  sensors_event_t a, g, temp;
  mpu.getEvent(&a, &g, &temp);
  bool isVibrating = abs(a.acceleration.x) > vibra-
tionThreshold || abs(a.acceleration.y) > vibration-
Threshold || abs(a.acceleration.z) > vibration-
Threshold;

  if (isVibrating) {
    digitalWrite(motorPin, HIGH);
  } else {
    digitalWrite(motorPin, LOW);
}

  Serial.print("Acceleration X: ");
  Serial.print(a.acceleration.x);
  Serial.print(" m/s^2, Y: ");
  Serial.print(a.acceleration.y);
  Serial.print(" m/s^2, Z: ");
  Serial.print(a.acceleration.z);
  Serial.println(" m/s^2");

  // Print the acceleration values in a format that
the Serial Plotter can use
  // The comments here are for your reference and
do not affect the plotter
  Serial.print(a.acceleration.x);  // X-axis
  Serial.print(",");
  Serial.print(a.acceleration.y);  // Y-axis
```

```
  Serial.print(",");
  Serial.println(a.acceleration.z);  // Z-axis

  // Add a delay to avoid flooding the serial moni-
tor and to debounce the vibration detection
  delay(100);
}
```

Fig. 5 illustrates the implementation of the proposed monitoring system. The setup comprises two carbon-fibre-reinforced (CFR) plates fastened together using six bolts. A vibromotor is attached beneath the lower plate using black insulating tape, while an accelerometer is mounted on the upper plate. To simulate mechanical damage, one of the central bolts is intentionally loosened, and a paper clip is inserted between the plates to create a slight separation.

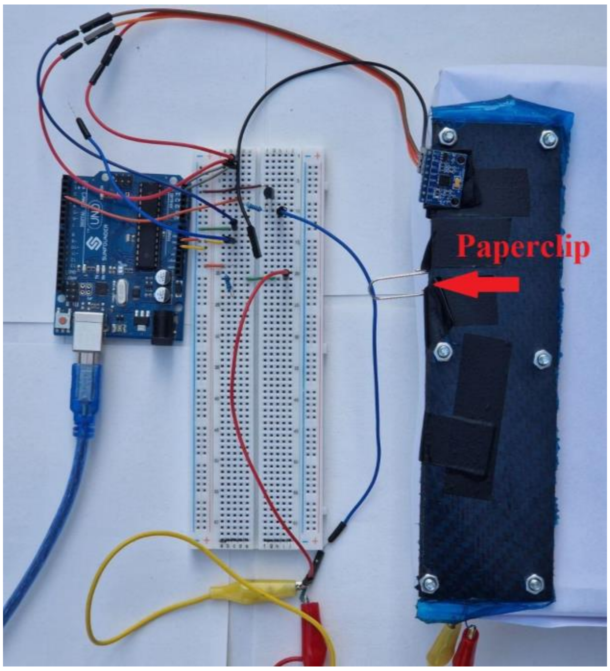

Fig. 5 Development of an Educational Setup for Monitoring Simulated Wind Blade Damage in an Arduino Environment: Two carbon-fiber-reinforced (CFR) plates are assembled using bolts. Simulated blade damage is introduced by loosening one of the central bolts and inserting a paper clip between the plates.

4. EXPERIMENTAL RESULTS

Fig. 6 presents the accelerometer data recorded before and after the introduction of the simulated damage upon insertion of a paper clip. The upper graph shows the vibration signal in the undamaged state, while the lower graph displays the signal after the simulated fault was introduced by loosening a bolt and inserting a paper clip. A noticeable reduction in the amplitude of the accelerometer signal from 0.5 to 0.3 m/s^2 is observed upon damage simulation. This attenuation indicates a change in the mechanical integrity of the system, confirming that the introduced defect significantly affected the transmission of vibrational energy. The results demonstrate the system's capability to detect early structural changes that may otherwise go unnoticed.

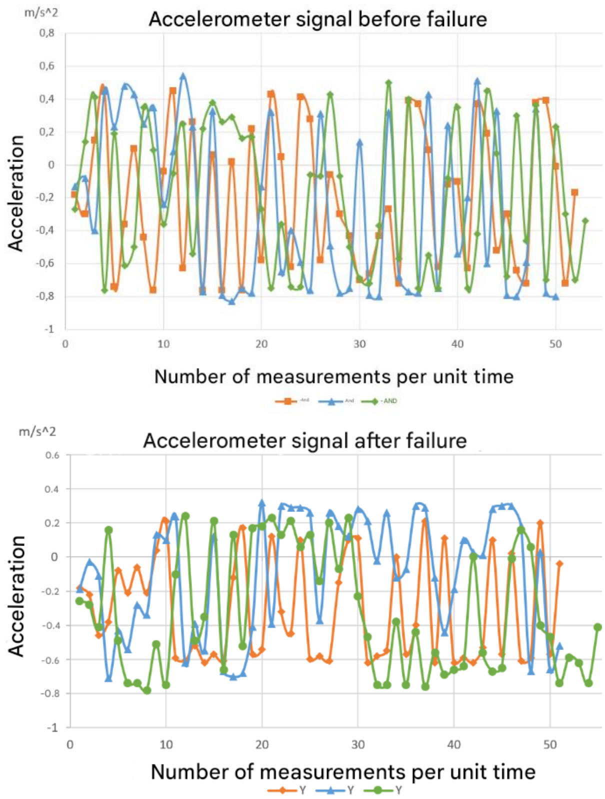

Fig. 6 Accelerometer data recorded prior to the simulated damage (top image) and following the simulated damage (bottom image).

6. CONCLUSION

This study presents an educational setup for monitoring damage in wind turbine blades, using a vibromotor, accelerometer, and carbon-fiber-reinforced (CFR) plates within an Arduino environment. The system successfully detects simulated damage, providing students with hands-on experience in structural health monitoring (SHM).

The setup offers an affordable and accessible platform for teaching vibration-based damage detection, allowing students to understand how early-stage damage affects the vibrational characteristics of wind turbine blades. By simulating real-world conditions, students gain practical insights into the importance of early damage detection in extending the lifespan of turbine components.

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