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Diagnosis and recovering on spatially distributed acceleration using consensus data fusion

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Abstract. The acceleration information is significant for the structural health monitoring, which is the basic measurement to identify structural dynamic characteristics and structural vibration. The efficiency of the accelerometer is subsequently important for the structural health monitoring. In this paper, the distance measure matrix and the support level matrix are constructed firstly and the synthesized support level and the fusion method are given subsequently. Furthermore, the synthesized support level can be served as the determination for diagnosis on accelerometers, while the consensus data fusion method can be used to recover the acceleration information in frequency domain. The acceleration acquisition measurements from the accelerometers located on the real structure National Aquatics Center are used to be the basic simulation data here. By calculating two groups of accelerometers, the validation and stability of diagnosis and recovering on acceleration based on the data fusion are proofed in the paper.

Keywords: accelerometer diagnosis; information recovering; data fusion; structural health monitoring

1. Introduction

The structural health monitoring system has now been more and more applied into large civil engineering projects (Ni 2009, Weston 2006). It offers serious alerts in damage identification, safety estimation and so on whenever the structure response sensors are in failure, ineffective or not in the proper locations (Yi 2011, 2012). Meanwhile, the loss is immeasurable caused by diagnosis, identification and alarm in mistake. There was a research report from Intelligent Maintenance System Center in America, in which it showed that the alarms in mistake which were caused by the sensor system in failure fault accounted for more than 40% (Zhang 2009). The accelerometers can be used in the structural health monitoring system in order to measure the accelerations and identify the dynamic characteristics and vibrations of the whole structure in real time (Menn 2004, Schulz 2003). The dynamic characteristics and vibrations of the whole structure are very important to estimate the working status of the structure, so the efficiency of the accelerometer system is very important for the following identification and estimation for the structural safety.

The fault diagnosis methods for sensors were researched in order to make sure the effective running of the structural health monitoring system. The neural network modeling with dynamic

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neurons in the state-space representation was proposed to diagnose the actuators and sensors fault, the faults can be detected and isolated by comparing the difference between the system input and output residuals (Luzar 2012). To reduce the uncertainty, imprecision and low reliability, the multi-sensor data fusion method was used to diagnose the equipment fault, the faults can be diagnosed by the change of the confidence and uncertainty of the D-S evidence theory (Ma 2012). Furthermore, the neural network and kalman filter based fusion fault diagnosis was proposed to detect the aeroengine sensor, in which the D-S theory and neural network and kalman filter based diagnosis systems were compared that they can be used to obtain better ability of rejecting noise (Yin 2011). The fault diagnosis methods for sensors are mostly focused on the sensor systems, however, the fault diagnosis methods considering the redundancy of the sensors and measurements are few.

When the accelerometers are used to identify the structural natural frequencies, the accelerometers are redundancy in hardware and the accelerations in different time periods are redundancy in time. In this paper, the diagnosis on accelerometers method based on the redundancy in hardware and redundancy in time is proposed, while the data fusion is used to give the fusion result for different accelerometers and accelerations in different time period. Furthermore, the diagnosis on accelerometers and recovering on accelerations are given by using this data fusion method. The data fusion method used in this paper is called Consistence Data Fusion Method, in which the distance measure is the fusion level, the support level matrix produced by distance measure matrix is the determination basis of the optimal fusion number, the maximum eigenvalue and the corresponding eigenvector of the support level matrix are used to calculate the synthesized support level and the fusion result. The data fusion method based on the distance measure (McKeown 1985, Luo 1988) was proposed in 1980s and had broader concerns in subsequently time. The researchers around the world proposed and improved the definition of distance measure, the fuzzification of the support level matrix and the optimal fusion method (Yu 2009, Liu 2009). Thirdly, the National Aquatics Center is used as a simulation example, the accelerations collected from the accelerometers located on the real National Aquatics Center are used to validate the proposed method, the diagnosis on accelerometers and recovering on accelerations based on data fusion method is well proofed according to the simulation on the accelerometers in sudden failure and drift failure and the selection on the two kinds of group of accelerometers.

2. Acceleration management based on data fusion

2.1 Distance measure and distance measure matrix

As the multi-sensors are used to measure the same parameter, the distance measure is defined to describe the dependency of two measurements. Under the same sampling time and sampling frequency, suppose the analysis data from the ith sensor and the jth sensor is are two c dimensions array, $X_i = [\alpha_1 \quad \alpha_2 \quad \cdots \quad \alpha_c]$, $X_j = [\beta_1 \quad \beta_2 \quad \cdots \quad \beta_c]$, then the distance measure d_{ij} between the ith sensor and the jth sensor can be expressed as

$$d_{ij} = \sqrt{(\alpha_1 - \beta_1)^2 + (\alpha_2 - \beta_2)^2 + \cdots + (\alpha_c - \beta_c)^2} \qquad (1)$$

The smaller the value of d_{ij}, the closer distance between the analysis data from the ith sensor and the jth sensor. So the distance measure d_{ij} can be used to be the fusion level between the ith sensor and the jth sensor.

If there are n sensors used to measure the same parameter, the distance measure matrix D_n can be obtained from the distance measure d_{ij} between the n sensors (Luo 1988)

$$D_n = \begin{bmatrix} d_{11} & d_{12} & \cdots & d_{1n} \\ d_{21} & d_{22} & \cdots & d_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ d_{n1} & d_{n2} & \cdots & d_{nn} \end{bmatrix} \tag{2}$$

The distance measure matrix D_n can be normalized as D_{ns} in order to give some convenience to the calculation and analysis, where the elements in the normalized distance measure matrix D_{ns} are expressed as $d_{ijs}\ (i, j = 1, 2, \cdots, n)$. The elements d_{ijs} can be calculated from $D_{ns} = D_n./d_{pq}$, where $d_{pq}\ (p, q = 1, 2, \cdots, n)$ is the biggest value among the elements d_{ij} in the distance measure matrix D_n.

2.2 Support level matrix

The boundary value $\varepsilon_{ij}\ (i, j = 1, 2, \cdots, n)$ can be used to distinguish the distance measure d_{ij}, while the boundary value is obtained from the experiences and the results from so many tests by the generalized data fusion method. It is supposed in the former method (Luo 1988) that

$$r_{ij} = \begin{cases} 1, & d_{ijs} \le \varepsilon_{ij} \\ 0, & d_{ijs} > \varepsilon_{ij} \end{cases} \tag{3}$$

in which r_{ij} is the support level between the ith sensor and the jth sensor. The fusion extent between the ith sensor and the jth sensor is the best when $r_{ij} = 1$, which is called the analysis data from these two sensors are supported by each other. Correspondingly, the fusion extent between the ith sensor and the jth sensor is the worst when $r_{ij} = 0$, which is called the analysis data from these two sensors are not supported by each other at all. The analysis data from the ith sensor is considered to be effective if the analysis data from the ith sensor is supported by a group of the sensors, while the number of the group of sensors is called the support number. Otherwise, the analysis data from the ith sensor is considered to be not effective if the analysis data from the ith sensor is not supported by a group of the sensors but a small amount of sensors. The optimal fusion number is the number of the effective sensors, while the number of the effective sensors is depending on both the value of ε_{ij} and the support number. Meanwhile, the number of the effective sensors and the value of ε_{ij} are decided with some subjective factors.

The fuzzification for the support level was proposed (Wang 1998, Diao 2002) and used in the paper, which can give better solution for the number of the effective sensors and the value of ε_{ij}. Supposed that $r_{ij} = 1 - d_{ijs}$, $i, j = 1, 2, \cdots, n$. The support level matrix R_n, which is constructed by the support level r_{ij} $(i, j = 1, 2, \cdots, n)$ among n sensors, can be expressed as

$$R_n = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ r_{n1} & r_{n2} & \cdots & r_{nn} \end{bmatrix} \tag{4}$$

2.3 Synthesized support level

Because the support level matrix R_n is a positive matrix, according to the Perron-Frobenius theorem (Gantmacher 2000), then there must be the maximum eigenvalue $\lambda > 0$ for this support level matrix R_n. Meanwhile, there must be positive corresponding eigenvector σ for this support level matrix R_n, while there is the relation $R_n\sigma = \lambda\sigma$, where $\sigma = [\sigma_1 \quad \sigma_2 \quad \cdots \quad \sigma_k \quad \cdots \quad \sigma_n]^T$

$$\begin{bmatrix} r_{11}-\lambda & r_{12} & \cdots & r_{1k} & \cdots & r_{1n} \\ r_{21} & r_{22}-\lambda & \cdots & r_{2k} & \cdots & r_{2n} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ r_{k1} & r_{k2} & \cdots & r_{kk}-\lambda & \cdots & r_{kn} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nk} & \cdots & r_{nn}-\lambda \end{bmatrix} \times \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \vdots \\ \sigma_k \\ \vdots \\ \sigma_n \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ \vdots \\ 0 \end{bmatrix} \tag{5}$$

The relation in Eq. (5) can be developed as $r_{k1}\sigma_1 + r_{k2}\sigma_2 + \cdots + r_{kn}\sigma_n = \lambda\sigma_k$ $(k = 1, 2, \cdots, n)$. It can be seen that $\lambda\sigma_k$ synthesizes the information from $r_{k1}, r_{k2}, \cdots, r_{kn}$, so $\lambda\sigma_k$ can be used to be the synthesized parameter for the information of these k sensors, and

$$\mu_k = \lambda\sigma_k \Big/ \sum_{i=1}^{n} \lambda\sigma_i = \sigma_k \Big/ \sum_{i=1}^{n} \sigma_i \quad (k = 1, 2, \cdots, n) \tag{6}$$

where μ_k is the synthesized support level of the kth sensor, while μ_k can describe the support level by all the information from the other sensors (Wang 1998, Diao 2002).

2.4 Fusion method

Depending on the synthesized support level $\mu_1, \mu_2, \cdots, \mu_n$, the fusion data X from multi-sensors can be expressed as

$$X = \sum_{i=1}^{n} \mu_i X_i \tag{7}$$

3. Diagnosis on accelerometers and recovering on accelerations

3.1 Diagnosis on accelerometers in failure fault

The accelerometers are usually used to measure the vibration response of the structure, while the structural dynamic characters and the estimation on comfort can be obtained from the acceleration information. Due to the accordance on the identification of the structural natural frequencies using the acceleration information, the accelerometers are redundancy on the devices and the efficiency of the accelerometers can be known from the identification of the structural natural frequencies.

The vector A can be constructed from the acceleration information measured from n accelerometers located on the structure

$$A = \begin{bmatrix} a_1(t) & a_2(t) & \cdots & a_i(t) & \cdots & a_n(t) \end{bmatrix} \tag{8}$$

in which $a_i(t)$ is the structural response time history of the ith accelerometer.

The information in frequency domain of the structural acceleration response time history can be obtained, while the frequency f_0 and the corresponding amplitude α_0 can be obtained from the power spectrum analysis. The information in frequency domain of the structural response time history of the ith accelerometer $a_i(t)(i=1,2,...,n)$ can be known by normalized in single accelerometer

$$f_0 = \begin{bmatrix} f_1 & f_2 & \cdots & f_j & \cdots & f_m \end{bmatrix} \tag{9}$$

$$\alpha_0(a_i(t)) = \begin{bmatrix} \alpha_{i1} & \alpha_{i2} & \cdots & \alpha_{ij} & \cdots & \alpha_{im} \end{bmatrix} \tag{10}$$

in which f_j is the jth in the m natural frequencies ; α_{ij} is the corresponding normalized amplitude of f_j for the ith accelerometer.

The redundancy is considered and used in the paper, considering the time histories in different time periods for the accelerometers, the amplitude distribution $\alpha_1(a_i(t))$, based on the special natural frequencies and the first time period of the information of the ith accelerometer, can be expressed as

$$\alpha_1(a_i(t)) = \begin{bmatrix} \alpha_{i1} & \alpha_{i2} & \cdots & \alpha_{ij} & \cdots & \alpha_{im} \end{bmatrix} \tag{11}$$

Then the amplitude distribution matrix $\alpha_1(A)$ from the n accelerometers during this first time period can be expressed as

$$\alpha_1(A) = \begin{bmatrix} \alpha_{11} & \alpha_{12} & \cdots & \alpha_{1m} \\ \alpha_{21} & \alpha_{22} & \cdots & \alpha_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ \alpha_{i1} & \alpha_{i2} & \cdots & \alpha_{im} \\ \vdots & \vdots & \vdots & \vdots \\ \alpha_{n1} & \alpha_{n2} & \cdots & \alpha_{nm} \end{bmatrix} \tag{12}$$

The amplitude distribution matrix can also be expressed as,

$$\alpha_1(A) = \left[\alpha_1(a_1(t)) \quad \alpha_1(a_2(t)) \quad \cdots \quad \alpha_1(a_i(t)) \quad \cdots \quad \alpha_1(a_n(t))\right]^T \tag{13}$$

The accelerations measured from the accelerometers are disturbed by noises. Furthermore, the amplitude distributions of the structural acceleration response time history are not same during the different time periods using the frequency domain analysis. In order to consider and deduce the uncertain on the amplitude distributions, the amplitude distribution matrix is constructed by several time periods. Supposed that there are n accelerometers and l time periods for frequency domain analysis, while the amplitude distribution matrix $\alpha_k(A)(k = 2,...,l)$ during the kth time period can be known as

$$\alpha_k(A) = \begin{bmatrix} \alpha_{1((k-1)*m+1)} & \alpha_{1((k-1)*m+2)} & \cdots & \alpha_{1((k-1)*m+j)} & \cdots & \alpha_{1(k*m)} \\ \alpha_{2((k-1)*m+1)} & \alpha_{2((k-1)*m+2)} & \cdots & \alpha_{2((k-1)*m+j)} & \cdots & \alpha_{2(k*m)} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \alpha_{i((k-1)*m+1)} & \alpha_{i((k-1)*m+2)} & \cdots & \alpha_{i((k-1)*m+j)} & \cdots & \alpha_{i(k*m)} \\ \vdots & \vdots & \vdots & \vdots & \cdots & \vdots \\ \alpha_{n((k-1)*m+1)} & \alpha_{n((k-1)*m+2)} & \cdots & \alpha_{n((k-1)*m+j)} & \cdots & \alpha_{n(k*m)} \end{bmatrix} \tag{14}$$

in which $\alpha_{i((k-1)*m+j)}$ is the corresponding normalized amplitude of the ith accelerometer during the kth time period.

The amplitude distribution of the ith accelerometer during all the time periods under m selected natural frequencies is $\alpha(a_i)$

$$\alpha(a_i(t)) = \left[\alpha_{i1} \quad \alpha_{i2} \quad \cdots \quad \alpha_{i((k-1)*m+j)} \quad \cdots \quad \alpha_{i(l*m)}\right] \tag{15}$$

The aggregative amplitude distribution matrix $\alpha(A)$ from the n accelerometers based on Eqs. (12) and (14)

$$\alpha(A) = \left[\alpha_1(A) \quad \alpha_2(A) \quad \cdots \quad \alpha_k(A) \quad \cdots \quad \alpha_l(A)\right] \tag{16}$$

The distance measure matrix can be calculated by $\alpha(A)$, furthermore, the support level and the synthesized support level can be calculated and expressed as

$$\mu_A = \left[\mu_1 \quad \mu_2 \quad \cdots \quad \mu_i \quad \cdots \quad \mu_n\right] \tag{17}$$

The principles for judging whether the accelerometer is effective based on the synthesized support level are: comparing the values of the synthesized support levels of all the sensors. If the values of the synthesized support levels are almost the same, then all the sensors work well. If there is one value which is bias to the others, then the accelerometer with this value is failure fault.

3.2 Decision on the number of the group of accelerometers

The proposed sensor diagnosis method is based on a group of accelerometers, so the number of the accelerometers is one of the most important factors for understanding the efficiency of the accelerometers. As we can see, the redundancy of the accelerometers is more with growing on the number of the accelerometers, while it is better for knowing the efficiency of the accelerometers.

Otherwise, the efficiency of the accelerometers can not be detected with a small number of accelerometers.

The decision on the number of the accelerometers is based on the distance measure matrix, and the distance measure matrix from n accelerometers can be expressed as Eq. (2), when the ith accelerometer is failure fault, the distance measure matrix can be expressed as

$$D_n^0 = \begin{bmatrix} d_{11} & d_{12} & \cdots & d'_{1i} & \cdots & d_{1n} \\ d_{21} & d_{22} & \cdots & d'_{2i} & \cdots & d_{2n} \\ \vdots & \vdots & \cdots & \vdots & \cdots & \vdots \\ d'_{i1} & d'_{i2} & \cdots & d'_{ii} & \cdots & d'_{in} \\ \vdots & \vdots & \cdots & \vdots & \cdots & \vdots \\ d_{n1} & d_{n2} & \cdots & d'_{ni} & \cdots & d_{nn} \end{bmatrix} \tag{18}$$

When there is one accelerometer in failure fault, the values of the $2n$-1 elements in the distance measure matrix will change；when there are two accelerometers in failure fault, the values of the $4n$-4 elements in the distance measure matrix will change. When there are k accelerometers in failure fault, the values of the $2nk$-k^2 elements in the distance measure matrix will change. The diagnosis method is based on the synthesized support level which is calculated by using the elements in support level matrix. In order to make sure that the synthesized support level can reflect the most normal information from the support level matrix, the number of the changed elements should be less than the number of the unchanged elements in support level matrix. Meanwhile, the elements in support level matrix change with the elements in distance measure matrix synchronously, so the number of the changed elements is expected to be less than the number of the unchanged elements in distance measure matrix, which can make sure that synthesized support level can reflect the most normal information. In the other words, when the number of the changed elements is larger than the number of the unchanged elements in distance measure matrix, the distance measure matrix cannot distinguish the support levels of the normal accelerometers and the failure accelerometers very well. So the relation between the number of the accelerometers in failure fault k and the minimum number of the group of the accelerometers used for sensor diagnosis n is

$$2nk - k^2 < \frac{1}{2}n^2 \tag{19}$$

Based on the physical significant of Eq. (21), it can be solved as

$$k < \frac{2-\sqrt{2}}{2}n \tag{20}$$

It means that when the number of accelerometers in failure fault accounts for $\frac{2-\sqrt{2}}{2}\times 100\%$ or more in the group of accelerometers, the accelerometer in failure fault cannot be diagnosed any more.

3.3 Recovering on the accelerations

When the pth accelerometer in failure fault is diagnosed, the information regarding the accelerometer in failure fault should be recovered in order to remaining the integrality of the information from the group of sensors. The recovering acceleration method is based on the amplitude distribution of the normal accelerometers in frequency domain, while there must be a fusion result which can reflect the information of the accelerometers in frequency domain and this fusion result would be the recovering acceleration information for the accelerometer in failure fault. The acceleration information matrix A' from the $n-1$ normal accelerometers is known as

$$A' = \left[a_1(t) \quad \cdots \quad a_{p-1}(t) \quad a_{p+1}(t) \quad \cdots \quad a_n(t)\right] \tag{21}$$

in which $a_{p-1}(t)$ is the structural response time history of the $(p-1)$th accelerometer.

The amplitude distribution matrix $\alpha_1(A')$ of the normal accelerometers can be expressed as

$$\alpha_1(A') = \begin{bmatrix} \alpha_{11} & \alpha_{12} & \cdots & \alpha_{1m} \\ \vdots & \vdots & \cdots & \vdots \\ \alpha_{(p-1)1} & \alpha_{(p-1)2} & \vdots & \alpha_{(p-1)m} \\ \alpha_{(p+1)1} & \alpha_{(p+1)2} & \cdots & \alpha_{(p+1)m} \\ \vdots & \vdots & \vdots & \vdots \\ \alpha_{n1} & \alpha_{n2} & \cdots & \alpha_{nm} \end{bmatrix} \tag{22}$$

This amplitude distribution matrix can also be expressed as

$$\alpha_1(A') = \left[\alpha_1(a_1(t)) \quad \cdots \quad \alpha_1(a_{p-1}(t)) \quad \alpha_1(a_{p+1}(t)) \quad \cdots \quad \alpha_1(a_n(t))\right]^T \tag{23}$$

The synthesized amplitude distribution matrix $\alpha(A')$ of the $n-1$ normal accelerometers can be expressed as

$$\alpha(A') = \left[\alpha_1(A') \quad \alpha_2(A') \quad \cdots \quad \alpha_k(A') \quad \cdots \quad \alpha_l(A')\right] \tag{24}$$

The distance measure matrix D'_n and the synthesized support levels of accelerometers $\mu_{A'}$ can be known from the synthesized amplitude distribution matrix $\alpha(A')$

$$D'_n = \begin{bmatrix} d_{11} & d_{12} & \cdots & d_{1(p-1)} & d_{1(p+1)} & \cdots & d_{1n} \\ d_{21} & d_{22} & \cdots & d_{2(p-1)} & d_{2(p+1)} & \cdots & d_{2n} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ d_{(p-1)1} & d_{(p-1)2} & \cdots & d_{(p-1)(p-1)} & d_{(p-1)(p+1)} & \cdots & d_{(p-1)n} \\ d_{(p+1)1} & d_{(p+1)2} & \cdots & d_{(p+1)(p-1)} & d_{(p+1)(p+1)} & \cdots & d_{(p+1)n} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ d_{n1} & d_{n2} & \cdots & d_{n(p-1)} & d_{n(p+1)} & \cdots & d_{nn} \end{bmatrix} \tag{25}$$

$$\mu_{A'} = \left[\mu'_1 \quad \cdots \quad \mu'_{p-1} \quad \mu'_{p+1} \quad \cdots \quad \mu'_n\right] \tag{26}$$

If the amplitude distribution of the pth accelerometer in frequency domain is expressed as

$$\alpha'(a_p(t)) = \left[\alpha'_{p1} \quad \alpha'_{p2} \quad \cdots \quad \alpha'_{p((k-1)*m+j)} \quad \cdots \quad \alpha'_{p(l*m)} \right] \tag{27}$$

Then the fusion result in frequency domain for the accelerometer using data fusion can be expressed as

$$\alpha'\left(a_p(t)\right) = \mu_{A'}\alpha\left(A'\right) \tag{28}$$

Furthermore, the fusion result in frequency domain can be used as the recovering acceleration information for the accelerometer in failure fault. This recovered information is helpful for the diagnosis of the accelerometers, which is not the exactly measurement of the original accelerometer. Then the new recovering information in frequency domain from the group of the accelerometers can be obtained and the amplitude distribution matrix by recovering information can be expressed as

$$\alpha(A'') = \left[\alpha(a_1(t)) \quad \cdots \quad \alpha(a_{p-1}(t)) \quad \alpha'(a_p(t)) \quad \alpha(a_{p+1}(t)) \quad \cdots \quad \alpha(a_n(t)) \right]^T \tag{29}$$

The distance measure matrix D''_n and the synthesized support level $\mu_{A''}$ can be known from the recovering amplitude distribution matrix $\alpha(A'')$

$$D''_n = \begin{bmatrix} d_{11} & d_{12} & \cdots & d''_{1p} & \cdots & d_{1n} \\ d_{21} & d_{22} & \cdots & d''_{2p} & \cdots & d_{2n} \\ \vdots & \vdots & \cdots & \vdots & \cdots & \vdots \\ d''_{p1} & d''_{p2} & \cdots & d''_{pp} & \cdots & d''_{pn} \\ \vdots & \vdots & \cdots & \vdots & \cdots & \vdots \\ d_{n1} & d_{n2} & \cdots & d''_{np} & \cdots & d_{nn} \end{bmatrix} \tag{30}$$

$$\mu_{A''} = \left[\mu''_1 \quad \cdots \quad \mu''_p \quad \cdots \quad \mu''_n \right] \tag{31}$$

At last, the efficiency of the other accelerometers can be diagnosed by the recovering synthesized support level $\mu_{A''}$.

4. Calculations based on the accelerations from National Aquatics Center in China

The accelerations measured from the accelerometers on the structural health monitoring system on the steel structure of the National Aquatics Center are used here as the basic data for proofing the validity of the proposed method.

The National Aquatics Center is located in the center of the Olympic Park in Beijing, China, the design sketch is shown in Fig. 1. It covers an area of 6295 square kilometers with the size of 177 m in the length, 177 m in the width and 30 m in the height. The space is separated into three parts with independent function spaces while the total architectural area is 80,000 m^2.

The National Aquatics Center consists of concrete frame tube structure, steel space structure and ETFE membrane inflatable pillow cover structure. The space structure is the important part for the architecture design and structure design. The design loads for the National Aquatics Center are gravity load, wind load, snow load, earthquake action, thermal action and so on. The vibration shapes of the steel structure are clear. The first vibration shape is translational motion in Y direction, mass participation accounts for 78%. The second vibration shape is translational motion in X direction, mass participation accounts for 19%. The forth vibration shape is torsion motion, mass participation accounts for 76%. The ratio between the torsion period and the first period is 0.78. As for the top 30 vibration shapes, the accumulative mass participation in translational motions in X and Y directions is 90%, the accumulative mass participation in Z direction is 35% and the accumulative mass participation in torsion motion is 85%.

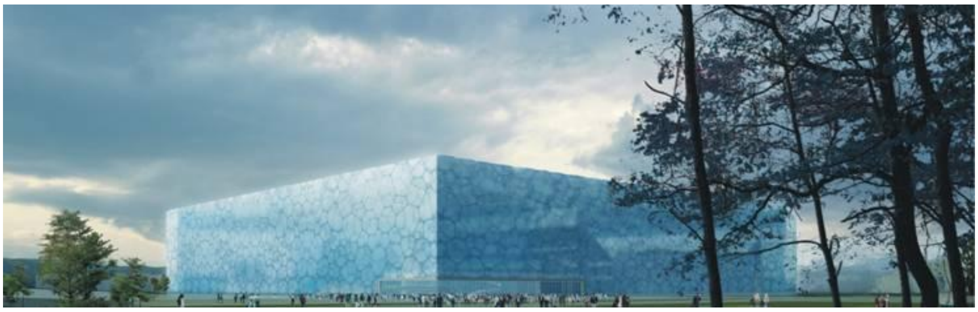
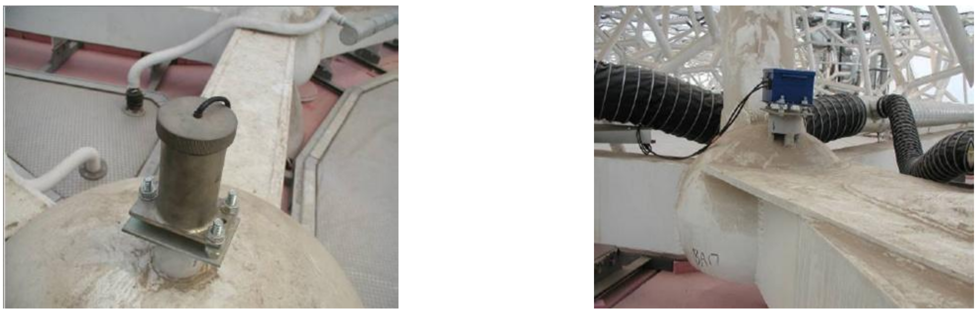


Fig. 1 The sketch of National Aquatics Center

According to the calculation result from the finite element of the National Aquatics Center, the structure may vibrate in vertical direction and translational direction. So the uniaxial accelerometers and biaxial accelerometers were selected to measure the accelerations and vibrations of the structure. The selection of accelerometers system was decided by considering the vibration caused by both the wind load and the earthquake action. The range and precision of the accelerometers was selected by considering not only the wind load but also the earthquake action. At last, the BA-02 uniaxial accelerometers and BA-22 biaxial accelerometers manufactured by Harbin BeiAo in China were used in this steel structure. The arrangements of the accelerometers is shown in Fig. 2. The performances of the accelerometers are shown in Table 1, the locations of the accelerometers are shown in Fig. 3. In conclusion, there are 28 accelerometers located on 18 placements.



(a)The arrangement of uniaxial accelerometer (b)The arrangement of biaxial accelerometer

Fig. 2 The arrangements of the accelerometers

Table 1 The performances of the accelerometers

Type	BA-02 uniaxial accelerometer	BA-22 biaxial accelerometer
Range	±2.0g	±2.0g
Frequency	DC-120Hz	DC-120Hz
Dynamic	>120dB	>120dB
Sensibility	Lower: ±2.5V/g Medium: ±40.0 V/g Higher: ±90.0 V/g	Lower: ±2.5V/g Medium: ±40.0 V/g Higher: ±90.0 V/g
Mass	262g	2.1kg

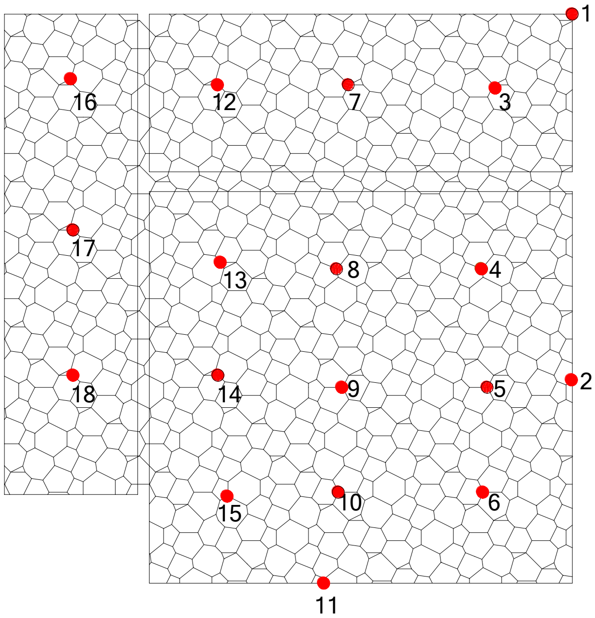


Fig. 3 The placements of the accelerometers

The acceleration data used here is collected from the seven structural vertical acceleration time histories in 10 minutes and 100 Hz with the noise filtering, the locations of these seven accelerometers are the placements with number 5, 7, 8, 9, 10, 14, 17. The top 1000 data from the acceleration time histories of the accelerometers with number 5, 8, 9, 10, 14, the three natural frequencies are selected to be the identification objects for these five accelerometers, and the three natural frequencies are 1.5625 Hz, 2.6367 Hz, 3.3203 Hz, then the special frequency vector is $f_0 = [1.5625 \quad 2.6367 \quad 3.3203]$. Two groups of accelerometers with different number of the accelerometers are selected to proof the diagnosis and recovering method, the number of time steps is all 1000 and there are 60 time periods.

4.1 The diagnosis for the first group of accelerometers

The first group of accelerometers consists of five accelerometers, the locations are the placements with number 5, 8, 9, 10, 14. The structural response time histories vector A from the group of five accelerometers is expressed as

$$A = \left[a_5(t), a_8(t), a_9(t), a_{10}(t), a_{14}(t)\right] \tag{32}$$

When all the accelerometers work normally, the amplitude distribution matrix for these five accelerometers in one time period is

$$\alpha(A) = \begin{bmatrix} 0.291 & 0.955 & 1 \\ 1 & 0.230 & 0.154 \\ 0.221 & 1 & 0.484 \\ 1 & 0.091 & 0.144 \\ 0.174 & 0.435 & 1 \end{bmatrix} \tag{33}$$

The normalized distance measure matrix for these five accelerometers is

$$D = \begin{bmatrix} 0 & 0.938 & 0.371 & 1 & 0.378 \\ 0.938 & 0 & 0.812 & 0.099 & 0.852 \\ 0.371 & 0.812 & 0 & 0.884 & 0.545 \\ 1 & 0.099 & 0.884 & 0 & 0.880 \\ 0.378 & 0.852 & 0.545 & 0.878 & 0 \end{bmatrix} \tag{34}$$

The support level matrix for these five accelerometers is

$$R = \begin{bmatrix} 1 & 0.062 & 0.630 & 0 & 0.620 \\ 0.062 & 1 & 0.190 & 0.900 & 0.150 \\ 0.630 & 0.190 & 1 & 0.120 & 0.460 \\ 0 & 0.900 & 0.120 & 1 & 0.120 \\ 0.620 & 0.150 & 0.460 & 0.120 & 1 \end{bmatrix} \tag{35}$$

The synthesized support level for these five accelerometers is

$$\mu = \begin{bmatrix} 0.218 & 0.180 & 0.222 & 0.164 & 0.217 \end{bmatrix} \tag{36}$$

The support level matrix and the synthesized support level for these five accelerometers in multiple time periods are

$$R_A = \begin{bmatrix} 1 & 0.1 & 0.31 & 0.068 & 0.43 \\ 0.1 & 1 & 0.17 & 0.46 & 0.048 \\ 0.31 & 0.17 & 1 & 0.077 & 0.27 \\ 0.068 & 0.46 & 0.077 & 1 & 0 \\ 0.43 & 0.048 & 0.27 & 0 & 1 \end{bmatrix} \tag{37}$$

$$\mu_A = \begin{bmatrix} 0.240 & 0.176 & 0.221 & 0.145 & 0.218 \end{bmatrix} \tag{38}$$

When the accelerometer located on the placement with number 5 is in failure fault, the sudden failure and drift failure are simulated here. The time history of the normal accelerometer located on the placement number 5 is denoised, which is shown in Fig. 4. It is supposed that there is a sudden failure for the accelerometer located on the placement number 5 after 5 minutes data acquisition, while the simulated time history of the accelerometer located on the placement number 5 in sudden failure is shown in Fig. 5. It is supposed that there is a drift failure for the accelerometer located on the placement number 5 after 5 minutes data acquisition, the maximum drift value is 10^{-4}m/s^2, while the simulated time history of the accelerometer located on the placement number 5 in drift failure is shown in Fig. 6.

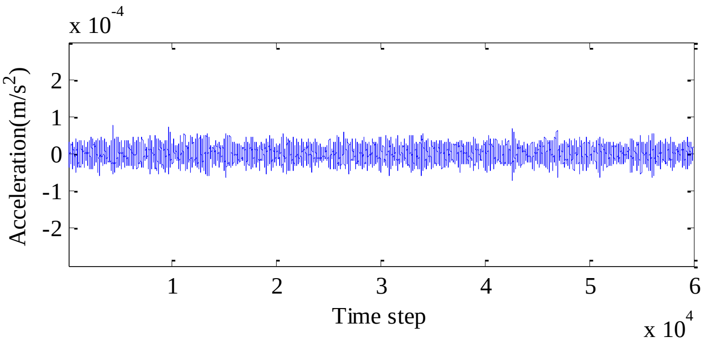


Fig. 4 The time history of accelerometer in normal working status

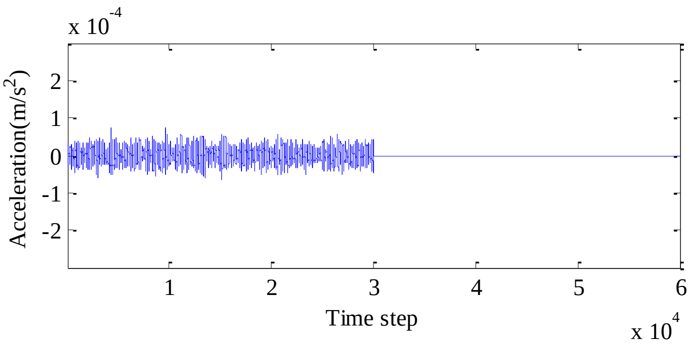


Fig. 5 The time history of accelerometer in sudden failure

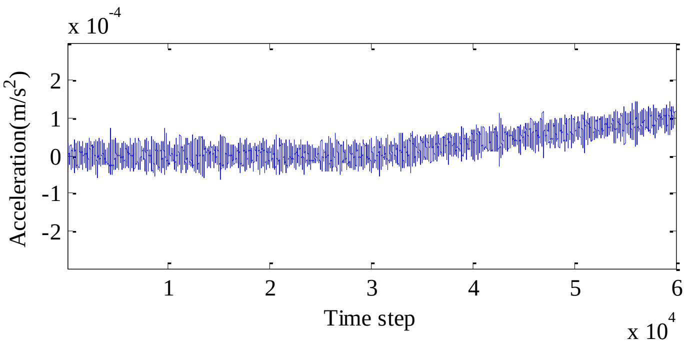


Fig. 6 The time history of accelerometer in drift failure

The support level matrices R_1 and R_2 are from the data when the accelerometer located on placement number 5 is in sudden failure and drift failure respectively, while the corresponding synthesized support level are μ_1 and μ_2.

$$R_1 = \begin{bmatrix} 1 & 0.068 & 0.12 & 0 & 0.15 \\ 0.068 & 1 & 0.29 & 0.54 & 0.18 \\ 0.12 & 0.29 & 1 & 0.21 & 0.38 \\ 0 & 0.54 & 0.21 & 1 & 0.14 \\ 0.15 & 0.18 & 0.38 & 0.14 & 1 \end{bmatrix} \tag{39}$$

$$\mu_1 = \begin{bmatrix} 0.082 & 0.258 & 0.229 & 0.236 & 0.196 \end{bmatrix} \tag{40}$$

$$R_2 = \begin{bmatrix} 1 & 0.069 & 0.13 & 0 & 0.17 \\ 0.069 & 1 & 0.27 & 0.52 & 0.16 \\ 0.13 & 0.27 & 1 & 0.18 & 0.36 \\ 0 & 0.52 & 0.18 & 1 & 0.11 \\ 0.17 & 0.16 & 0.36 & 0.11 & 1 \end{bmatrix} \tag{41}$$

$$\mu_2 = \begin{bmatrix} 0.094 & 0.257 & 0.226 & 0.230 & 0.193 \end{bmatrix} \tag{42}$$

According to the calculation of the synthesized support level and the simulation on the sudden failure and drift failure of the accelerometer located on the placement number 5, it can be seen that the value of the synthesized support level of accelerometer located on the placement number 5 is smaller than the values of the synthesized support levels of the other four normal accelerometers located on the other placements.

It is supposed that there is a sudden failure and drift failure respectively for the accelerometer located on the placement number 8 after 5 minutes data acquisition, the maximum drift value is 10^{-4} m/s^2. The support level matrices R_1' and R_2' are from the data when the accelerometer located on placement number 8 is in sudden failure and drift failure respectively, while the corresponding synthesized support level are μ_1' and μ_2'.

$$R_1' = \begin{bmatrix} 1 & 0.014 & 0.39 & 0.19 & 0.5 \\ 0.014 & 1 & 0.034 & 0.12 & 0 \\ 0.39 & 0.034 & 1 & 0.19 & 0.37 \\ 0.19 & 0.12 & 0.19 & 1 & 0.13 \\ 0.5 & 0 & 0.37 & 0.13 & 1 \end{bmatrix} \tag{43}$$

$$\mu_1' = \begin{bmatrix} 0.284 & 0.033 & 0.258 & 0.152 & 0.274 \end{bmatrix} \tag{44}$$

$$R_2' = \begin{bmatrix} 1 & 0.018 & 0.37 & 0.16 & 0.49 \\ 0.018 & 1 & 0.037 & 0.15 & 0 \\ 0.37 & 0.037 & 1 & 0.17 & 0.35 \\ 0.16 & 0.15 & 0.17 & 1 & 0.099 \\ 0.49 & 0 & 0.35 & 0.099 & 1 \end{bmatrix} \tag{45}$$

$$\mu_2' = \begin{bmatrix} 0.287 & 0.040 & 0.258 & 0.139 & 0.276 \end{bmatrix} \tag{46}$$

According to the calculation of the synthesized support level and the simulation on the sudden failure and drift failure of the accelerometer located on the placement number 8, it can be seen that the value of the synthesized support level of accelerometer located on the placement number 5 is smaller than the values of the synthesized support levels of the other four normal accelerometers located on the other placements. In the other words, according to the calculations of the synthesized support levels and the simulations on the sudden failure and drift failure of the accelerometers located on the placement number 5 and placement number 8 respectively, the values of the synthesized support levels can significantly distinguish the accelerometers in abnormal status, which means the diagnosis method using the synthesized support level is effective and stable.

It can be known from Eq. (20) that, the maximum number of the diagnosis accelerometers is one from the first group of accelerometers. If there are two accelerometers considered to be in failure fault, for example, the accelerometers located on the placement number 5 and number 8 are both in failure fault and the accelerometer located on the placement number 5 is simulated in sudden failure and the accelerometer located on the placement number 8 is simulated in drift failure, then the support level matrix and the synthesized support level of this group of accelerometers are separately

$$R'' = \begin{bmatrix} 1 & 0.4 & 0.12 & 0 & 0.15 \\ 0.4 & 1 & 0.083 & 0.19 & 0.048 \\ 0.12 & 0.083 & 1 & 0.21 & 0.38 \\ 0 & 0.19 & 0.21 & 1 & 0.14 \\ 0.15 & 0.048 & 0.38 & 0.14 & 1 \end{bmatrix} \tag{47}$$

$$\mu'' = \begin{bmatrix} 0.199 & 0.201 & 0.224 & 0.165 & 0.212 \end{bmatrix} \tag{48}$$

It can be seen that the accelerometers in failure fault cannot be diagnosed from the values of the synthesized support levels. The main reason is that the number of the group of accelerometers is so small. The number of the group of accelerometers is five and the number of the accelerometers in failure fault is two. In this situation, there are sixteen elements change their values in the distance measure matrix in which there are twenty-five elements, so the support level matrix cannot be used to diagnose the efficiency of the accelerometers in failure fault.

When the accelerometer located on the placement number 5 is in sudden failure, the information of this accelerometer in frequency domain can be recovered by the information from the other four normal accelerometers. In the other words, the information of the accelerometer located on the placement number 5 in frequency domain can be recovered by the information from the accelerometers located on the placements number 8, 9, 10 and 14.

The structural response time histories vector A' from the other four normal accelerometers located on the placements number 8, 9, 10 and 14 and the synthesized support level can be expressed and calculated as

$$A' = \begin{bmatrix} a_8(t) & a_9(t) & a_{10}(t) & a_{14}(t) \end{bmatrix} \tag{49}$$

$$\mu_{A'} = \begin{bmatrix} 0.339 & 0.214 & 0.313 & 0.134 \end{bmatrix} \tag{50}$$

The recovering information of accelerometer located on the placement number 5 can be obtained from Eq. (28), which is expanded as

$$\alpha'\left(a_5(t)\right) = \mu_{A'}\alpha\left(A'\right) \tag{51}$$

$\mu_{A'}$ is shown in Eq. (50) and $\alpha\left(A'\right)$ can be obtained from Eq. (33) as

$$\alpha(A') = \begin{bmatrix} 1 & 0.230 & 0.154 \\ 0.221 & 1 & 0.484 \\ 1 & 0.091 & 0.144 \\ 0.174 & 0.435 & 1 \end{bmatrix} \tag{52}$$

The amplitude distribution matrix of the first group of accelerometers using recovering information of accelerometer located on the placement number 5 is

$$\alpha'(A) = \begin{bmatrix} 0.722 & 0.379 & 0.335 \\ 1 & 0.230 & 0.154 \\ 0.221 & 1 & 0.484 \\ 1 & 0.091 & 0.144 \\ 0.174 & 0.435 & 1 \end{bmatrix} \tag{53}$$

The synthesized support level calculated by the information from the recovering information of the accelerometer in failure fault and the information of the accelerometers in normal is

$$\mu_{A''} = \begin{bmatrix} 0.285 & 0.240 & 0.155 & 0.218 & 0.103 \end{bmatrix} \tag{54}$$

If the accelerometer located on the placement number 8 is simulated to be in sudden failure, the synthesized support level for this group of accelerometers is

$$\mu'_{A''} = \begin{bmatrix} 0.289 & 0.085 & 0.220 & 0.220 & 0.187 \end{bmatrix} \tag{55}$$

According to the calculations of the synthesized support levels and the simulations on the sudden failure of the accelerometers located on the placement number 8, the values of the synthesized support levels can significantly distinguish the accelerometers in abnormal status using the recovering information.

4.2 The diagnosis for the second group of accelerometers

The second group of accelerometers consists of seven accelerometers; the locations are the placements with number 5, 7, 8, 9, 10, 14, 17. The structural response time histories vector B from the group of seven accelerometers is expressed as

$$B=\begin{bmatrix} a_5(t) & a_7(t) & a_8(t) & a_9(t) & a_{10}(t) & a_{14}(t) & a_{17}(t) \end{bmatrix} \tag{56}$$

When all the accelerometers work normally, the amplitude distribution matrix for these seven accelerometers in one time period is

$$\alpha(B)=\begin{bmatrix} 0.291 & 0.955 & 1 \\ 0.935 & 0.681 & 0.824 \\ 1 & 0.230 & 0.154 \\ 0.221 & 1 & 0.484 \\ 1 & 0.091 & 0.144 \\ 0.174 & 0.435 & 1 \\ 0.471 & 1 & 0.627 \end{bmatrix} \tag{57}$$

The synthesized support level for these seven accelerometers is

$$\mu_B=\begin{bmatrix} 0.162 & 0.150 & 0.130 & 0.165 & 0.118 & 0.151 & 0.123 \end{bmatrix} \tag{58}$$

The accelerometers located on the placements number 5 and 8 are simulated to be in failure fault respectively, and the calculation results of the synthesized support level of the group of the accelerometers are shown in Table 2. It can be seen from Table 2, the group of seven accelerometers can be used to diagnose the situation when the accelerometers located on the placements number 5 and 8 are both in failure fault. Comparing with the first group of five accelerometers, it can be known that the number of the diagnosed accelerometers in failure fault using the second group of accelerometers is more than the number of the diagnosed accelerometers in failure fault using the first group of accelerometers. This is to say, the more the number of the group of accelerometers, the more the number of the diagnosed accelerometers in failure fault.

Table 2 The synthesized support levels of the accelerometers under different failures

Placements and failure types	Synthesized support level $[\mu_5,\mu_7,\mu_8,\mu_9,\mu_{10},\mu_{14},\mu_{17}]$
No. 5, sudden	[0.0590,0.1738,0.1587,0.1794,0.1453,0.1503,0.1335]
No. 5, drift	[0.0677,0.1729,0.1573,0.1792,0.1428,0.1500,0.1301]
No. 8, sudden	[0.1834,0.1617,0.0363,0.1811,0.1082,0.1750,0.1544]
No. 8, drift	[0.1814,0.1601,0.0487,0.1799,0.1058,0.1728,0.1513]
No. 5 and No. 8, sudden	[0.0989,0.1781,0.0791,0.1900,0.1187,0.1711,0.1634]
No.5, sudden; No. 8, drift	[0.0950,0.1780,0.0908,0.1903,0.1183,0.1676,0.1599]

When the accelerometer located on the placement number 5 is in sudden failure, the information of this accelerometer in frequency domain can be recovered by the information the accelerometers located on the placements number 7, 8, 9, 10, 14 and 17.

The structural response time histories vector B' from the other six normal accelerometers located on the placements number 7, 8, 9, 10, 14 and 17, and the synthesized support level can be expressed and calculated as

$$B' = \left[a_7(t), a_8(t), a_9(t), a_{10}(t), a_{14}(t), a_{17}(t)\right] \tag{59}$$

$$\mu_{B'} = \begin{bmatrix} 0.187 & 0.171 & 0.191 & 0.159 & 0.156 & 0.137 \end{bmatrix} \tag{60}$$

The recovering information of accelerometer located on the placement number 5 can be obtained from Eq. (28), which is expanded as

$$\alpha'\left(a_5(t)\right) = \mu_{B'}\alpha\left(B'\right) \tag{61}$$

$\mu_{B'}$ is shown in Eq. (60) and $\alpha\left(B'\right)$ can be obtained from Eq. (57) as

$$\alpha(B') = \begin{bmatrix} 0.935 & 0.681 & 0.824 \\ 1 & 0.681 & 0.824 \\ 0.221 & 1 & 0.484 \\ 1 & 0.091 & 0.144 \\ 0.174 & 0.435 & 1 \\ 0.471 & 1 & 0.627 \end{bmatrix} \tag{62}$$

The amplitude distribution matrix of the second group of accelerometers in one time period using recovering information of accelerometer located on the placement number 5 is

$$\alpha'(B) = \begin{bmatrix} 0.638 & 0.576 & 0.537 \\ 0.935 & 0.681 & 0.824 \\ 1 & 0.230 & 0.154 \\ 0.221 & 1 & 0.484 \\ 1 & 0.091 & 0.144 \\ 0.174 & 0.435 & 1 \\ 0.471 & 1 & 0.627 \end{bmatrix} \tag{63}$$

The synthesized support level calculated by the information from the recovering information of the accelerometer in failure fault and the information of the accelerometers in normal is

$$\mu_{B'} = \begin{bmatrix} 0.2011 & 0.1501 & 0.1358 & 0.1533 & 0.1247 & 0.1256 & 0.1093 \end{bmatrix} \tag{64}$$

If the accelerometer located on the placement number 8 is simulated to be in sudden failure, the synthesized support level for this group of accelerometers is

$$\mu_{B''} = \begin{bmatrix} 0.2116 & 0.1639 & 0.0519 & 0.1696 & 0.1205 & 0.1459 & 0.1365 \end{bmatrix} \tag{65}$$

According to the calculations of the synthesized support levels and the simulations on the sudden failure of the accelerometers located on the placement number 8, the values of the synthesized support levels can significantly distinguish the accelerometers in abnormal status using the recovering information.

If the accelerometer located on the placement number 8 is simulated to be in sudden failure and the accelerometer located on the placement number 10 is simulated to be in drift failure, the synthesized support level for this group of accelerometers is

$$\mu'_{B''} = \begin{bmatrix} 0.2114 & 0.1636 & 0.0754 & 0.1730 & 0.0815 & 0.1499 & 0.1452 \end{bmatrix} \tag{66}$$

According to the calculations of the synthesized support levels and the simulations on the failure of the accelerometers located on the placement number 8 and 10, the values of the synthesized support levels can significantly distinguish the accelerometers in abnormal status using the recovering information.

5. Conclusions

The above proposed method is a diagnosis on accelerometers and information recovering method on acceleration based on consensus data fusion. According to the characteristics of accelerations in structural health monitoring system, the acceleration information in frequency domain is obtained, and the calculation methods for the synthesized support level and the fusion result are given. Based on the calculation of synthesized support level using amplitude distribution matrix and distance measure matrix, the diagnosis on accelerometers is proposed. Furthermore, the acceleration information in frequency domain is recovered by using the information from the other normal accelerometers. By comparing the diagnosis results and recovering information application for two groups of accelerometers, it can be seen that the proposed method is valid and therefore can be used for a real structural health monitoring system.

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