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DYNAMIC LOAD IDENTIFICATION OF ENGINEERING STRUCTURE BASED ON IMPROVED REGULARIZATION METHOD

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Dynamic load identification is of great value in engineering problems. In this paper, an improved regularization method is designed to solve the ill-posed problem of load recognition, the filter operator is introduced to optimize the solution of the equation, and simulation experiments were carried out on the model to compare the performance of the traditional regularization method and the improved method proposed in this paper. The results show that the load identification errors of the improved method proposed in this paper at points A and B are 0.03 N and 0.01 N respectively, which are much smaller than 0.12 N and 0.1 N of the traditional method, and the proposed method is not sensitive to noise, with a higher application value in reality. The experimental results prove the reliability of the proposed method, which indicates that the method designed in this paper is worthy of being popularized and applied in practice. This study can make some contributions to solving the ill-posed problem of dynamic load identification.

Keywords: regularization; dynamic load identification; ill-posedness; filter operator.

1. Introduction

Dynamic load has been widely used in engineering structures [1], which can effectively reflect the dynamic performance of engineering, so as to master the reliability and safety of engineering structures and play an important role in fault diagnosis and vibration control. The concept of dynamic load identification first appeared in the field of military aviation, which were extensively studied in various engineering fields soon after. With the development of science and technology, dynamic load recognition technology has also been constantly developing and innovating, and more and more recognition methods with higher precision and wider application range, such as wavelet analysis [2], neural network [3], etc. appear. Song et al. [4] designed a method based on fiber Bragg grating (FBG) sensor, i.e., the strain obtained by FBG was taken as the signal, the matrix was generated by Kalman filter, and then load identification was performed by least squares method. It was found from the simulation experiment

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that the method had good stability and real-time performance. Liu et al. [5] designed a time-domain Galerkin method, i.e., establishing a forward model through shape function, residual function and weighting function to perform load identification. The calculation of three numerical examples showed that the method could effectively overcome noise with high accuracy. Dumitriu and Fologea [6] studied the correlation between the dynamic response of two-axle bogie and the axial displacement during the cycle on the track with vertical irregularity and found through calculation that the correlation was mainly related to the speed, frequency and suspension damping. Mîţiu and Comeaga et al. [7] studied the principle and method of controlling the dynamic response of the system by changing mechanical or electrical parameters. The regularization technology which was an effective method was widely used. Liu et al. [8] combined the Gegenbauer polynomial with the regularization method to identify the dynamic load of random structures. Numerical simulations showed that the method could identify the dynamic load stably and effectively. Jia et al. [9] combined the regularization method with orthogonal decomposition and obtained the optimal regularization parameters by generalized cross-validation (CGV) method. The simulation experiments indicated that the load identified by this method was consistent with the actual load. In this paper, based on the regularization method, an improved regularization method is designed, and the effectiveness of the proposed method is proved by the simulation experiment on the model. This study provides some theoretical support for the better application of the regularization method in dynamic load identification.

2. Dynamic load identification

There are two main methods for determining dynamic loads, i.e., direct and indirect methods. The former refers to the direct measurement of loads or related parameters by sensors, but in reality, direct measurement is a very difficult or infeasible work [10]. For example, the dynamic load of ship propellers, helicopter rotors, etc. cannot be obtained by installing sensors, and sensors may have an impact on the performance of the structure in some precision structures, making it impossible to accurately measure the load. The method of indirectly measuring the load refers to inverting the load based on a priori structural dynamic characteristic by measurement of structural response (displacement, velocity, etc.), that is, dynamic load identification. There are many difficult problems in the identification of dynamic loads:

(1)Ill-posed problem: dynamic load identification is an inverse problem [11], and its structural matrix has ill-conditioned problems when it is in the inversion and has ill-posedness [12].

(2)Noise: There may be noise in the response data and structure inversion matrix [13].

(3)Arrangement of measuring points: In the process of actual identification, the arrangement of measuring points will have some impact on the recognition accuracy. Therefore, one needs to select the best measuring point.

(4)Nonlinear systems: The current identification methods are mostly used in the processing of linear systems, which are not applicable to nonlinear systems.

3. Regularization theory

An operator is expressed by $T: X \to Y$, and then the operator equation is $Tx = y$. The singular system of T is set as $\{\sigma_i, u_i, v_i\}$. The necessary and sufficient condition for operator equation solvable can be written as: $\sum_i \frac{|u_i^T y|}{\sigma_i^2} < \infty$.

The main idea of the regularization method is an optimization problem:

$$\min_{x \in R} \|Tx - y\|_2^2 + \alpha^2 \|x\|_2^2,$$

where α is the regularization parameter.

Finally, the regularization solution can be expressed as:

$$f = \sum_{i=1} \frac{\sigma_i^2}{\sigma_i^2 + \alpha^2} \frac{u_i^T y}{\sigma_i} v_i.$$

4. Dynamic load identification based on improved regularization method

4.1. Load identification model

The geometric nonlinearity of the structure is ignored. Suppose that the engineering structure is a linear elastic system, then the relationship between engineering structure response and load can be expressed as $y(t) = \int_0^t h(t-\tau) f(\tau) = h(t) * f(t)$, in which $h(t)$ indicates the impulse response function, $y(t)$ represents the response at the measuring point, $f(t)$ represents impact loads, and $*$ represents convolution operations. The equation is discretized:

$$H = \Delta t \begin{bmatrix} h(\Delta t) & 0 & \cdots & 0 \\ h(2\Delta t) & \mathrm{h}(\Delta \mathrm{t}) & \ddots & \vdots \\ \vdots & \vdots & \ddots & 0 \\ h(n\Delta t) & h((n-1)\Delta t) & \cdots & \mathrm{h}(\Delta \mathrm{t}) \end{bmatrix},\ F = [f(0) \cdots f(n-1)\Delta t]^T,\ Y = [y(\Delta t) \cdots \mathrm{y}(\mathrm{n}\Delta \mathrm{t})]^T,$$

where Δ indicates the sampling time interval.

Then the mode of impact load identification can be expressed as $Y = HF$, it is solved by the traditional least square method, and the solution is:

$$F = H^{+}F = \sum_{i=1}^{m} \frac{1}{s_i}\left(u_i^T Y\right)v_i \,, \tag{1}$$

where H^{+} represents the Moore-Penrose pseudo-inverse, u_i and v_i represent left and right singular value vectors respectively, and s_i represents the singular value.

4.2. The improved regularization method

In order to better solve the ill-posed problem in the recognition equation, in this study, a filter operator is proposed, $k_\lambda(s_i) = \frac{s_i^\sigma}{\lambda + s_i^\sigma}, \sigma \geq 1$, where λ represents regularization parameters. In the filter operator, $k_\lambda < 1$, and $\lambda \to 0, k_\lambda \to 1$. When $\sigma = 1$, $k_\lambda(s_i) = \frac{s_i}{\lambda + s_i} < \lambda^{-1}s_i$; when $\sigma > 1, \lambda + s_i^\sigma \geq \lambda^{1/p}s_i^{\sigma/q}$ is obtained by Young's inequality. $k_\lambda \leq \lambda^{-\frac{1}{\sigma}}s_i$ is obtained when $p = \sigma, q = \frac{\sigma}{\sigma - 1}$. When $\sigma \geq 1$, $k_\lambda \leq \lambda^{-\frac{1}{\sigma}}s_i$.

By combining with the filter operator, the solution of the recognition equation can be transformed into:

$$F = \sum_{i=1}^{m} k_\lambda(s_i)\frac{u_i^T Y}{s_i}v_i \,. \tag{2}$$

The filter operator is an improved regularization operator. After transforming the recognition equation by combining with the filter operator, the obtained solution can be an improved regularization solution. When $\sigma = 2$, the improved recognition equation is the same as the traditional regularization equation. In order to be able to compare, $\sigma = 3$ is taken for the simulation experiment in this study.

5. Numerical simulation

5.1. Simulation model

An aluminium alloy plate with one end fixed was taken as the model for the simulation experiment. The size of the model was 1 m × 1 m, the thickness was 0.001 m, the density was 2.7 g/cm^3, and the Poisson's ratio was 0.3. As shown in Fig. 1, two vertical dynamic loads F1 and F2 were applied on the plate, in which F1 is a sine wave load of 4 cycles, with an amplitude of 10 N and a cycle of 0.05 s, and F2 is a triangular wave load of 2 cycles, with an amplitude of 10 N and a cycle of 0.2 s. The measuring position of dynamic response of F1 was measuring point A, and the measuring position of dynamic response of F2 was measuring point B.

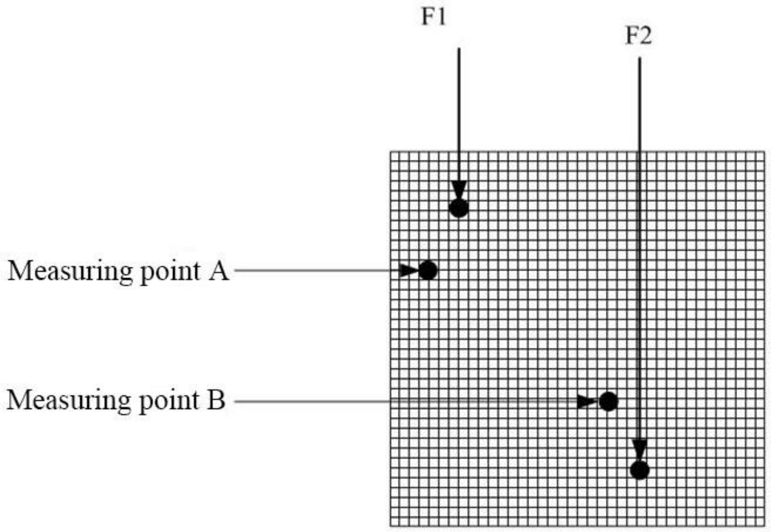

Fig. 1 The simulation model

5.2. Load identification

The load of points A and B in the model is identified by the traditional regularization method (hereinafter referred to as Tra) and the improved regularization method (hereinafter referred to as Imp) designed in this paper. The recognition results are shown in Fig. 2 and 3.

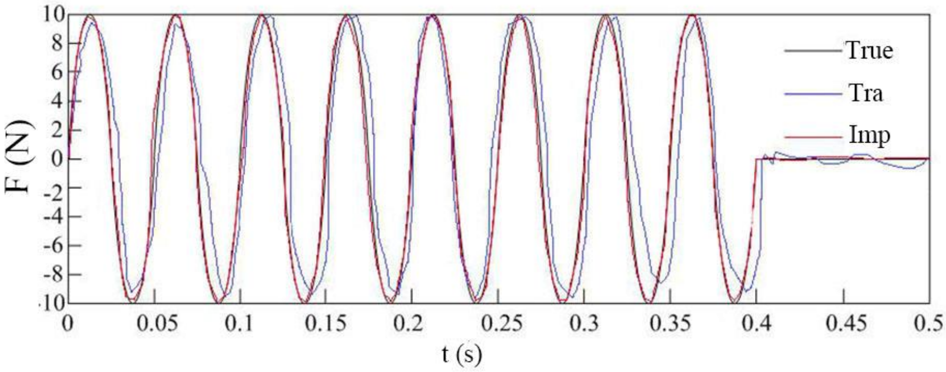

Fig. 2 The recognition result of point A

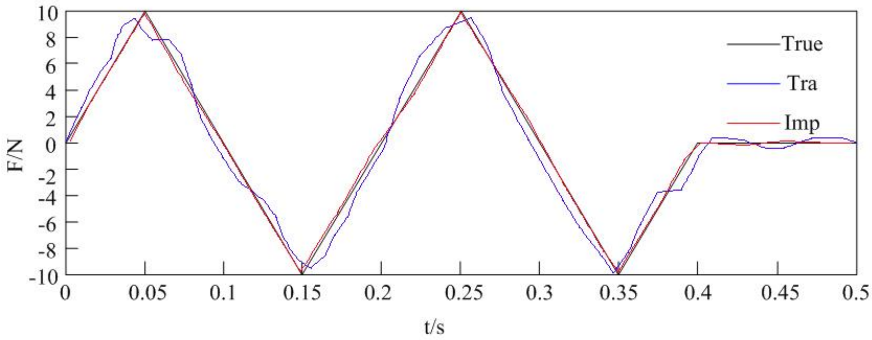

Fig. 3 The recognition result of point B

It can be found from Fig. 2 and 3 that the recognition result of Tra has a certain error compared with the actual value, and the identified load fluctuation is larger, while the curve obtained by Imp is basically fitted with the actual value, and the fluctuations are relatively smaller, although there are also fluctuations.

The time interval 0-0.01 s is taken as an example, and the specific situations of actual load and identification load are shown in Table 1.

Table 1

The identification value of point A

Time (s)	0	0.002	0.004	0.006	0.008	0.01
Actual load (N)	0	1.98	3.67	5.26	7.13	9.11
Tra identification load (N)	0.12	2.13	3.42	4.16	7.26	9.37
Average error (N)	0.12					
Imp identification load	0	2.01	3.74	5.32	7.08	9.17
Average error (N)	0.03					

Table 2

The identification value of point B

Time (s)	0	0.002	0.004	0.006	0.008	0.01
Actual load (N)	0	0.2	0.4	0.6	0.8	1.0
Tra identification load (N)	0.13	0.31	0.52	0.49	0.91	1.24
Average error (N)	0.1					
Imp identification load	0	0.19	0.41	0.6	0.78	1.1
Average error (N)	0.01					

It can be found from Table 1 and 2 that the error of Imp is smaller than that of Tra. In terms of the recognition result of point A, the average error of Tra is 0.12 N between 0 and 0.01 s, while the average error of Imp is 0.03 N. In terms of the recognition result of point B, the average error of Tra is 0.1 N, while the average error of Imp is 0.01 N, which proves the reliability of the proposed method.

To further understand the recognition effect of the improved method on the dynamic load, 10% and 20% noises were added respectively to compare the recognition error. The results are shown in Table 3.

Table 3

Error comparison under different noise levels

Noise		0%	10%	20%
Point A	Tra	0.12	3.68	14.12
	Imp	0.03	0.83	1.04
Point B	Tra	0.1	8.77	14.52
	Imp	0.01	1.02	1.16

It can be found from Table 3 that Tra was greatly affected by the noise; with the increase of error, the error of Tra increased, with a high increase speed, indicating that the method was sensitive to noise and could not accurately recognize the load when there were many noises in the data; the error value of the Imp method was smaller than that of Tra and kept stable, without large changes caused by the increase of noise, indicating that the method was not sensitive to noise and had a better availability in practice.

6. Discussion

As an important parameter in the engineering structure, dynamic loads have a great influence on the engineering structure with certain destructiveness and unpredictability. Therefore, the acquisition of the data is a very important task. The identification of dynamic load has high practical value in the fields of aerospace, transportation, wind and disaster prevention, etc., which can provide important theoretical support for fault monitoring and diagnosis of engineering.

The regularization method has significant advantages in solving ill-posed problems [14], so its application in dynamic load identification has been widely concerned by researchers. At present, the research on regularization includes L curve [15], singular value decomposition [16], GCV method [17], etc. In this paper, based on the regularization method, the filter operator is introduced to obtain an improved regularization method, and then a model is designed for the simulation experiment. In the experiment of this study, two kinds of dynamic loads are simulated, and then the traditional regularization method and improved regularization method are used to perform identification. It can be seen from the recognition results of Fig. 2 and 3 that the improved method has obvious advantages and less error and is closer to the value of the actual dynamic load, while the traditional method has larger fluctuations and error. Taking 0-0.1s as an example to extract the data and perform analysis, it can be found that the average error of the traditional method is 0.12 N and 0.1 N respectively, while the error of the improved method is 0.03 N and 0.01 N respectively. There is a significant gap between the two, which proves the effectiveness of the proposed method. In terms of the results of noise analysis (Table 3), it can be found that the improved method is not sensitive to noise and has stable and small error, indicating that the proposed method has higher application value in practice.

The identification problem of dynamic load is very complicated and difficult. Although some results of load identification based on the improved regularization method are obtained in this study, there are still many shortcomings, such as the selection of the optimal measuring point, the load identification of the nonlinear system, etc., and further research is needed.

7. Conclusion

In this paper, based on the regularization method, an improved regularization method is designed by the filter operator, and a model is designed for simulation experiment. The results show that the improved regularization method designed in this paper has smaller error and is not sensitive to noise, which has a good recognition effect on dynamic load and high application value. This study can make some contributions for the better application of the regularization method in dynamic load identification, which is conducive to the further development of dynamic load identification.

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