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Restoration of a temporal indicator specific to each vibratory sources for a predictive maintenance

X. Chiementin [a,*], F. Bolaers [a], L. Rasolofondraibe [b], J.-P. Dron [a]

[a] GReSPI, Groupe de Recherche en Sciences Pour l'Ingénieur, University of Reims Champagne-Ardenne, BP 1039, 51687 Reims Cedex 2, France
[b] CReSTIC, Centre de Recherche en Sciences et Technologies de l'Information et de la Communication, University of Reims Champagne-Ardenne, BP 1039, 51687 Reims Cedex 2, France

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ABSTRACT

The monitoring of rotating machinery is increasingly important for industry. Partly, it is made from indicators given by vibration analysis. These indicators give only the overall state of operation of the studied machine. Indeed, the piezoelectric sensors, which are used for vibration analysis, record the vibrations generated by the various components of the machine. Numerous studies have developed techniques for locating and quantifying the vibration sources from the recorded signals. Thus, it is legitimate to believe that these sources can give us an indicator which should be characteristic of the damage of each critical component and which should allow to follow the severity of a defect. This paper studies the feasibility (i) firstly, to restore an indicator (RMS value) for each component, (ii) secondly, to monitor the evolution of this indicator through the severity of the defect.

1. Introduction

Nowadays, the maintenance of machinery is essential for the good operation of the productivity and the safety of the staff. Many studies focus on a predictive maintenance, in particular the monitoring of the component of the machine. Partly, predictive maintenance monitors the deviation of the indicators which represent the working order of the machine. These indicators are determined from vibration signals obtained with piezoelectric sensors [1]. However, the signals recorded by the sensors are often the result of a mixture of sources (for example, from several rolling bearings). Therefore, these indicators only diagnose the general working order. The computation of an indicator which characterizes each source would be a major asset for the monitoring and the follow-up of the damage. The restoration of each source from the recorded signals and the computation of indicators can improve their diagnosis.

However, the inversion is an unstable problem due to the measurement errors or noise in the signals. To stabilize the problem, studies suggest using over-determined systems, i.e. systems with more observations than sources [2,3]. These methods require the use of parameters called ''regularization parameters'' which are difficult to determine. They can be evaluated according to the uncertainties of the mixture matrix [4], on the mixture matrix and observations [5], or on the principle of L-curve [6]. Even if these parameters are determined, the inversion may remove a source. Moreover, these studies are trying to restore the sources over a wide frequency band with a large number of sensors which are placed ''randomly'', while the stability depends largely on the frequency and on the position of the sensors.

* Corresponding author.
E-mail address: xavier.chiementin@univ-reims.fr (X. Chiementin).

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Fabunmi [7] has highlighted the existence of a link between modal analysis and the number of determinable sources on a narrow frequency band. He shows that the number of modes participating in the response of the structure must be equal or superior to the number of sources. Lee and Park [8] use this relationship to make a selection of sensors which can stabilize the inversion. However, this selection is made after having positioned many sensors. In a previous paper [9], we propose to position a limited number of sensors which are used to restore the sources around several frequencies (which are characteristic of the presence of a defect) and to avoid regularization methods that can remove vibratory sources. Two approaches have been developed. Each of them can determine the areas where the restitution is stable. These areas are illustrated by conditioning maps. Those two approaches provide a reliable restoration due to the stability of the solution. They are compared to the methods which use the over-determined systems and the methods of regularization, including the L-curve principle [10]. The aim of this paper is to restore an indicator specific to each vibratory sources using inverse approach. We are studying the particular case of a fault in rolling bearings, because rolling bearings are always present in rotating machines.

2. Inverse problems in vibratory analysis

2.1. Description

The inverse problems can restore sources (input) from observations (output). In the field of vibration, the responses of a structure, $y_j(t)$, are the results of the convolution product between the temporal signal of the sources, $x_i(t)$, and the impulse response of the structure $t_{i,j}(t)$

$$y_j(t) = \sum_{1}^{p} t_{i,j}(t)^{*} x_i(t), \quad i = 1, \ldots, m \Rightarrow Y(f) = T(f) \cdot X(f) \tag{1}$$

where p is the number of sources, m is the number of vibratory responses/observations. In the frequential field, the convolution product becomes a simple product, where $\mathbf{Y}(\omega)$, $\mathbf{X}(\omega)$ and $\mathbf{T}(\omega)$ are, respectively, the vectors of the responses and of the sources, and the mixture matrix. Note that if $\mathbf{Y}(\omega)$ and $\mathbf{X}(\omega)$ have the same unit, $\mathbf{T}(\omega)$ is the transmissibility matrix.

The decomposition in singular values of the mixture matrix provides a simple and effective solution to the linear inverse problem

$$\mathbf{T} = \mathbf{U} \cdot \mathbf{\Sigma} \mathbf{V}^t \tag{2}$$

where $\mathbf{U} = (u_1; \ldots; u_p)$ and $\mathbf{V} = (v_1; \ldots; v_m)$ are the orthogonal matrices. Their size are, respectively $(p;p)$ and $(m;m)$. $\mathbf{\Sigma}$ is a diagonal matrix whose elements are singular values σ_i of the matrix $\mathbf{T}$. The orthogonal vectors v_k and u_k are, respectively, called right singular vectors and left singular vectors.

To apply inverse problems in mechanical systems, a preliminary step is necessary. The matrix $\mathbf{T}$ must be determined thanks to a shaker. After this step, the inversion can be made when the structure operates, thanks to measurements made by sensors.

Generally, inverse problems are ill-posed problems within the meaning of Hadamard [11], i.e. they do not satisfy one of these criteria: uniqueness, existence and stability of the solution. In the vibratory field, stability is difficult to satisfy. Indeed, small errors on the data of the responses or on the impulse responses can generate important errors on computed sources. These errors are increased by the number of conditioning of the matrix $\mathbf{T}$, noted $c(\mathbf{T})$. Thus, a high conditioning number means an ill-conditioned matrix and a low conditioning number means a well-conditioned matrix. In other words, the inversion is stable for a small number of conditioning.

2.2. Modal analysis and conditioning number

By definition, the conditioning number for the norm 1 is defined:

$$c(\mathbf{T}) = ||\mathbf{T}||||\mathbf{T}||^{-1} \tag{3}$$

hence

$$c(\mathbf{T}) = \frac{1}{|\det(\mathbf{T})|} ||\mathbf{T}|| \left\| {}^{t}Com(\mathbf{T}) \right\| \text{ with } \mathbf{T}^{-1} = \frac{{}^{t}Com(\mathbf{T})}{\det(\mathbf{T})} \tag{4}$$

We want to get the closest to 1 conditioning number, i.e. to minimize the function f_{obj}, which is defined as the difference between the product of the highest values of the columns of $\|\mathbf{T}\|$ and $\|{}^{t}Com(\mathbf{T})\|$, and the determinant of $\mathbf{T}$

$$f_{obj} = |||\mathbf{T}|| \cdot ||{}^{t}Com(\mathbf{T})|| - \det(\mathbf{T})| \text{ with } \det(\mathbf{T}) \neq 0 \tag{5}$$

However, this relationship is directly unusable. We can simplify the problem and declare that the inversion will be stable if the denominator, $det(\mathbf{T})$, is not null.