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# Self-sensing techniques of piezoelectric actuators in detecting unbalance faults in a rotating machine

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**Abstract**

Sensors are inevitable components in a machine or in a mechatronic system, to measure physical quantities. Due to the inherent property of a piezoelectric material, it can be used as an actuator to bring in a displacement in the system by applying an actuator voltage or it can be used as a sensor where a force applied on it is translated as voltage. This property called as self-sensing, is one way to reduce the number of sensors needed in an active system. In the present application, piezoelectric actuators are mounted at the bearings of a rotor. The bearing displacement can be determined from the deflection of the piezos. This deflection can be reconstructed from the current and voltage. By feeding the reconstructed deflection to a finite element (FE) model, faults such as unbalance can be detected. The modal expansion theory helps to determine the deflection at any degree of freedom from few measured signals such as the bearing displacements. Moreover, the forces at each node can be calculated and detected for presence of unbalance faults. With the help of least squares minimization, the magnitude and phase of the unbalance can be determined.


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*Keywords:* Unbalance detection, Piezoelectric actuators, Self-sensing, Modal Expansion method

## 1. Introduction

Rotating machines are inevitably used in most of the industrial applications. Either due to defects before the start of operation or due to effects during and after the operation, the machines are prone to faults. Defects before start of operation might be due to manufacturing faults, wrong choice of tolerances, imperfect mounting. Effects during or

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after operation might be due to fatigue and thereby wear of components, abrasion, temperature influences. All these causes lead to different types of faults such as unbalance, misalignment, cracks on the rotor shafts etc. Hence it is necessary to develop fault detection and isolation (FDI) methods to implement corrective actions or signal an alarm, before any fatal injury to an operator or breakdown of the machine is caused.

In today's age, sensors, actuators and control algorithms together achieve the common goal of fault identification. The control algorithms either raise an indication that a fault has been detected or initiate corrective actions through the actuators. The sensors located at vital and feasible positions observe the system and measure relevant physical quantities. Efforts have been made in the past to reduce the number of sensors to detect faults with a good accuracy. In [1, 2] displacement at selected degrees of freedom along a rotor shaft are measured and using the method of modal expansion the displacements at any other degree of freedom in the rotor are calculated. Thus, the number of sensors necessary for accurate fault detection can be reduced.

Piezoelectric materials can act as a sensor and as an actuator simultaneously and hence they can be used as self-sensing actuators. It is capable of generating a displacement when an electric voltage is applied on it. Conversely, when a force is applied on them, it produces an electric voltage. The former is its actuator property and the latter is its sensor property. In [3, 4] self-sensing property of a piezoelectric actuator has been described. This property is useful to further reduce the number of sensors in a mechatronic system. In [3], the author reconstructs the strain of the actuator from measured electrical signals and develops a control algorithm to reduce the vibration of a structure. In the present application, piezoelectric actuators are mounted at the bearings of a rotor test bench, in order to isolate the vibrations [5]. Also model based unbalance detection has been implemented in the same test bench [6]. Until now, the model based fault detection is being done with the help of displacement sensors located along the length of the rotor shaft.

In this paper, the self-sensing property of piezoelectric actuators is used to minimize the number of sensors required for fault detection. The deflection of the piezoelectric actuators due to unbalance forces is reconstructed from measured voltage and current. With the help of the equivalent vibration minimization method as described in [1], the magnitude and phase of unbalance faults in a rotor are determined. Another method known as equivalent load minimization method [1,2] is also used and compared.

In section 2, presents the experimental test setup available in the institute, on which the tests are performed. In section 3, self-sensing property of the piezoelectric actuators is described and reconstruction of piezo deflection from electric signals is explained. Section 4 presents the fundamentals of the modal expansion method, equivalent vibration minimization theory and equivalent load minimization theory. Section 5 shows the implementation of the methods and presents the results.

**Nomenclature**

| | |
|---|---|
| U | Voltage of piezoelectric actuator |
| q | Charge |
| A | Cross-section area |
| $\Delta l$ | Deflection |
| F | Force |
| M | Mass matrix of rotor system |
| D | Damping matrix |
| K | Stiffness matrix |
| $x$ | Displacement |
| $\Phi$ | Modal vector matrix |
| $\omega$ | Rotational speed |
| $m^*\varepsilon$ | Unbalance magnitude |
| $\beta$ | Unbalance phase |

## 2. Test bench and its modeling

The self-sensing and fault detection methods mentioned above have been tested on a rotor test bench in our institute and its model which can be seen in the CAD diagram as shown in Fig. 1. The rotor shaft (length 1.17 m) with a disc together weighing 22 kg is mounted on two sides with ball bearing planes. On one side, it is supported by a double bearing assembly with piezoelectric actuators mounted on x- and y-directions in both bearings. In total, there are four piezoelectric actuators. The other side of the rotor has a passive bearing only. The rotor is driven by an asynchronous motor with a maximum speed of 17700rpm.

Strain gauges are clamped along the length of the piezos. The test bench is equipped with two displacement sensor planes positioned along the length of the rotor shaft and four load sensors at the active bearing planes. At each plane of measurement, sensors are present in x- and y-directions. An encoder measures the angular position of the rotor. A dSpace control interface is used for data acquisition and control. Data from the sensors and actuators are captured with a sampling frequency of 2500Hz.

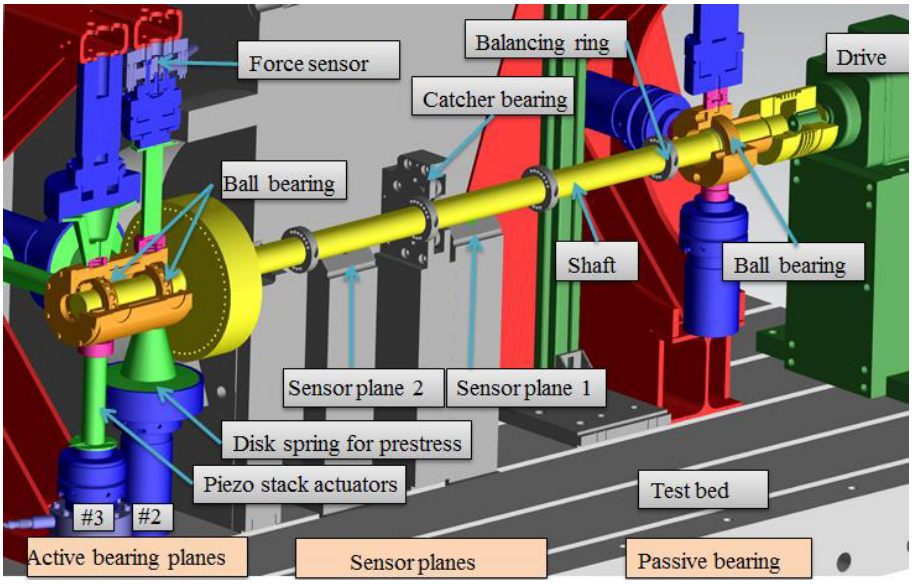


Fig. 1. CAD Diagram of the test bench

The test bench with its rotating components and supporting components are modeled according to Timoshenko beam theory in MATLAB, with the help of the toolbox *rotorbuild* which had been developed within the institute.

## 3. Self-sensing techniques of piezoelectric actuators

Piezoelectric actuators belong to the modern class of actuators with an inherent capacity to generate an electric field when a force is applied on them. When an electric field is applied they strain and thereby generating a deflection. They are correspondingly represented in the linearized equations Eq. (1).

$$\frac{q}{A} = e\frac{\Delta l}{l} + \varepsilon_S \frac{U}{l}$$
$$\frac{F}{A} = c^E \frac{\Delta l}{l} - e^T \frac{U}{l} \qquad (1)$$

The quantities $q$ and $\Delta l$ are the charge and deflection of the piezoelectric actuator. $F$ and $U$ are the amount of external force and the electric voltage applied to the actuator. The actuator parameters are the elasticity constant $c^E$, piezoelectric constant $e$ and the clamped permittivity constant $\varepsilon_S$. $A$ and $l$ in the equation represent the cross-section area and thickness of the actuator ceramic respectively.

Using the electrical quantities such as electrical voltage and charge (which can be integrated from measured current) and the piezoelectric constants, the mechanical quantities such as the strain and force acting on the actuator can be calculated. In reality, the linearised behavior holds true only for a small band of voltage amplitudes. In broader operating range, a hysteresis can be seen. A generalized piezoelectric equation can be written as in Eq. (2). The different functions $f_1$, $f_2$ and $g_2$ are non-linear hysteresis functions.

$$\begin{aligned} q &= f_1(\Delta l) + f_2(U) \\ F &= c^E \Delta l + g_2(U) \end{aligned} \tag{2}$$

The piezoelectric actuators dealt with in the present work are cylindrical stack actuators. They are 113 mm long and 25 mm in diameter, capable of operating at a maximum voltage of 1000 V and maximum force of 14 kN (also known as blocking force).

### 3.2 Reconstructing the mechanical quantities

This section explains how the actuator deflection can be reconstructed from the measured electrical signals. As it can be seen from Eq. (1) and (2), the charge obtained at the electrodes is a sum of charge caused by the electric voltage applied on the actuator and the charge caused due to the mechanical deflection, which can also be referred to as mechanical charge. The equation can be rearranged as given in Eq. (3).

$$\Delta l = f_1^{-1}(q - f_2(U)) \tag{3}$$

Initially, the hysteresis represented by the function $f_2$ is reconstructed. It describes the clamped permittivity of the actuator and relates the electric voltage at constant deflection. The experimental procedure has been explained in [3]. In order to avoid the influence of the strain, the mechanical system has been examined for an anti-resonance frequency, where the deflection at the piezoelectric actuators is the lowest. At this point, the charge can be directly related to the voltage only. In the present system, the anti-resonance frequency of the rotor test bench has been found to be at 110 Hz. A sinusoidal actuation voltage of frequency equal to this anti-resonance frequency was applied to the actuator, with different amplitudes. The voltage and current are measured, and the charge is obtained by integrating the current signal. Curve fitting has been done from these measured voltage and charge to approximate the hysteresis function $f_2$. Fig. 2 shows the hysteresis curves so obtained from the measurement and reconstructed after curve fitting. The reconstructed charge signal is able to approximate the measurement data with sufficient accuracy. The figure clearly shows that as the amplitude of the actuation voltage increases, the permittivity exhibits an increasing hysteresis behavior.

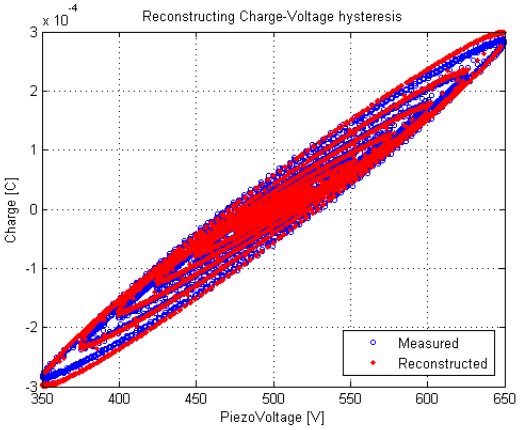


Fig. 2. Comparison of hysteresis behavior in a piezoelectric actuator

In the next step, estimation of the hysteresis function $f_1^{-1}$ as given in Eq. (3) between the mechanical charge and the strain is performed. The rotor has been driven to the maximum speed, to cover a broad range of strain on the piezoelectric actuators, without any actuation voltage. The relation between the deflection signals and the mechanical charge has been examined in each rotational frequency interval of 500rpm. Through curve fitting, the hysteresis function has been reproduced, the result of which can be seen in Fig 3. It should be noted that the strain gauge bound to the piezoelectric actuator measures the deflection (*Δl*) and not the strain (*Δl/l*). As it can be seen, the deflection signals could be reproduced very well with self-sensing reconstruction. It can also be observed from the plot that, the amplitude of the reconstructed signals is slightly higher than the measured deflection.

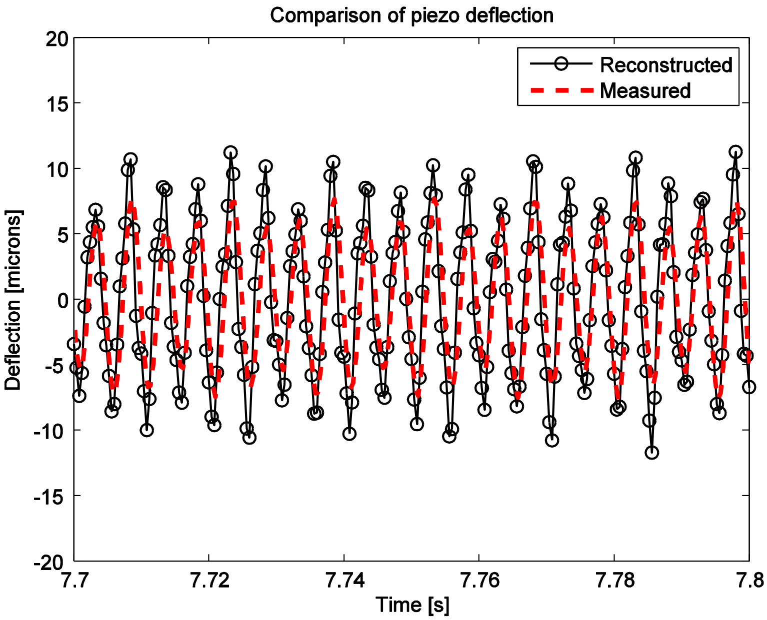


Fig. 3. Piezoelectric actuator deflection – comparison of measured and reconstructed using self-sensing

## 4. Fault detection

For a better estimation of faults, it is desired to use as many sensors as possible at different finite element nodes. But in reality, it is neither feasible nor a cost-effective solution. In such cases, the sensors can be positioned at a more accessible position. The displacement or force at a different degree of freedom (dof) can be estimated with the help of the model. The modal expansion theory estimates the displacement of all nodes, given an accurate model and the measured displacement at a particular node.

### *4.1 Modal expansion method*

The equation of motion of a mechanical vibrating system is given in Eq. (4), where *M*, *D* and *K* represent the mass, damping and stiffness matrices respectively. The vectors $\ddot{x}, \dot{x}$ and $x$ represent the acceleration, velocity and displacement at different dof, and *F* is the excitation force.

$$M\ddot{x} + D\dot{x} + Kx = F \tag{4}$$

The dofs at which the sensors are positioned can be mentioned as $x_m$ and it is related to the total degrees of freedom *x* using the matrix *C*, as given in Eq. (5). In this equation the vector $\Delta x$ and $\Delta x_m$ represent the difference of the fault-caused displacement from the initial residual displacement.

$$\Delta x_m = C\Delta x \tag{5}$$

The mode shapes of all dofs can be obtained from the eigenvector matrix Φ. With the help of the mode shapes, and Eq. (5), the complete displacement vector at all dofs can be derived as seen in Eq. (6). [1,2]

$$\Delta x(t) = \{\Phi[(C\Phi)^T (C\Phi)]^{-1} (C\Phi)^T\}\Delta x_m(t) = [T]\Delta x_m(t) \tag{6}$$

The matrix *T* transforms the displacement from selected dofs to all dofs, and it can be calculated a priori from the finite element model.

### *4.2 Estimation of fault parameters*

The selected dofs are the nodes where the sensors are positioned, which in our case are the self-sensing piezoelectric actuators. The measurements at these dofs should be expanded to all the dofs using the relation given in Eq. (6).

$$F_{unb} = m\varepsilon\omega^2 \sin(\omega t + \beta) \tag{7}$$

The theoretical unbalance force can be computed from Eq. (7). The unbalance parameters are the magnitude of unbalance *(m* $\varepsilon$ )* and the phase *(β)*. The vibration at all the dofs ( $\Delta x_{ml}$ ) is compared with the measured vibration ( $\Delta x_m$ ). By the method of least squares minimization, the vibrations are compared and the unbalance parameters causing the vibration are then identified with the help of Eq. (8). This is referred to as equivalent vibration minimization method [1].

$$\min\left\{\int \left|\Delta x_{ml}(t) - \Delta x_m(t)\right|^2 dt\right\} \tag{8}$$

Another similar method is the equivalent load minimization method. In this method, the forces at the nodes (computed from FE) are compared to the theoretical unbalance faults ($F_{unb}$). With the help the least squares minimization method as given in Eq. (9), the fault parameters can be calculated.

$$\min\left\{\int \left|F_{ml}(t) - F_{unb}(t)\right|^2 dt\right\} \tag{9}$$

## 5. Results and discussion

### *5.1 Implementation*

The fault detected in this paper is unbalance, and diagnosed for two parameters which are the unbalance magnitude (*m.r*) and the phase (*β*). In [1], the least squares algorithm is run to obtain both the parameters. However, in this paper the phase is detected by a correlation analysis between the signals from the model and the measurement. Then the signals from the model are phase shifted and a least squares minimization algorithm is performed as given in Eq. (8) and (9). This ensures a better convergence of the least squares algorithm because of reduced number of parameters.

The concepts are compared with simulated data and measured data. In simulation, the unbalance forces are given as inputs to the state space model of the rotor. The vibration displacement signals at the location of the piezoelectric actuators are taken as the unbalance caused vibrations. Faults are diagnosed with equivalent vibration minimization method.

Using the equations of motion Eq. (4), structural forces can be reconstructed. Using these force signals, with the help of equivalent load minimization method, fault parameters can be calculated as well.

### *5.2 Results*

The results are shown in Table 1-3. As it can be observed in Table 1, different unbalance magnitudes and phases are experimented, with equivalent load minimization method. The algorithm has detected the unbalance faults with good accuracy. The percentage error of unbalance magnitude indicates a benchmark, with which further actual measured data could be compared.

Table 1. Fault detection with Equivalent load minimization method (simulation)

| Rotational frequency | Unbalance | | Detected unbalance | | Error in unbalance magnitude |
|---|---|---|---|---|---|
| (rpm) | Magnitude (gmm) | Phase (deg) | Magnitude (gmm) | Phase (deg) | (%) |
| 8000 | 90 | 200 | 85.09 | 199.2 | -5.45 |
| 8000 | 100 | 200 | 94.48 | 199.2 | -5.52 |
| 8000 | 150 | 200 | 141.71 | 199.2 | -5.53 |
| 8000 | 150 | 100 | 140.92 | 96 | -6.07 |
| 8000 | 150 | 75 | 142.02 | 76.8 | -5.32 |
| 8000 | 150 | 45 | 141.87 | 50.4 | -5.42 |

In Table 2, the same set of simulation is performed and parameters are calculated using the equivalent vibration minimization method. When compared with Table 1, the results are almost same, with no significant advantage in accuracy.

Table 2. Fault detection with Equivalent vibration minimization method (simulation)

| Rotational frequency | Unbalance | | Detected unbalance | | Error in unbalance magnitude |
|---|---|---|---|---|---|
| (rpm) | Magnitude (gmm) | Phase (deg) | Magnitude (gmm) | Phase (deg) | (%) |
| 8000 | 90 | 200 | 83.91 | 201.2 | -6.78 |
| 8000 | 100 | 200 | 93.9 | 201.2 | -6.1 |
| 8000 | 150 | 200 | 143.9 | 201.2 | -4.06 |
| 8000 | 150 | 100 | 143.9 | 100.8 | -4.06 |
| 8000 | 150 | 75 | 143.5 | 79.2 | -4.07 |
| 8000 | 150 | 45 | 143.9 | 43.2 | -4.06 |

In Table 3, the unbalance parameters are diagnosed from data measured at the test bench. The same unbalance fault has been tested with data from different rotational speeds. As it can be seen, there is a significant decrease in the accuracy compared to the simulations. This is because, the FE model is not accurate enough at the bearing dofs. A more accurate model can definitely lead to better results. Another inference is the decreasing error, with increasing rotor frequency. The reason is due to the higher unbalance forces as the rotational frequency increases.

This causes a more significant deflection at the piezoelectric actuators, thereby more accurate in parameter prediction, as the signal to noise ratio improves.

Table 3. Fault detection with Equivalent vibration minimization method (from measured data)

| Rotational frequency | Unbalance | | Detected unbalance | | Error in unbalance magnitude |
|---|---|---|---|---|---|
| (rpm) | Magnitude (gmm) | Phase (deg) | Magnitude (gmm) | Phase (deg) | (%) |
| 6000 | 74 | 225 | 41.64 | 273.6 | -43.72 |
| 8000 | 74 | 225 | 44.91 | 256.1 | -40.54 |
| 9000 | 74 | 225 | 63.05 | 201.6 | -14.8 |

## 6. Conclusion

This paper demonstrates the ability to detect unbalance faults (magnitude and phase) using the self-sensing property of piezoelectric actuators. The deflection of the piezoelectric actuator upon an external load, in this case the unbalance caused forces is reconstructed from the measured voltage and current signals of the actuator. The equivalent load minimization and equivalent vibration minimization methods are used to determine the magnitude and phase of the unbalance faults from the piezo deflection signals. The results show good ability of the method in determining the faults from reconstructed deflection signals. However, the accuracy of the results depends very much on the exactness of the model to the real test bench.

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