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# A Smart Sensing Technology for the Condition Monitoring of Railway

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**Abstract—***In recent years there has been increasing need for adopting smart sensing technologies to structural health monitoring (SHM) application for various types of structure. Thus the impedance–based structural health monitoring method has come to the forefront in the SHM community due to its potential of in situ measurement and real world application. This method had attracted several researchers in the recent past for aerospace, civil, mechanical, timber and biological structures. Smart materials such as piezoelectric (lead Zirconate titanate) and macro fiber composite (MFC) transducers are either surface bonded or embedded with the host structure to be monitored. These smart materials with an applied input sinusoidal voltage interact with the structure; to sense, measure, and process and detect any change in the selected variables (stress, strain damage) at critical locations .SHM can also be used for monitoring the Railway infrastructure such as railway bridges, rail tracks, rail fishplate joint, and other track fastener. The smart sensing technologies reduce human inspection, reduce maintenance by detecting damage or looseness before they escalate and also improve the safety and reliability of Railway transportation. This paper presents some of the important developments in monitoring and path forward in providing an important method for Railway using electromechanical impedance–based structural health monitoring. The emphasis is on railway fishplate joint monitoring using inexpensive and fully automatic monitoring systems.*

## 1. INTRODUCTION

The growth of real time SHM and estimate damage detection techniques has pay attention in the direction of safety and long-term reliability of structure. The main purpose of SHM systems is to monitor a structure and detect incipient damage, if possible in its normal operation condition, to minimize repair and maintenance costs and to avoid any kind of unwanted circumstances.

## 2. BACKGROUND STUDY

Among the various existing SHM methods, the electromechanical impedance (EMI) technique has been observed as one of the most promising technique for various complex and huge structures, as reported in a number of studies found in the literature[1-3]. The method was first used on a four bay space truss structure and afterwards used by researches for several complex structures such as a spot welded structural joints, civil structural components, a reinforced concrete bridge, civil pipelines, airplane structure ,bolted joint and a Wind Turbine blades [4-9].In this context, SHM method based on EMI technique has been regarded as one of the most promising, and it is distinguished by its simplicity and using low-cost components, such as piezoelectric transducers of PZT.

## 3. NEED FOR CONDITION MONITORING IN RAILWAY

In Railway system the bolted joints are the most prevalent forms of fastener and the entire network relay on the large number of joints. The insulated rail joint (IRJ) is considered as a necessary evil by the rail transportation and maintenance industry. In terms of mechanical performance, these joint bars have a lower vertical bending stiffness than the rail track itself [10]. As a result, large deflections in the joint region are generated while wheels pass through. Because of the widespread use of bolted joints, they are also often the subject of mechanical failures or looseness. A condition based monitoring approach must be adopted in order to realize the looseness of rail joints. Fish plate is an indispensable component of Railway track lines. It joints to track with high tension Nut and Bolt as shown in Fig. 1. In railroad tracks, fishplate joint bars are being used to connect the ends of adjoining rails .Fish plate is basically a connector which is used to connect the gaps in railway tracks which is provided to allow expansion due to heat.

The traditional method for monitoring of Fish Plate joint is the manual inspection by a trained person and timely maintenance of the joint. However these techniques is time consummating, so the bolt loosening monitoring has become an important research area in efforts to prevent failures in Fishplate and variety of mechanical bolted joint.

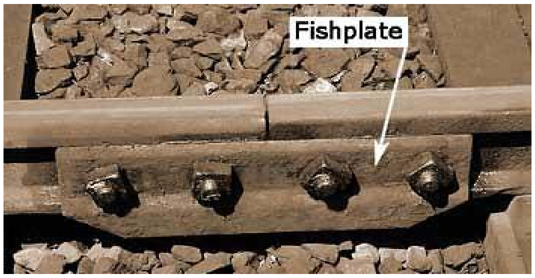


**Fig. 1: Fishplate with nut & bolt joint**

Thus, the development of effective looseness monitoring system is necessary to avoid sudden failures in Railway. This monitoring process requires hardware and record the impedance of damage and undamaged structure for early warning to nearest railway cabin. This paper discussed the implementation of a low-cost impedance analyzer for real time structural health monitoring using PZT for accurate and efficient E/M impedance measurement.

## 4. PIEZOELECTRIC IMPEDANCE TECHNIQUE

The EMI technique has been regarded as one of the most promising technique which use low cost component such as PZT.The principle of piezoelectric impedance –based SHM technique is to utilize high frequency (30–400 kHz) structural excitation, and measure the impedance of a piezoelectric patch attached to a structure. The EMI-based damage detection method is to track an electrical point impedance of the PZT patch bonded onto the structure to be monitored. Physical changes in the structure may cause changes in the structural mechanical impedance, which may accordingly induce changes in the EMI of the PZT patch. Those changes in the impedances of the PZT patches are used to identify incipient damage in the structure. Therefore the variation on mechanical impedance caused by crack or looseness can be evaluated by measuring the electrical impedance of the PZT in appropriate frequency range [11-13].

Fig. 2 shows the well-known one-dimensional model representation of a mechanical system containing a piezoelectric sensor attracted to the structure to be monitor.

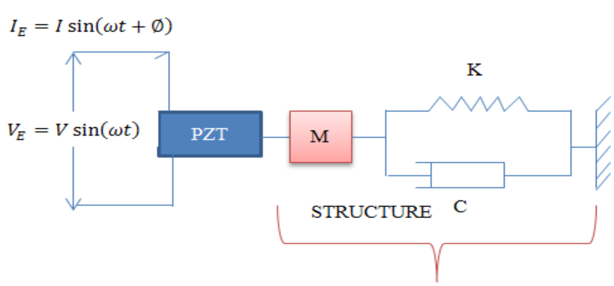


**Fig. 2: One dimensional coupling between structure and PZT**

The Wave Equation for the PZT patch connected to the structure leads to Eq. (1), for a frequency dependent electrical admittance.[13].

$$Y(\omega) = I\omega a\left[\bar{\varepsilon}_{33}^{T}(1 - I\delta) - \frac{Z_S(\omega)}{Z_S(\omega)+Z_a(\omega)} d_{31}^2 \hat{y}_{11}^2\right] \tag{1}$$

Where Y(ω) is the electrical admittance (inverse of electrical impedance), $Z_a(\omega)$ and $Z_S(\omega)$ are the impedance of PZT and structure respectively, $\hat{y}_{11}^2$ the complex Young's modulus of the PZT in the direction 1 under zero electrifield $d_{31}^2$ is the piezoelectric coupling constant at zero stress, $\bar{\varepsilon}_{33}^{T}$ is the dielectric constant at no stress, (δ) is the dielectric loss tangent of the piezoelectric patch, and a is a geometric constant of the PZT patch. The equation indicates that the electrical impedance of the PZT bonded onto the structure is directly related to the mechanical impedance of the host structure.

In the EMI technique, the PZT sensor is bonded to the surface of the monitored structure by high-strength epoxy adhesive. The configuration used the PZT as sensor and actuator. The main basic concept of EMI method based SHM approach is that the presence of damage or looseness in the host structure will change its mechanical impedance and thus the EMI admittance of the PZT patch which can be directly measured by an electrical impedance analyzer, LCR meter or simple impedance measurement circuit. For overcome the issue of in situ measurement a simple measurement circuit is shown in Fig. 3 for impedance measurement [14].

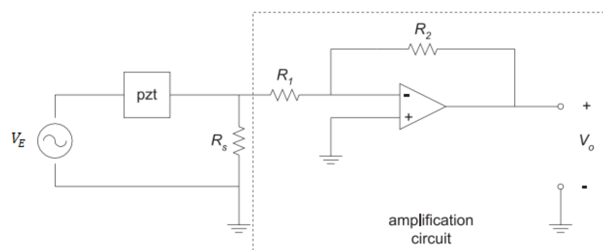


**Fig. 3: Circuit proposed for PZT impedance analysis.**

The approximated impedance of the PZT ($Z_{PZT}$) is given in equation.

$$V_o = \frac{R_S}{Z_{PZT} + R_S} V_E \tag{2}$$

$$Z_{PZT} = \frac{R_S(V_E - V_O)}{V_O} \tag{3}$$

The impedance analyzer used for the monitoring is to obtain the impedance in the frequency domain, the discrete Fourier transforms (DFTs) of signals $V_E$ and $V_o$ are calculated by using a spectrum analyzer.

## 5. IMPEDANCE MEASUREMENT

The impedance expresses a complex valued function dependent on frequency. For each corresponding frequency, it can be represented in terms of the real and imaginary parts or magnitude and phase. The easiest way to calculate the corresponding impedance, for a given excitation frequency $f_E$ by formula given in equation 1

$$Z(\omega) = \frac{V_E(\omega)}{I_{PZT}(\omega)} \text{ Where } \omega = 2\pi f_E \qquad \textbf{(4)}$$

Where $V_E(\omega)$ and $I_{PZT}(\omega)$ are the excitation voltage and current at PZT sensor respectively. An impedance vector consists of a real part (resistance, R) and an imaginary part (reactance, I) as shown in Fig. 4.

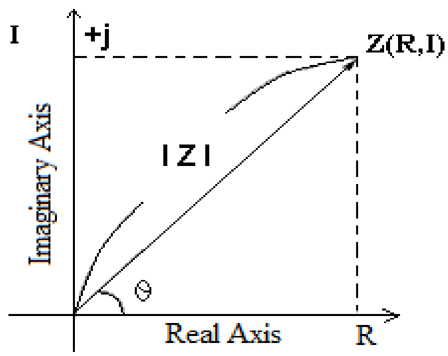


**Fig. 4: Graphical representation of Impedance**

Impedance can be expressed using the rectangular-coordinate form $R + jI$ or in the polar form as a magnitude and phase angle $|Z|\angle\theta$.

$$Z = R + jI = |Z|\angle\theta \qquad \textbf{(5)}$$

From the equation (5) we can write the relation between $R$, $I$ and $Z$.

$$R = |Z|\cos\theta \qquad (5.a)$$

$$I = |Z|\sin\theta \qquad (5.b)$$

$$|Z| = \sqrt{R^2 + I^2} \qquad (5.c)$$

$$\theta = \tan^{-1}\left({}^{I}/_{R}\right) \qquad (5.d)$$

Equations (5.a) to (5.d) are used to calculate impedance $|Z|$ and phase $\theta$.In general a current is not measured directly a shunt resistance $R_S$ is used for this purpose. Fig. 3 shows a portable circuit for measurement of current and voltage from PZT.

## 6. EXPERIMENTAL SETUP

A typical impedance based SHM system for monitor the impedance is provided in Fig. 5.The function generator generates the of 1 volt root mean square (RMS) voltage with a frequency range of 30–100 kHz for excitation . The PZT sensor which bonded to structure is provide a voltage signal which is fed to the amplifier stage and corresponding output voltage is measures with different frequency range.

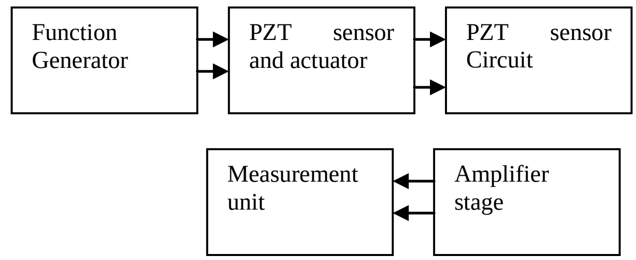


**Fig. 5: Block diagram of impedance based SHM system**

### 6.1 Operation and Architecture

Impedance-based SHM performs three major operations: excitation signal generation, sensor actuation and sensing, and damage assessment. An excitation signal can be generated by a traditional function generator or by a Digital signal processor. Here we take the Agilent 33220A function generator for generating the excitation signal. Then an amplifier stage is used to get the proper voltage level at the output stage.

### 6.2 Bolted Joint Monitoring

It is estimated that most of the mechanical failures are related to failure of the fastener. One important mode of fastener failure is self-loosening of bolted joints. Self-loosening is especially problematic when the bolted joint is in an inaccessible location, and on a complex structure like Fishplate or railway bridge. Here we have taken a structure, which is used for looseness test was a bolted structure. Fig. 6 shows an example study for the electromechanical impedance based monitoring technique. A built-in PZT sensor is used to detect artificial damage (by loose the nut and bolt) on two aluminum plates having dimension 22.92 cm x 5.2 cm x 0.6 cm and 15 cm x 5.2 cm x 0.6cm respectively is joint with a bolt of radius 1.2cm.

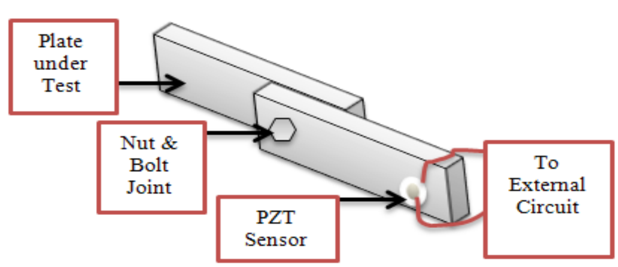


**Fig. 6: Complete Structure used for measurement Impedance**

The damage developed at the joint by loose the bolt. The PZT sensor was placed on one of the aluminum plate for recording of impedance data. The dimension of the structure under test is tabulated in Table 1.

**Table 1: Dimension of Structure and Sensor**

| Materials /parameters | Dimension |
|---|---|
| | **Physical property** |
| Aluminum plate 1 | 0.6 cm × 5.2 cm × 22.92 cm |
| Aluminum plate 2 | 0.6cm ×5.2cm × 15 cm |
| Overlap length | 7.62 cm |
| Nut detail(radius) | 1.2cm |
| PZT sensor | 1cm ×1cm×0.025cm |
| Distance of sensor from Bolt Joint | 6.35 cm |

To evaluate the proposed method in detecting the damage, tests were carried on an aluminum plate. Structural damage was simulated by loose the steel nut which is situated at some distance from the transducer. The experiment described here is used in the literature to evaluate and compare SHM systems. The addition nut and bolt attached to the specimen changes the mechanical impedance of the structure induced by damage, such as looseness and crack. This procedure has the advantage of not causing permanent damage in the specimen. Fig. 7 shows the experimental arrangement.

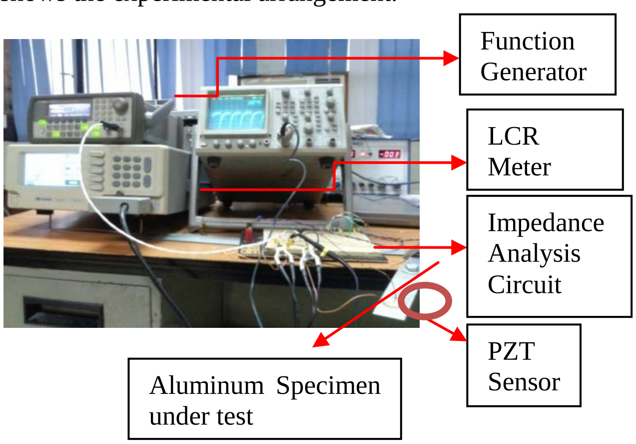


**Fig. 7: Overall experimental arrangement for Impedance measurement**

## 7. RESULT AND DISCUSSION

The LCR meter connected to the PZT provides the necessary 1 V RMS sinusoidal electric input. The output is recorded for a desired frequency range (30 kHz to 100 kHz), that is, as conductance. However, the conductance signature has been mostly used. In the present study, conductance signature was considered as the looseness of the bolted joint.

The RMS voltage of the PZT transducer obtained by simple circuit as shown in Fig. 3.The frequency range between 30 to 100 kHz the output voltage varies from 0.4 to 1 Volt. Fig. 8 shows a qualitative comparison between the damage and undamaged voltage output obtained from the impedance measurement circuit. Here we notice that there is a huge difference in voltage level of standalone PZT and integrated PZT with damage. The experiment result is reliable with that of the theoretical analysis with equation (2) which is directly related to calculate impedance in equation (3).

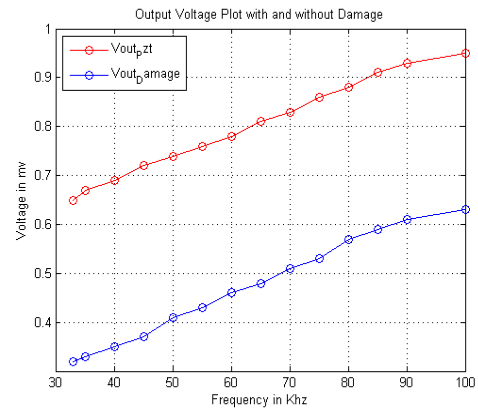


**Fig. 8: Voltage Measurements in Damage and Undamaged condition**

A frequency range from 30 to 100 kHz is displayed to allow a more detailed comparison between the signatures. We observe significant variations in the shape of the impedance in Fig. 9 and RMS voltage signatures compared to the baseline in Fig. 8, especially for damage near the transducer. These variations indicate that the RMS voltage signature is sensitive to damage.

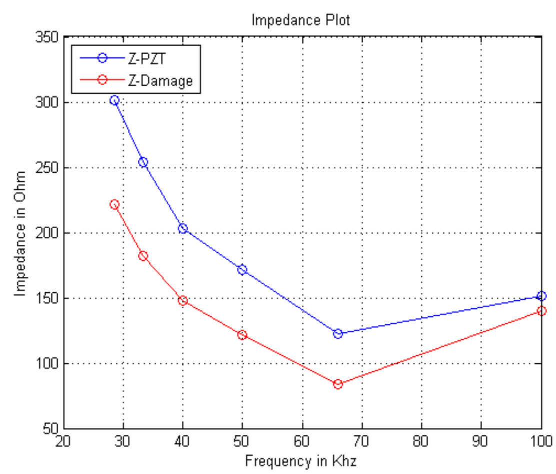


**Fig. 9: Impedance Measurement in Damage and Undamaged condition**

The analysis of data is done with respect to frequency that provides a good sensitivity for damage detection. The selection of the appropriate frequency range is critical which depend on the structure, PZT transducer and type of damage on the structure.

## 8. CONCLUSION

This research paper presented a smart sensing technique based on piezoelectric sensors. The architecture used in SHM application for Railway condition Monitoring is low cost, stability and able to detect looseness of a Fishplate. As the system able to differentiate the impedance between damage and undamaged condition so a monitoring system can be develop for looseness monitoring of fish bolt from the rail structural and provide an early warning to nearest Railway cabin. The variations in the RMS voltage signatures are similar to the variations in the impedance signatures. The Railway Condition monitoring system can be designed by a microcontroller with other additional features such as multiple PZT transducers and wireless communication concept for real-time application.

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