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Development of a Smart Instrumentation for Analyzing Railway Track Health Monitoring Using Forced Vibration

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Abstract—**Harmonic responses play a prominent role in determining metallic faults in railways. Therefore, it is useful to develop some instrumentation governed by the principles of forced vibration to evaluate the health condition of a railway track. The conventional systems developed to identify track damage have large deviations in measurements and are not reliable for examining track faults such as track drainage faults and surface damaged faults. This study focuses on the development of an instrument that analyzes track damage wirelessly in real time. Based on forced vibration, the relation between the harmonic response with the amplitude is demonstrated. The developed instrument was validated on an actual railway track. The result shows that, the developed instrument can be used to determine the serviceability of the railway track, thus avoiding any potential catastrophic events.**

Keywords—Harmonic response; Track damage; Forced vibration; Instrumentation

I. INTRODUCTION

The railway system is considered to be the backbone of a country's infrastructure economy[1][2]. It is a widely used form of transportation but unfortunately due to lack of condition monitoring, the railway tracks can become distorted, which can lead to track failure[1]. Track failure can be devastating as it can cause loss of both human lives and railway assets. In 2019, Pakistan alone had over 100 railway accidents, the majority of which were due to track failure[3]. Railway tracks are subjected to various dynamic loading conditions which can cause rail cracks and corrosion. If these track faults are not identified in a timely manner, then this leads towards catastrophic railway accidents. For track fault identification, various damage detection methodologies are implemented such as sonar[4], Infra-Red Thermography[5] and Inertial Measurement Units (IMUs)[6][7]. The vibration based fault diagnosis Track Recording Vehicles (TRV)[8][9] used for the determination of track faults are not suitable as a low cost solution.

These TRVs are special purpose trains mounted with various instruments for monitoring the health and condition of the rail tracks. Due to their size, they are not ideal for analyzing a sudden track fault.

Over the last decade, various advanced sensor techniques such as cameras[3], laser technology[10] and sonar[4] have been applied to track fault diagnosis. These techniques can be applied cumulatively in the form of a TRV or standalone, for track condition monitoring[9]. It is noted that except sonar, none of these technologies can be used to determine internal properties of the railway track. However, sonars are considered to be expensive and they involve a significant ongoing cost for maintenance[3]. Therefore, other techniques have been investigated and one of particular promise is to utilize the non-linear characteristics of metallic beams by implementing numerical, analytical and experimental approaches. Recent publications suggest that non-linearity in the harmonics indicates damage, and with the increase of the damage, the amplitude of the non-linearity becomes dominant[11][2].

Hence in this research, smart instrumentation is developed by using the forced vibration methodology, which analyzes the non-linearity in form of the harmonic response of the track, using an IMU (accelerometer) and wireless module (for the transmission of the sensory data to the cloud platform).

II. RAIL TRACK FAULTS

Sudden increases in rail traffic brings with it an increase in track damage. It is noted that, there is 100% increase in rail traffic if there is a 10% decrease in the road traffic[12]. The existing tracks have already exceeded their service life and are prone to failure due to the extreme events that they have endured. The potential impact on the railway tracks are mentioned below as:

- Track buckling due to excessive heat[2].
- Squats and turnout frogs formation on the surface of the track due to sudden braking[13][14][15].
- Track corrugation near coastal areas due to environmental factors [16][17].
- Ballast from the track bed getting washed away due to improper drainage[18][19].

These track faults need to be addressed as lives and assets are dependent on it. In most of the developing countries preventive measures are already taken, but in order to completely eradicate the possibility of track failure, predictive maintenance is required on a frequent basis[18]. The railway condition monitoring proposed in this research converts the preventive maintenance to predictive maintenance[20].

III. FORCED VIBRATION

In order to produce the vibration on the railway track, forced vibration is repeatedly applied [12].-The two approaches that are commonly implemented for producing the forced vibration on a mechanical structure are impact hammer testing and excitation motor [21]. In impact hammer testing, an instantaneous force is applied on the structure for calculating its harmonics. Whereas in excitation motor, continuous impulse force is applied on the structure by mounting an uneven mass on the rotor of the motor[22].
Therefore, for this research, continuous forced vibration approach using excitation motor is applied in order to produce continuous vibration on the track. The excitation motor used in this research is a 24V and 2A DC motor that rotates at a speed of 120 rpm. The entire device is packed with a 24V, 15AH rechargeable battery which has a duration of 5 hours, a weight of 0.30 kg and is mounted on the rotor of the excitation motor as shown in figure 1.

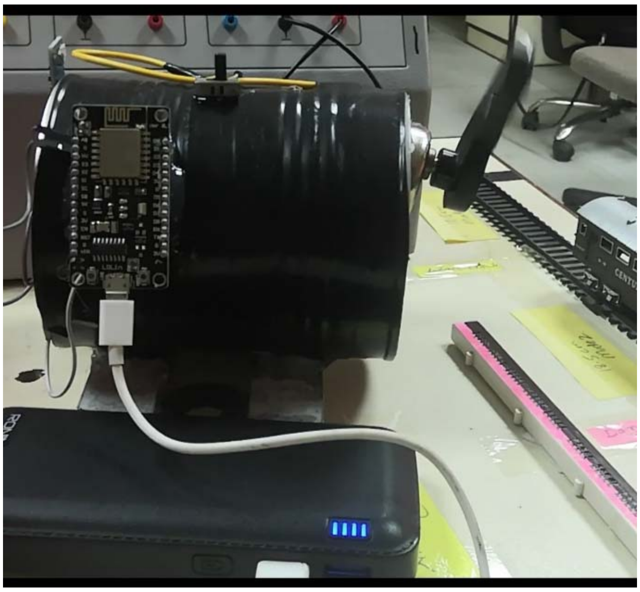

Fig.1. Developed Device

For computing the mathematical model, a mass M of 0.30kg is attached on the rotor which rotates at a radius of R having an angular speed of ω. The excitation motor causes the track to vibrate. The internal damping of the rail track restores the rail track to its equilibrium position when the force is applied from the excitation motor. The rail track has a position of $x > 0$ associated with sliding distance $\cancel{x}$ $|x|$ to the right of the equilibrium position $x=0$, due to the excitation motor. Likewise, $x < 0$ means the rail track moves at a distance of $|x|$ to the left. The mathematical model of the track vibration produced by excitation motor is stated in the equation 1:

$$M\ddot{x}(t) + kx(t) = 2RM\omega^2 \cos(\omega t) (1)$$

Newton's second law (if we consider the frictional force as negligible) provides force F = ma and a = $\ddot{x}(t)$ where x represents the rail track's center of mass in terms of its width. Hooke's law gives force F = $-kx(t)$. The x can be extended with respect to $x(t)$ by considering moment of inertia equations. Let m_1 = m − M be the track mass of that particular area, m_2 = M be the excitation motor mass, x_1 = x(t) the moment arm for m1 and x_2 = x(t) + R cos θ the moment arm for m2. Then θ = ωt provides:

$$x(t) = \frac{m_1x_1+m_2x_2}{m_1+m_2} \quad (2)$$
$$= \frac{(m-M)x(t)+M(x(t)+R\cos\theta}{m}$$
$$= x(t) + \frac{RM}{m} cos\ \omega t$$

Simplifying the equations by considering mx^n=-kx, we get,

$$mx^n(t) + kx(t) = RM\omega^2 cos\omega t \quad (3)$$

IV. DEVELOPMENT AND WORKING OF THE INSTRUMENTATION

The Inertial Measurement Units are the most cost efficient alternatives to expensive testing techniques like Fiber Bragg Grating implemented worldwide for the identification of the track damage[2]. The most popular of the IMU sensors are the accelerometer. For prototyping purposes, accelerometer module ADXL320 is used in the developed instrument for the determination of the track damage.

i. Assembling the Device

The accelerometer ADXL320 that is used in this methodology is an analog sensor that is implemented for measuring the non-linear harmonic response. The ADXL320 is connected with a wireless MCU module named Node MCU[2]. For determining track faults like drainage, the track lacks ballast that is usually found underneath the track and on the track bed. Due to the absence of the ballast, the track can vibrate laterally in the Y-axis. To make the device less complex, it is known that the damage of the track can be easily analyzed using only the Y dimension. Therefore, in the development of this device, the lateral motion is considered. Y-pin of ADXL320 is connected with the A0 pin of Node MCU as shown in the figure 2.

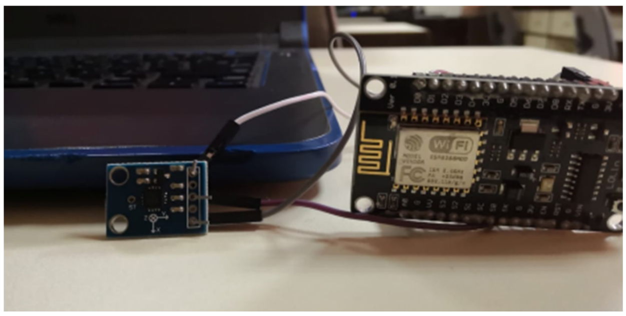

Fig.2. Connectivity with Node MCU

The reading fetched from the accelerometer are transmitted to an online cloud server named as Thingspeak which broadcasts the data remotely as shown in the figure 3.

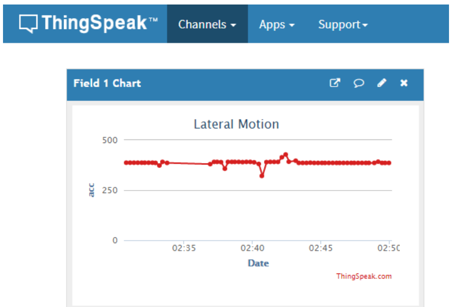

Fig.3. Accessing Cloud Platform

V. MEASUREMENTS

i. Hilbert Transform

The Hilbert transform is concerned with the harmonic response amplitude[23] acquired from the accelerometer ADXL320. Any non-linearity in the harmonic response reading acquired from the Y-axis data of the accelerometer can be used to identify the track faults. The mathematical form of the Hilbert transform is:

$$\alpha(t) = \frac{1}{\pi} p \int \frac{a_z(\tau)}{t-\tau} d_\tau \qquad (4)$$

In the equation 4, the p is representation of the Cauchy principle value which is obtained from the single integral function. Where analytic signal of the y-axis acceleration amplitude is defined below by equation 5.

$$\beta(t) = a_z(t) + j\alpha(t) \qquad (5)$$

The j represents the iota which has value of sqrt(-1). Thus, the beta (t) that expresses the polar form is mentioned as below:

$$\beta(t) = amp_{inst}(t)e^{in(t)} \qquad (6)$$

While the transient amplitude of the non-linear acceleration is computed using the following equation:

$$amp_{inst}(t) = \sqrt{a_z^2(t) + \alpha^2(t)} \qquad (7)$$

The Hilbert amplitude of the harmonic response of the track measured using accelerometer (ADXL320) is represented in figure 4. The X-axis represents the frequencies in which the track is vibrating with its respected amplitude represented in the Y-axis.

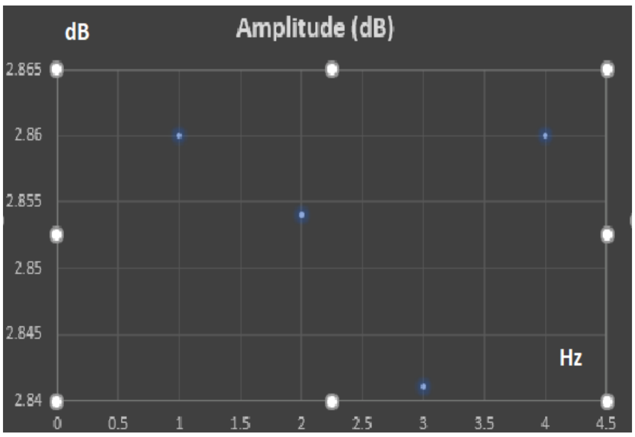

Fig.4: Hilbert Transformation of Accelerometer ADXL320 data

VI. RESULTS

Results obtained after the implementation of the Hilbert transformation on the accelerometer data acquired of the intact track, the track facing drainage issues and the damaged track are discussed as follow:

i. Intact Railway Track

The developed instrumentation is initially tested on an intact railway track (track with no faults) as shown in the figure 5.

Fig.5: Validating on Actual Track

The readings acquired of the harmonic response of the intact track are given in table 1.

TABLE 1. HARMONIC RESPONSE OF INTACT TRACK

Frequency Hz	Amplitude of the Intact Track dB
0-1	2.86
1-2	2.854
2-3	2.841
3-4	2.86

ii. *Track Facing Drainage Issue*

The developed instrumentation is then tested on a track suffering from the drainage issues, as shown in Figure 6.

Fig.6. Track with Drainage Issue

The acquired harmonic response readings of the track facing the drainage issues are mentioned in the table 2:

TABLE 2. HARMONIC RESPONSE OF TRACK FACING DRAINAGE ISSUES

Frequency Hz	Amplitude of the track facing drainage issues (dB)
0-1	2.959
1-2	2.955
2-3	2.959
3-4	2.959

iii. *Surface Damaged Railway Track*

The final test with a surface damaged track that had exceeded its elastic limits and could possibly risk failure as shown in figure 7, was carried out.

Fig.7. Surface Damaged Track

The readings acquired from the surface damaged track are listed in table 3.

TABLE 3. HARMONIC RESPONSE OF SURFACE DAMAGED TRACK

Frequency (Hz)	Amplitude of the Surface Damaged track (dB)
0-1	6.076
1-2	6.860
2-3	5.625
3-4	5.951

iv. *Overall Comparison*

For properly analyzing the variation of the amplitudes from the acquired readings of various tracks: table 1, table 2 and table 3 are organized together in a cumulative tabular form as shown in the table 4.

TABLE 4. HARMONIC RESPONSE OF SURFACE DAMAGED TRACK

Frequency (Hz)	Amplitude of the Intact track (dB)	Amplitude of the track facing drainage issues (dB)	Amplitude of the Surface Damaged Track (dB)	Difference b/w the intact track and track facing drainage issues (dB)	Difference b/w the intact track and Surface damaged track (dB)
0-1	2/860	2.959	6.076	0.099	3.216
1-2	2.854	2.9550	6.860	0.101	4.006
2-3	2.8410	2.959	5.625	0.118	2.784
3-4	2.860	2.959	5.951	0.099	3.091

It was concluded from the table 4 that the damaged track had low frequency vibrations (1Hz to 5 Hz) with an amplitude of more than 5 dB while the track facing drainage issue, amplitude ranged from 2.9 dB to 5 dB.

VII. CONCLUSIONS

The conclusion to this study is made with the table 4, which shows a clear evident difference between an intact track and the damaged track by comparing their amplitudes. After further analyzing the various railway tracks as mentioned in this study, it is known that if the amplitude of the track measured from the developed instrumentation is more than 5 dB (as mentioned in table 3 and table 4), then that track is classified in to a damaged track and it needs to be repaired or replaced, immediately.

But if the amplitude of the track ranges between 2.9 dB to 5 dB as given in table 2 and table 5, then the track is recognized to suffer from drainage issues and it requires a proper inspection. Whereas, any track reading below 2.9 dB falls in the category of intact track.

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