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An approach towards sensor selection and placement based on experimental modal analysis

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Abstract
Real-time continuous machine condition monitoring requires an accurate measurement of the vibration spectrum at a critical point. In some processes, such as milling, this point is the tool tip, but direct measurement here is normally not possible due to process requirements. We proposed an approach for sensor selection and placement at strategic locations to measure and infer the desired vibration conditions. The sensor placement locations are identified based on our proposed moderated sensitivity indicator. This indicator is quantified using each location's sensitivity as well as its measurement quality (Fisher Information). Upon selection, Radial Basis Functions (RBF) are trained to carry out the vibration spectrum inference process. Our preliminary trials indicate that we are able to achieve inference errors of 5.4%.

Keywords: Vibration sensitivity measurement, sensor placement, fisher information, radial basis function, frequency spectrum.

1. Introduction

Various machine condition monitoring methods have been proposed and evaluated in the past decades. Generally, they can be grouped into two main categories [1]: (a) direct method, which requires the machine tool to be removed from the machine in order to physically evaluate its condition. Such method is not suitable for real-time condition monitoring. (b) indirect method, which relies on sensor measurement of the machining variables (e.g. vibration, force, and current), and to compare them against the machine's normal operational signatures. This method is preferred as the machine's operation is not interrupted and real-time condition monitoring is possible.

The indirect method of machine condition monitoring relies on the sensory system deployed to monitor the machine's condition. One of the important factors determining the effectiveness of such method is the placement of the sensors. Extensive research works pertaining to the sensor placement methodologies have been developed to evaluate and quantify the performance. Salama et al. [2] proposed using Modal Kinetic Energy as a way to rank the importance of candidate sensors locations. Kammer [3] proposed an iterative method using the Effective Independent method, based on the maximization of the determinant of the Fisher Information Matrix, to determine the ranking to the sensors locations. Other performance indices such as Error Covariance Matrix and Information Entropy can be applied to sensor location evaluation too.

In this paper, we propose an approach for sensor selection and placement for real-time machine condition monitoring. A precision machining center is served as the system in the background in order to illustrate the proposed idea. The critical point is defined at the tip of the cutting tool. The unwanted vibration source may arise from a worn lead screw or crack bearings of the machine, and this resultant vibration will propagate to the other part of the machine. Since the quality of the machined part is highly dependent on the machine's health, real-time monitoring of the vibration spectrum at this point is necessary to maintain the production quality. The main objective of this paper is to identify suitable sensor placement locations to infer the actual vibration spectrum of the critical location.

2. Proposed approach

The vibration spectrum Y_r at the tool tip (critical point L_r) may be represented by multiple (m) discrete vibration frequencies of interest during its operation. Y_i represents the vibration spectrum at a sensor placement location with the same discrete vibration frequencies of interest at location L_i. Note that there can be multiple sensor placement locations where $i: 1 \rightarrow n$

$$Y_r = \{(a_{r1,}\omega_1), (a_{r2,}\omega_2), \cdots, (a_{rm,}\omega_m)\} \quad (1)$$

$$Y_i = \{(a_{i1,}\omega_1), (a_{i2,}\omega_2), \cdots, (a_{im,}\omega_m)\} \quad (2)$$

where a_{rm} and a_{im} represent the vibration amplitude at L_r and L_i respectively given the frequency of interest ω_m.

The vibration relationship between L_r and L_i is related to the machine mechanical structure, and this relationship can be approximated from the sensitivity s_{ij} which governs how a small vibration at the critical point with the frequency of interest ω_j can be picked at the sensor location i.

$$s_{ij} = \frac{a_{ij}}{a_{rj}} \quad (3)$$

where s_{ij} is the computed vibration sensitivity, a_{ij} and a_{rj} are the amplitudes of the vibration measurements at L_i and L_r

respectively with the frequency of interest ω_j given that $i: 1 \rightarrow n$ and $j: 1 \rightarrow m$

The locations for sensor placement may be constrained on the type of sensor that can be placed. Hence, relying solely on the sensitivities measurement for sensor placement runs the risk of allowing less reliable signals to pass through the selection process without penalty. Therefore, Fisher Information is used as a signal quality indicator for the vibration measurement. The higher the Fisher Information, the better the signal quality.

$$\tilde{f}_{ij} = \frac{a_{ij}}{\sigma_{ij}^2} \quad (4)$$

where $\tilde{f}_{ij}$ is the Fisher Information, σ_{ij}^2 denotes the variance of the measurement from sensor placement location L_i for frequency of interest ω_j.

Since we proposed the placement and selection of sensors to be based on both sensitivities and Fisher Information. The cost function to moderate the sensitivities is then defined as

$$k_{ij} = \alpha + (1-\alpha)\left[\frac{\tilde{f}_{ij} - \min \tilde{f}_{ij}}{\max \tilde{f}_{ij} - \min \tilde{f}_{ij}}\right] \quad (5)$$

where $\max \tilde{f}_{ij}$ and $\min \tilde{f}_{ij}$ are the highest and lowest Fisher Information amongst all sensor placement locations given the same frequency of interest. α is a user-defined parameter to balance the original sensitivity against its quality. For the following experiment, we used $\alpha = 0.8$.

The moderated sensitivity for final sensor placement and selection is given as

$$\tilde{s}_{ij} = k_{ij} \, x \, s_{ij} \quad (6)$$

3. Experimental sensitivity analysis

The experiment setup depicts in Figure 1 includes: (a) custom made test fixture emulating a milling machine, (b) a vibration motor attached to the test fixture to simulate the vibration generated from a cutting tool, (c) accelerometers to measure the vibration, and (d) NI Compact DAQ for data acquisition.

The vibration motor is controlled to run at an operating frequency of 100Hz in the direction of x-axis. Data collected from the accelerometers are processed, and its corresponding sensitivities and Fisher Information are obtained using Eqn. (3) and (4). The moderated sensitivities are calculated by Eqn. (6) and the results are plotted in Figure 2. The result shows that sensor location (7,1) is the most sensitive. Therefore, it is selected to infer the vibration spectrum at the tool tip. Figure 3(a) illustrates the vibration measurement at the tool tip and sensor location (7,1). A RBF network is then trained to replicate the vibration spectrum of the tool tip using the data at sensor location (7,1). Figure 3(b) shows the RBF verification result whereby the trained RBF is able to approximate the desired output accurately with mean square error of 5.4% in subsequent independent trials.

4. Conclusion

An approach for sensor placement and selection for real-time machine condition monitoring has been proposed and validated in this paper. The approach uses a minimal series of sensors mounted at key locations of a machine to measure and infer the actual vibration spectrum at a critical location where it is not suitable to mount a sensor. The sensor selection is based on an indicator which leverages on sensitivity and the Fisher Information at a frequency of interest. The top ranked sensor at the frequency of interest is then being identified and selected to infer the actual vibration spectrum at the critical location using RBF.

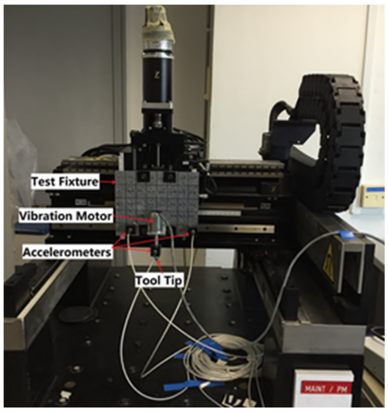

Figure 1. Experiment setup

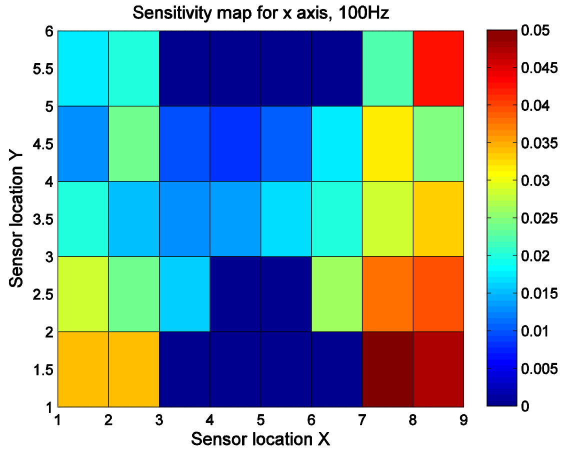

Figure 2. Moderated sensitivity map

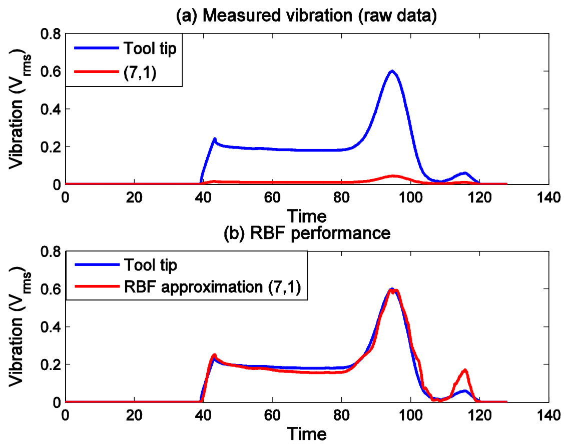

Figure 3. RBF inference result

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