



Optimal sensor placement for space modal identification of crane structures based on an improved harmony search algorithm*

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Abstract: The problem of optimal sensor placement plays a key role in the success of structural health monitoring (SHM) systems. In this study, a new method is presented to investigate the optimization problem of sensor placement on gantry crane structures. The method is a combination of an improved harmony search (HS) algorithm and the modal assurance criterion (MAC). Firstly, we review previous studies on setting reasonable values for HS parameters that have the most impact on the result, and highlight the lack of general rules governing this aspect. Based on more efficient HS algorithms resulting from those studies, we apply our proposed technique to the optimization problem of sensor placement on gantry crane structures. The purpose of the optimization method is to select the optimal sensor locations on gantry crane girders to establish a sensor network for an SHM system. Our results show that the HS algorithm is a powerful search and optimization technique that can lead to a better solution to the problem of engineering optimization. The mode of a crane structure could be identified more easily when different mode shape orientations are considered comprehensively.

Key words: Harmony search (HS) algorithm, Optimal sensor placement, Gantry crane, Modal assurance criterion (MAC), Structural health monitoring (SHM)

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1 Introduction

Structural health monitoring (SHM) systems are very helpful for indicating the onset and progress of structural damage. They can provide early warnings of problems and can be used to evaluate the safety and reliability of structures. As the most common form of machinery used for carrying materials, cranes are widely used in industrial plants, construc-

tion sites, shipyards, and ports. With the development of the crane manufacturing market, the structure of cranes has become more complicated. However, significant human and economic loss may occur due to fatal accidents caused by human error or natural disasters. Existing management systems cannot always ensure the safety and reliability of crane structures. Inspection and maintenance methods are costly and time-consuming. New non-destructive testing techniques are needed for inspection for structural damage or cracks in the main frame caused by fatigue or distortion, and to provide real time information about the condition of the structure (CRANESInspect, 2014). Therefore, SHM systems on crane structures have become a major subject of research (Chen *et al.*, 2012; Ding *et al.*, 2012).

Sensors are an essential part of an SHM system and are used for data collection and remote control.

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Therefore, the design of a sensor network is an important and challenging task. The number of sensors required and the best locations for them to achieve optimum sensitivity need to be determined to measure the dynamic response of the impacted structure (Pei, 2010).

Existing theories of sensor placement optimization generally can be divided into two distinct classes. Theories in the first class aim to distinguish different modes of structure and monitor the structural operation by mode parameter identification. Those in the second class are developed to select the best locations for sensors to indicate the onset and progress of structural damage to enable evaluation of the safety and reliability of the structure. The method based on the effective independence algorithm is well known (Kammer, 1991). This method aims to make the mode shapes as linearly independent as possible by minimizing the norm of the Fisher information matrix and selecting measurement locations to maximize the information about the modal responses of the data. Concepts for maximizing the measured kinetic energy were developed by Salama *et al.* (1987) as a means of ranking the importance of candidate sensor locations. Guyan (1965) presented a method to select sensor locations that improve performance by providing information on modal responses by reducing the size of the stiffness and mass matrices. Carne and Dohrmann (1995) showed that sensors can be placed at a set of key points to distinguish different modes. Using the singular value decomposition method, Kim and Park (1997) argued that a maximum allowable number of degrees of freedom can be deleted at each iteration. The iterative scheme is similar to the effective independent method, but overcomes the shortcomings of the previous methods. On the other hand, some methods for damage detection have been developed from the general framework of the finite element modal. Cobb and Liebst (1997) presented the optimal sensor placement for the purpose of detecting structural damage. Shi *et al.* (2000) proved that the element modal strain energy change ratio is sensitive to local damage and can be used as an indicator to locate the site of structural damage. The use of information entropy as a performance measure of sensor configuration to investigate the problem of estimating the optimal sensor locations for parameter estimation in structural dynamics has been re-visited by Papadimitriou and

Lombaert (2012). Bruggi and Mariani (2013) did some work on optimal sensor placement to detect damage in flexible plates. Some research has concentrated on the determination of the optimal reference sensor, assuming random excitation within a weak stationary process. Predicted power spectral amplitudes and an initial finite element modal have been used as a basis for defining the validation criterion of possible sensor positions (Brehm *et al.*, 2013). Many approaches to sensor placement for observing systems and for damage detection have been published (van der Linden *et al.*, 2010). Here, we briefly review some of the most widely used methods.

A large number of meta-heuristic algorithms have been developed to solve various engineering optimization problems, including sensor placement, such as genetic algorithm (GA) and particle swarm optimization (Li *et al.*, 2000; Zhang, 2005; Ma *et al.*, 2007). Other optimization algorithms have been described by Li (2012), including GA, simulated annealing algorithm, tabu search algorithm, and cross entropy algorithm. Using the improved discrete particle swarm optimization, Lian *et al.* (2013) proposed a novel fitness function derived from the nearest neighbor index to overcome the drawbacks of the effective independence method for the optimal sensor placement in large structures. A single wavelet-packet and the empirical mode decomposition method are combined with artificial neural networks for the online identification-location of single or multiple-combined damage in a five-bay truss-type structure (Garcia-Perez1 *et al.*, 2013).

As a new meta-heuristic algorithm, the harmony search (HS) algorithm has been shown to achieve excellent results in a wide range of optimization problems. As shown by a number of studies, this algorithm features several innovative aspects in its operational procedure that foster its use in diverse fields, such as construction, engineering, robotics, telecommunications, health, and energy (Manjarres *et al.*, 2013). The HS algorithm was adopted in research for its simple mathematical requirements and strong effectiveness and robustness in yielding the best solution.

Compared to conventional mathematical optimization algorithms, the HS algorithm imposes fewer mathematical requirements and does not require the initial value setting of decision variables. Since the HS algorithm uses stochastic random searches,

derivative information is also unnecessary. Furthermore, the HS algorithm can generate a new vector after considering all existing vectors, which is better than GA, which considers only two parent vectors to yield a better solution.

However, the selection of reasonable parameter values is considered a challenging task not only for the HS algorithm but also for other meta-heuristic algorithms. The difficulty is caused mainly by the absence of appropriate general rules governing this aspect. The problem of parameter setting has been guided by experimental trials lacking sufficient mathematical robustness.

In this study, an optimization method that combines the HS algorithm with the modal assurance criterion (MAC) is proposed to design sensor networks of SHM by finding the optimal location for each sensor on a gantry crane girder. This paper describes previous studies on parameter setting in optimization algorithms that has had a significant influence on the result. A new method is introduced and shown to be valid and powerful for its application to the optimization problem of sensor layout on a simulated crane structure.

2 Sensor placement criterion

The characteristics of an arbitrary linear vibrating system can be calculated and shown in the second-order differential equation (Eq. (1)) with the help of mass (\mathbf{M}), damping (\mathbf{C}), and stiffness (\mathbf{K}) matrices by applying the finite element method.

$$\mathbf{M}\ddot{\mathbf{X}} + \mathbf{C}\dot{\mathbf{X}} + \mathbf{K}\mathbf{X} = 0. \quad (1)$$

If the damping is not taken into consideration, the solution of this equation will be reached by linear combination of harmonic function, and then it will lead to an eigenvalue problem as

$$(\lambda\mathbf{M} + \mathbf{K})\phi = 0, \quad (2)$$

where λ is the eigenvalue and ϕ is its corresponding eigenvector. If the mass-matrix is diagonal, the corresponding eigenvectors are orthogonally straight. On the basis of this orthogonal condition, the MAC (Allemang and Brown, 1982) was developed as a method for distinguishing between eigenvalues. The

normalized scalar product of two sets of vectors Φ_i and Φ_j can be calculated by this criterion (Eq. (3)), and put into the MAC-matrix (Carne and Dohrmann, 1995):

$$\text{MAC}_{ij} = \frac{|\Phi_i^T \Phi_j|^2}{(\Phi_i^T \Phi_i)(\Phi_j^T \Phi_j)}, \quad (3)$$

where Φ_i means the mode shapes vector for the i th mode. The MAC-matrix can provide information on the orthogonality of the considered vector sets. If 1.0 is found in the off-diagonal matrix, it means that vector Φ_i is identical to vector Φ_j up to a scalar multiple. A zero in the matrix identifies orthogonal vectors. Thus, the target is to choose sensor locations such that the scalar values become as small as possible for the lowest off-diagonal terms in the MAC-matrix, which means that the considered vectors are orthogonal and distinguishable.

To design an optimal sensor network, finding the number and locations of sensors to meet the requirement of modes distinction is the problem. This can be expressed as an optimization problem which can be solved by an optimization algorithm. In this study, an improved HS algorithm was adopted to solve this optimization problem.

Objective:

$$\min f(x) = \min \left[\text{MAC}_{ij} = \frac{|\Phi_i^T \Phi_j|^2}{(\Phi_i^T \Phi_i)(\Phi_j^T \Phi_j)} \right], \quad i \neq j. \quad (4)$$

The maximum value of off-diagonal terms in the MAC-matrix can be found with Eq. (4). The final goal is to minimize the maximum value as much as possible by selecting a subset of measure points from potential locations.

3 Harmony search meta-heuristic algorithm

3.1 Harmony search algorithm

Harmony search (HS) algorithm is a meta-heuristic optimization algorithm proposed by Geem *et al.* (2001). Just as some algorithms are inspired by natural phenomena, the HS algorithm imitates the music improvisation process where musicians

improvise their instruments' pitch by searching for a perfect state of harmony. Fig. 1 shows the details of analogy between music improvisation and engineering optimization. In music improvisation, each player sounds any pitch within the possible range, together making one harmony vector. If all the pitches make good harmony, the experience is stored in each player's memory, and the possibility of making good harmony increases next time. The final goal is to achieve a perfect state of harmony. Similarly in engineering optimization, each decision variable initially chooses any value within the possible range, together making a solution vector. If all the values of the decision variables according to the objective function make a good solution, the experience is stored in each variable's memory, and the possibility of arriving at a perfect solution increases every time.

The optimization procedure of the HS meta-heuristic is described in Fig. 2. The algorithm consists of Steps 1 to 5 as follows (Geem et al., 2001; Lee and Geem, 2004; 2005):

Step 1: Initialize the optimization problem. Initialization of the objective function and the algorithm parameters include harmony memory considering rate (HMCR), pitch adjusting rate (PAR), and harmony memory size (HMS), which is the number of solution vectors in harmony memory.

Step 2: Initialize the harmony memory (HM). Generate initial harmony (solution vectors) as many as the HMS.

Step 3: Improvise a new harmony from the new HM. Generation of a new harmony vector is based on three operators: memory consideration, pitch adjustment, and random choosing.

Step 4: Update the HM. In this step, if the new harmony vector is better than the worst harmony in the HM in terms of the objective function value, the new harmony is included in the HM, and the existing worst harmony is excluded from the HM. The new harmony vector will be stored in the HM with other selected vectors.

Step 5: Repeat Steps 3 and 4 until the termination criterion is satisfied.

The HS algorithm attracts researchers from various fields, especially those working on optimization problems. Consequently, interest in this algorithm led researchers to improve and develop its performance in parameters setting and generation of new harmony (new solution vector). The features of this

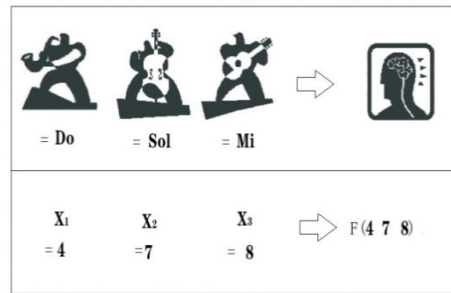


Fig. 1 Analogy between music improvisation and engineering optimization (Reprinted from (Geem et al., 2001), Copyright 2001, with permission from Simulation Councils Inc.)

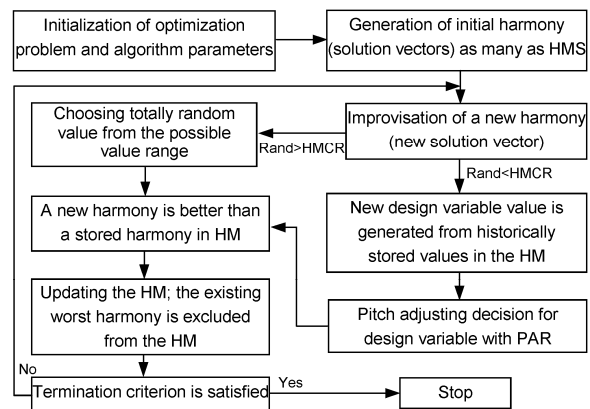


Fig. 2 Optimization procedure of the HS algorithm (Geem et al., 2001; Lee and Geem, 2004; 2005)

algorithm, such as simplicity, robustness, and flexibility, are attractive to explorers. The researches on HS's modification and improvement cover three aspects that can be expressed as follows (Alia and Mandava, 2011). The first idea is the improvement based on parameters setting. This kind of modification tries to enhance the possibility of finding the best solution by increasing the value of these parameters with the rise of the generation number and deeply improve the efficiency and reliability of the HS algorithm. However, the parameters' values are adjusted dynamically depending on the increment of the generation number. If no threshold for the acceptable value is selected in calculation, it is difficult to confirm that the limiting case of iteration is sufficient to finding the best solution because it is unknown to the researchers. The values of the objective functions obtained from each generation are forced to converge for the increment of the parameters' values. Therefore, it might decrease the possibility of

obtaining a global solution because it gets stuck in the local optimal problem. The second idea is the hybridization of HS with other meta-heuristic algorithms, such as GA and simulated annealing algorithm (Alia and Mandava, 2011; Fesanghary *et al.*, 2008). Although these approaches improved the performance and convergence capability of HS in dealing with prematurity problems, the computational complexity of the original HS method also increases in its application. The last idea is the improvement in terms of the improvisation of the harmony vector. According to the original HS method, only one new harmony vector is improvised in each generation. Some researchers believe that many more new harmony vectors should be improvised in each generation (Li *et al.*, 2006). In this framework, it enhances the ability to explore optimal solutions and speeds up convergence without the increment of computational complexity.

3.2 Analysis of parameters in the harmony search procedure

In the HS algorithm, HMCR and PAR are the key parameters used to improve the efficiency of the algorithm. The value of the parameters can be set between 0 and 1.0. However, a value of 0 or 1.0 is not recommended because of the possibility that the solution may be improved by values not stored in the HM. The HMCR indicates the probability of choosing one value from the historic value stored in the HM. A PAR value means that the algorithm will select a neighboring value with the probability of $PAR \times HMCR$.

In this section, the influence of the parameter setting on the speed of convergence and the efficiency of solving an optimization problem was explored by the mathematical function maximization problem expressed as Eq. (5). The maximum value of the function was set as 38.85 approximately, which is predetermined. The proper range of the parameter setting was explored in this section by the statistical analysis technique. To understand the role of each parameter in the HS, a parametric analysis is shown as follows. Each parameter was allowed to vary while the other functions had fixed values.

Objective function:

$$\begin{aligned} \max F(x_1, x_2) &= 21.5 + x_1 \sin(4\pi x_1) + x_2 \sin(20\pi x_2), \\ \text{s.t. } -3 \leq x_1 &\leq 12.1, \quad 4.1 \leq x_2 \leq 5.8. \end{aligned} \quad (5)$$

3.2.1 Analysis of the HMCR

In this section, the HS algorithm parameters were set as follows: HMS=10, and PAR=0.5. In a limiting case of approximate maximum value of objective function (VOF)=38.85 and total iterations (TI)=20000, the process of calculation will stop when the VOF is over 38.85 or the TI is beyond 20000. The discrete value of the HMCR varies in the range of (0, 1.0). The bandwidth value is 0.05. Fig. 3a shows the average value of the generation number (the number of searches) versus the discrete value of the HMCR. Every mark depicted in pictures means the average iteration number fifty times the calculation. Three different kinds of marks mean the results of three times of calculation. A similar result is presented in Fig. 3b when TI=2000. The percentages of invalid iteration (which means that the iteration number is equal to the limited iteration) in the two cases above were shown in Fig. 4. The higher proportion means a lower probability of finding an optimal solution.

From Figs. 3 and 4, a conclusion can be deduced that the value of the HMCR is recommended to be chosen within the range of [0.6, 0.8]. This is more reasonable considering the efficiency and speed of convergence in the HS algorithm. A high acceptable rate means that limited good solutions from the history are more likely to be selected to achieve the best solution, but it decreases the probability of updating the HM and generating new solutions within possible range. Obviously, the lower rate may result in the worse efficiency for obtaining the best solution. On the other hand, the conclusion above is verified by Fig. 5, which shows the research in three different cases. Although the average generation number changes dramatically because that rate of the PAR is adjusted, a reasonable value of the HMCR is also located in the range of [0.6, 0.8].

3.2.2 Analysis of the PAR

In this section, the HS algorithm parameters were set as follows: HMS=10 and HMCR=0.7. Termination criterion was expressed as VOF=38.85 (approximate maximum value of objective function), which means that the process of iteration will stop only when the obtained VOF is over 38.85. The result of the average number of generation versus the

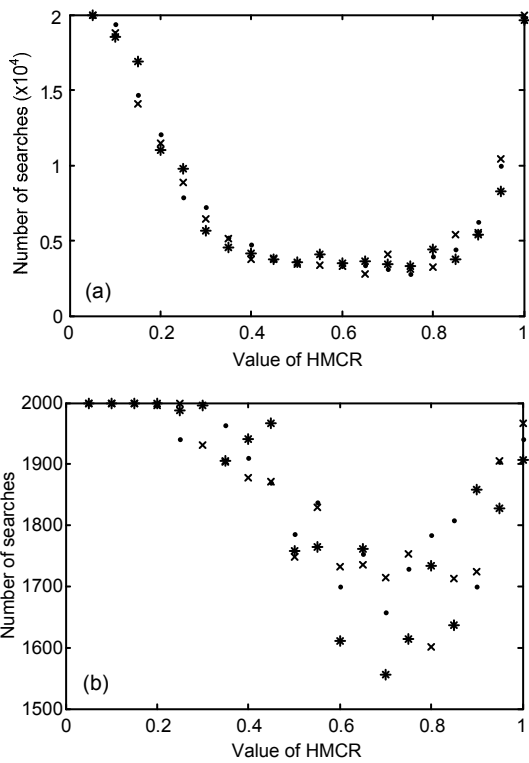


Fig. 3 Average generation number vs. value of HMCR (a) VOF=38.85, PAR=0.5, TI=20 000; (b) VOF=38.85, PAR=0.5, TI=2000

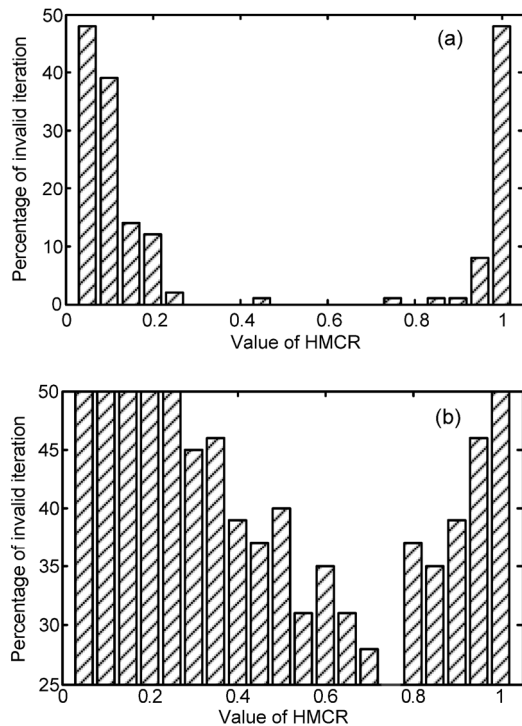


Fig. 4 Percentage of over limiting cases in 50 times calculation: (a) TI=20 000; (b) TI=2000

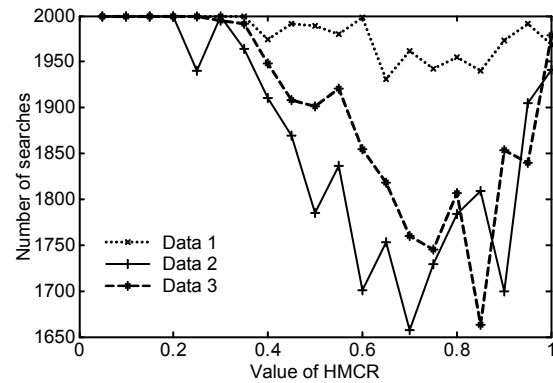


Fig. 5 Average generation number vs. the value of HMCR
Data 1: PAR=0.15; Data 2: PAR=0.50; Data 3: PAR=0.95

discrete value of PAR is presented in Fig. 6a in a statistical way that is used in Fig. 3a. The value of the PAR was selected in the range of (0, 1.0). The bandwidth value is 0.05. Fig. 6b reveals the research in the limiting case of TI=2000; the calculation will stop when the VOF is over 38.85 or the generation number reaches 2000. The corresponding percentage of over limiting case in 50 times of the calculation in this case (Fig. 6b) is depicted in Fig. 7. High percentage means low efficiency of exploring and speed of convergence in the process of the optimization problem.

In this part, it is known from research that the value of the PAR would be better if selected in the range of [0.30, 0.50]. The rate in this range is helpful to improve the efficiency and robustness of the algorithm, including the speed of solution convergence. If the acceptable rate is too low, the solution will converge more slowly and get stuck in a local optimal solution, which decreases the reliability and effectiveness of the HS algorithm in practice. However, a high rate of PAR may result in a low probability of finding the best solution in a fine-tuning process.

3.2.3 A new parameter setting

As mentioned before, the HM contains all the selected sub-optimal solutions. The authors integrate a new parameter in the HS structure, which can be expressed as new harmony memory (NHM) generated in each iteration instead of only one new solution vector. New harmony memory size (NHMS) refers to the number of new solution vectors improvised in

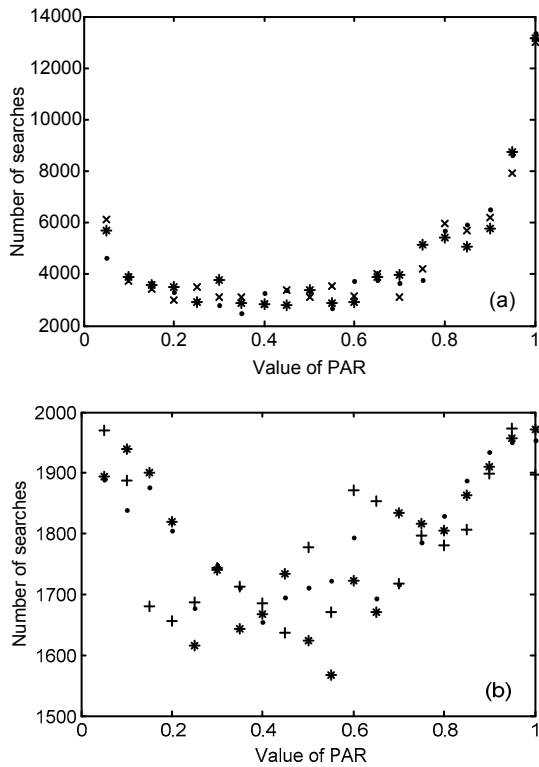


Fig. 6 Average generation number versus the value of PAR
 (a) VOF=38.85, HMCR=0.7, TI=no limits; (b) VOF=38.85, HMCR=0.7, TI=2000

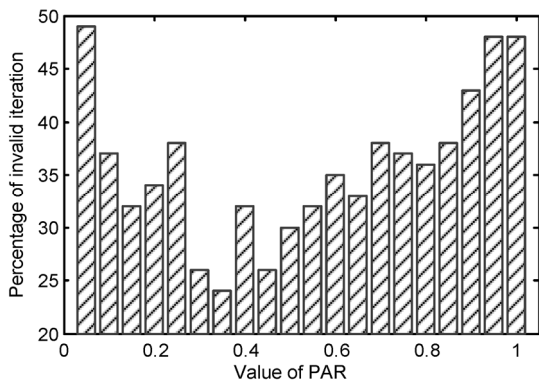


Fig. 7 Percentage of over limiting case in 50 times calculation

every generation. The method enhances the efficiency of algorithm as well as speed of solution convergence and reduces the number of generation to find an optimal solution.

To further understand the improved method in the algorithm, the mathematical function maximization problem above was considered as an example to

deduce the conclusion on parameters setting. The objective function is expressed as Eq. (4). The parameters in the HS algorithm were set as follow: HMCR=0.75, PAR=0.45, and HMS=10. Terminal criterion is that the process of calculation will stop only if the VOF is beyond 38.85. Fig. 8 shows the comparison of the number of searches by two methods in the HS algorithm. Fig. 8 (Data 1) shows the number of searches based on the improved HS. Here, the value of the new parameter (NHMS) was set as 10. Compared to the result of the original HS method (Fig. 8, Data 2), the improved HS definitely enhanced the algorithm with a better efficiency (Fig. 8, Data 1).

Although Fig. 8 shows the improvement of the modified HS algorithm, further work should be carried out to explore the reasonable values of the NHMS. A case of calculation may be chosen here: HMCR=0.75, PAR=0.45, and HMS=10. The value of the NHMS and TI vary in the range of [1, 5000], respectively, which are subjected to the constrain equation: $NHMS \times TI = 5000$. In the limiting case of $NHMS \times TI = 5000$, the process of calculation will never stop unless the number of generation is equal to the corresponding value of iteration. Fig. 9 shows that the ability of obtaining the optimal solution decreases with the increase of the parameter's value (NHMS). It is obvious especially when the value of the NHMS is beyond 2000. The obtained convergence value of the objective function is far from the expected optimal solution. Therefore, the value of the NHMS must be selected in a rational range.

Furthermore, the efficiency of the HS algorithm is also affected by the number of all the solution vectors generated in the calculation. Fig. 10 shows another limiting case of calculation, which is as follows: HMCR=0.75, PAR=0.45, and HMS=10. The NHMS was adopted dynamically in the range of [1, 5000]. The process of exploring the objective solution will not come to an end unless the optimal solution (VOF=38.85) is found without a limiting case of iteration. The ordinate (Fig. 10) represents the mean of the total number of solution vectors generated in a five-time calculation. The larger the value of the NHMS, the more new solution vectors generated in the calculation (Fig. 10a). The mathematical result is depicted in Fig. 10b when the value

of the NHMS is set in the range of [1, 250]. A conclusion can be reached that the proper value of the NHMS would be better selected within 100 in this case.

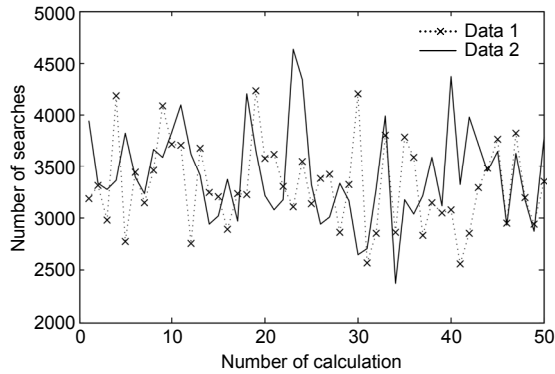


Fig. 8 Comparison between improved and original method
Data 1: 10×TI, improved method; Data 2: TI, original method

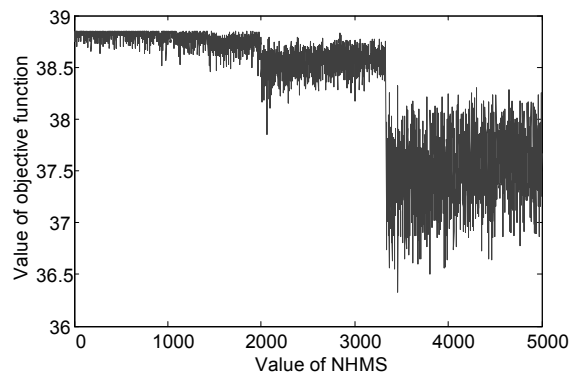


Fig. 9 Average convergence value vs. the value of NHMS
NHMS×TI=5000

According to Figs. 8–10, the result suggests that the value of the NHMS must be set in a rational range instead of no limits. The value setting is affected by many factors, such as the value of the HMS, complexity of the optimization problem in practice, and qualification that is needed. However, it is difficult to establish the termination criterion when the optimal solution is unknown to researchers, if no threshold for acceptable value is set in the calculation. The convergence value of the objective function results from limited searches may be insufficient to meet the qualification that is needed unless it converges in a larger number of generations. Nevertheless, the optimization problem can be solved at

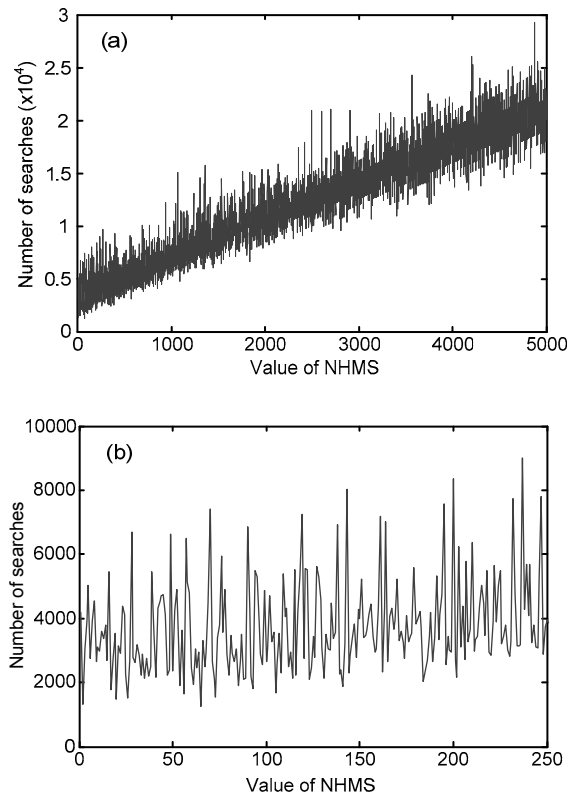


Fig. 10 The number all generated vectors vs. the value of NHMS
(a) NHMS=1–5000, VOF=38.85, TI=no limits; (b) NHMS=1–250, VOF=38.85, TI=no limits

the cost of more time. Value setting of the NHMS enhances the efficiency of exploration and speed of convergence so that the number of generation is reduced in the procedure of solving the optimization problem.

4 Case studies on engineering optimization based on the improved HS algorithm

4.1 Engineering background

The crane structure is made up of a mechanical device—structural hardware as well as electrical equipment. All the heavy loads are supported by its structural hardware. The type of crane that is required by the research objective in this study is gantry crane, as shown in Fig. 11, which is a double-girder portal crane with two trolleys on the girders installed in the shipyard for a maximum capacity of 300 t. Some design parameters of this crane are listed in Table 1.

Simulated modal of the crane structure can be established by the finite element software (Fig. 12). The finite element modal was simplified partly to meet the qualification of the analysis. Research would be started based on the load case that put the crane operation and constraint conditions in practice. Modal parameters can be concluded based on the finite element modal analysis. The first 10 modes analytical frequencies of the crane structure are listed in Table 2.



Fig. 11 Gantry crane structure

Table 1 Design parameters of crane structure

Parameter	Value
Track center (m)	85
Crab traversing range (m)	78
Load-lifting height (m)	50
Load-lifting speed (m/min)	0.8–5
Rated travelling speed (m/min)	1.0–30
Crab traversing speed (m/min)	2.0–30
Total mass (t)	1298
Up crab mass (t)	124
Down crab mass (t)	93

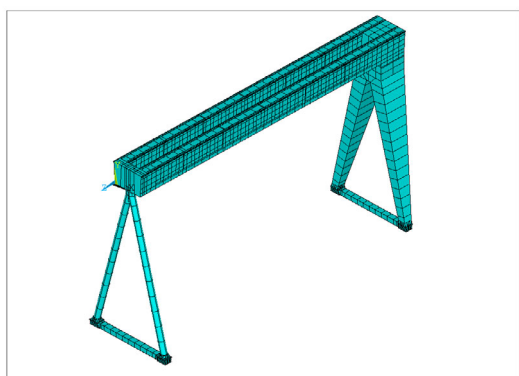


Fig. 12 Finite element modal of crane structure

Table 2 The first 10 modes analytical frequencies of crane structure

Mode	Frequency (Hz)	Crane shape	Mode	Frequency (Hz)	Crane shape
1st	0.021011	S-P-V	6th	0.101257	T-H-V
2nd	0.046271	A-H-V	7th	0.107395	S-V
3rd	0.062345	S-H	8th	0.116299	A-V-H
4th	0.085016	A-H	9th	0.118168	A-V-H
5th	0.097679	S-V	10th	0.129761	T-V-H

S: symmetry; A: anti-symmetry; H: horizontal; V: vertical; P: parallel; T: torsion

4.2 The optimal sensor placement

Mode shape measurements are distributed over the structure and more sensitive to local structure damage than modal frequency, which is a global dynamic parameter. The test mode shapes obtained from the sensor network consist of a plenty of damage information (Shi *et al.*, 2000). Since only a limited number of locations can be selected from potential measurement points, a subset of points that significantly contribute to the preservation of the orthogonality of the eigenvectors must be identified so as to avoid aliasing.

The eigenvectors of the analytical mode shapes can be calculated by the finite element method. In this section, the crane girder is studied, and the potential measurement points are partly chosen along the track of crabs traversing on the double girders (Fig. 12), because the girders are directly excited by the wheel load from the crab with lifting payload and strong stiffness.

According to previous investigation, the improved HS algorithm combined with MAC was used as a new optimization approach to select target locations of sensors. Moreover, the parameters setting in the optimization process are set as follows: HMCR=0.75, PAR=0.45. The HMS was set 10 relative in the process of calculation. However, the possible range of solution vectors would change with the number of required sensors. The value of the NHMS should be adopted dynamically; it should be increased correspondingly so as to improve the effectiveness of the calculation if the possible range of decision variable is larger than before. The objective function that worked as valuation function is expressed as Eq. (4) by the optimization criterion of

MAC. The function is used to select those measurement points which can lead to the lowest possible off-diagonal terms in the MAC-matrix.

Fig. 13 shows the analysis based on the selected eigenvectors in 1D space. The order of 10 calculated eigenvectors is shown in the subtitle of Fig. 14. The mode shape in the 3D space is expressed as X , Y , and Z , which mean three different orientations and mutually orthogonal. X parallels to the direction of crane travelling, Y is vertical, and Z parallels to the direction of crab traversing on the girders. The measurement points were selected independently on condition that only a single orientation of vibration was considered. As is shown in Fig. 13, there is no need to increase the number of sensors when it is equal to 5, since the VOF does not change dramatically and is still somewhat over 0.6 in spite of placing more sensors. However, the threshold for acceptable value is 0.25 (Carne and Dohrmann, 1995). The conclusion can be deduced that the mode shapes in single orientation are difficult to differentiate for high mutual correspondence between the eigenvectors. A set of sensor locations on the girders is insufficient to meet the target of parameter identification, shape visualization, and even robustness.

Furthermore, Fig. 14 (Case 2) presents the history of the VOF versus the number of sensors when the orientation of excitation in 3D space is considered comprehensively. The calculated eigenvectors used in the selection process and their potential locations on the girders are the same as in Fig. 13. Case 2 (Fig. 14) shows that the ability of distinction and visualization for mode shapes cannot be enhanced while the number of sensors is more than 15. However, compared to the conclusion depicted in Fig. 13, the ability of distinction and visualization improves dramatically through a subset of selected points. According to the mathematical result, the number of sensors could be set at 13 while the valuation function could meet the qualification of threshold for acceptable value (0.25).

Apparently, great changes could be shown in Fig. 14 (Case 3) when the number of considered eigenvectors is 8. The number of selected key points is only 6 when the threshold for the acceptable value is achieved. From Fig. 14, it can be concluded that

more sensors are needed to improve the ability of distinction and visualization when more mode shapes are selected in the calculation. Strict mathematical result is listed in Table 3 when the number of sensors is 2, 5, 10, 15, and 20. The values of the objective function demonstrate whether a set of selected points is acceptable and effective for the sensor network system.

From another point of view, when the number of sensors are limited to 15, the column chart of the MAC-matrix is depicted in Fig. 15 when the number of calculated eigenvectors is 10 (Fig. 15a) and 8 (Fig. 15b). The latter (Fig. 15b) shows that the mean of off-diagonal MAC-matrix is 0.0223; however, the former is 0.0708 (Fig. 15a). The conclusion verifies that objective mode shapes selected in the calculation greatly affect the ability of differentiation and visualization.

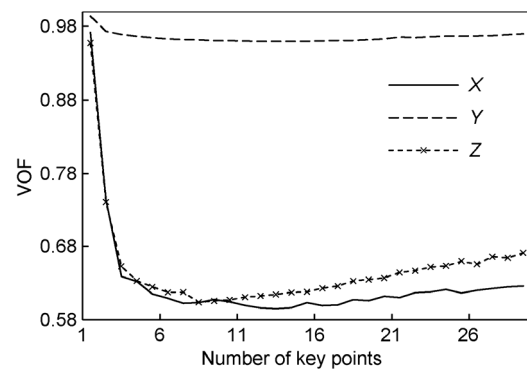


Fig. 13 VOF vs. the number of sensors in Case 1

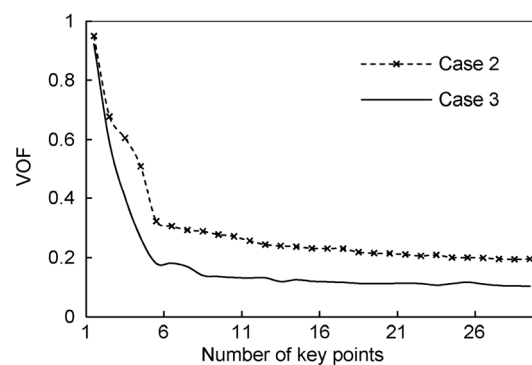
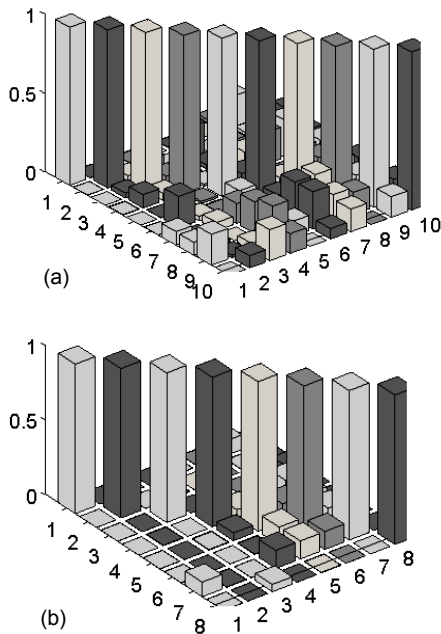


Fig. 14 VOF vs. the number of sensors in Cases 2 and 3
Case 2: calculated eigenvectors can be expressed as 1, 2, 3, 4, 5, 6, 7, 8, 10, and 15; Case 3: calculated eigenvectors can be expressed as 1, 2, 3, 5, 7, 8, 10, and 15

Table 3 Comparison of mathematical results for sensor optimization

Case	Number of eigenvectors	Orientation of vibration	Number of selected points/VOF				
			2/VOF	5/VOF	10/VOF	15/VOF	20/VOF
1	10	X	0.9718	0.6321	0.6075	0.5964	0.6059
	10	Y	0.9939	0.9665	0.9606	0.9596	0.9619
	10	Z	0.9575	0.6330	0.6056	0.6172	0.6348
2	10	All	0.9493	0.5094	0.2768	0.2367	0.2181
3	8	All	0.9225	0.2663	0.1361	0.1254	0.1122

**Fig. 15 Column chart of MAC-matrix**

(a) The number of selected eigenvectors is 10; (b) The number of selected eigenvectors is 8

The HS algorithm proved to be effective was validated through its application for this problem. As is shown in Fig. 14, the VOF changes dramatically at the original time of calculation, which verifies its advance in finding the best solution for the optimization problem.

4.3 Distribution of sensor network

Based on the above analysis, the distribution of selected measurement points can be shown in the following figures. The limited number of sensors is set at 15; the selected measurement points can be placed on the girders in any of the cases that are listed in Table 3. Fig. 16a shows sensor placement on girders in Case 1 (Table 3). Five measurement

points were selected in each orientation of excitation independently. The result of the case that different mode shape orientations are considered comprehensively is presented in Fig. 16b. The distribution of selected points is depicted in Fig. 16c while the number of eigenvectors considered in the calculation is 8 (Case 3 listed in Table 3).

According to previous studies, the vibration characteristic of the gantry crane structure can be conducted as follows:

1. From the analysis in Table 2, the motion of structure can be seen in a different orientation along with torsion and buckling. Local buckling may be the main effect on the crane structure in case of high frequency. Thus, it is difficult to enhance the visualization of mode shapes considered in calculation through a limited number of sensors.

2. The girders are supported by its landing legs on each side and somewhat moveable. The dynamic behavior of the girders is very simple in a single orientation of vibration for the strong stiffness of its cross section and the constrains condition caused by its landing legs. Thus, the uniaxial mode shapes are difficult to distinguish for its high correspondence. This is definitely different from some bridges where only the vertical orientation is considered.

3. Candidate locations can be placed along the track of crab traversing on the girders for the simple dynamic behavior of girders and excitation directly from the crab.

5 Conclusions

In this paper, the value setting of parameters in HS is explored through a mathematical function maximization problem. According to the research, a

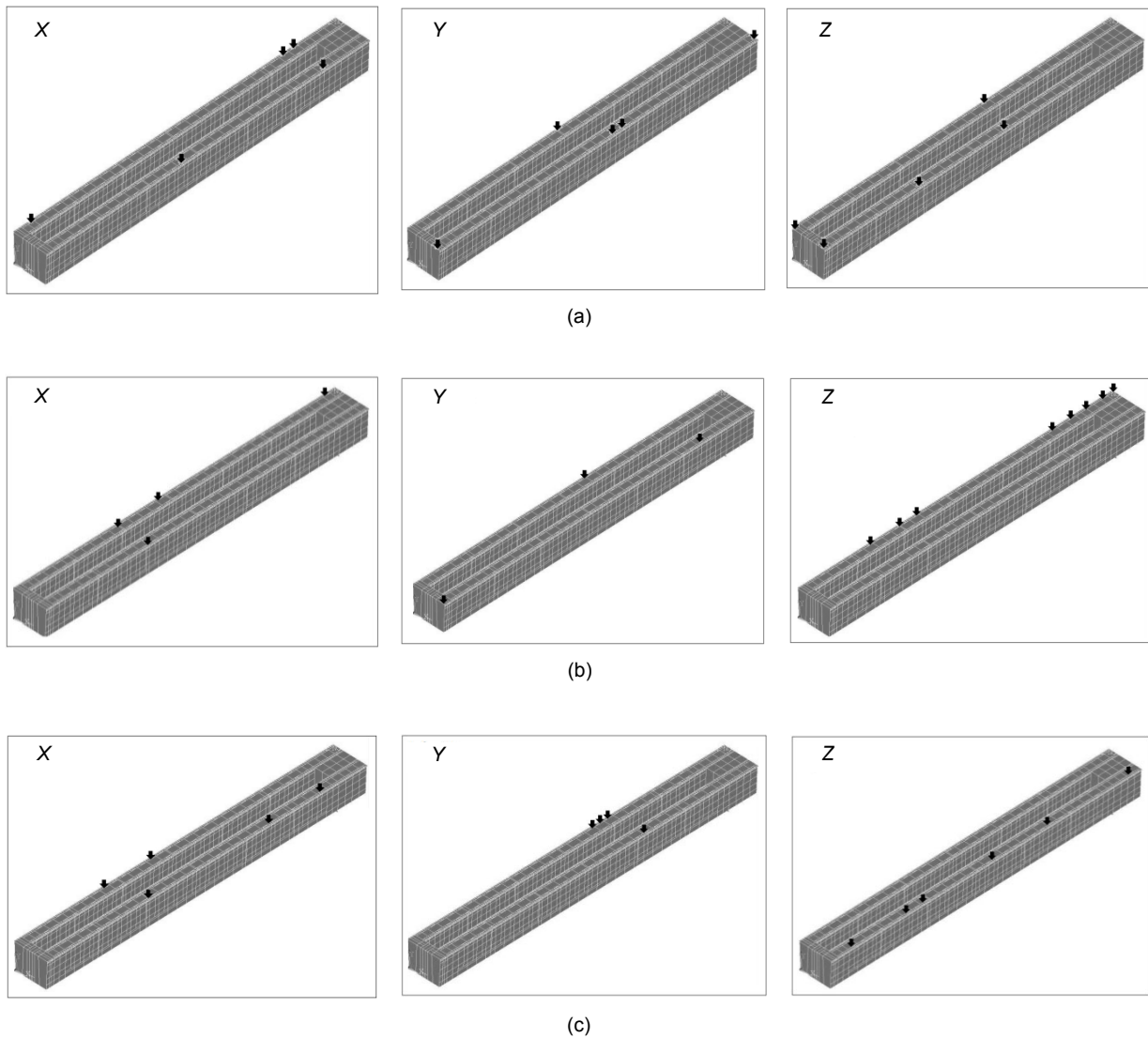


Fig. 16 Distribution of selected measurement points in Case 1 (a), Case 2 (b), and Case 3 (c)

reasonable range for the value of the HMCR is proposed at 0.6–0.8; the value of the PAR is set from 0.3 to 0.5. The conclusions are of significance in solving the problem of engineering optimization. For the general HS algorithm, the NHMS must be set as a new parameter in an improved program. The conclusion shows that the parameter value should be set appropriately in accordance with the value of the HMS as well as the complexity of engineering optimization problems in practice.

From the perspective of engineering application, the conclusions reveal that the ability of distinction, visualization, and parameter identification is

significantly affected by the eigenvectors selected in the calculation and the distribution of selected points. However, whether the orientation of excitation should be taken into consideration or not depends on the vibration characteristics of the structure. Because the crane structure operates in a 3D space, it is capable of contributing greatly to enhance the ability of distinction and parameter identification if the orientation of the vibration is considered in the calculation. In addition, the more eigenvectors selected in the calculation, the more sensors are needed in the measurement process to meet the qualification of threshold for the acceptable value.

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中文概要

- 题目:** 基于改进和声搜索算法识别门式起重机结构空间模态的传感器优化布置方法研究
- 目的:** 采用一种新型改进的和声搜索算法, 对基于空间模态识别的传感器布置的优化方法进行研究。根据对门式起重机结构动力特性研究, 得

到更为理想的测点布置方案和优化结果。

创新点: 1. 研究和声搜索算法的参数合理取值范围, 提高计算效率; 2. 利用和声搜索算法结合模态置信度准则对起重机梁的空间模态识别进行研究, 提出测点布置的合理优化方案。

方法: 1. 基于一种改进的和声搜索算法与模态置信度准则相结合的方法对最优的传感器布置方案进行研究, 通过建立的评估函数对优化得到的布置方案进行评估比较, 得到近似最优的测点位置和传感器数目; 2. 结合门式起重机结构的动力学特性研究结果, 对其在二维和三维空间的振动模态分别进行研究比较, 得到更为理想的优化布置方案。

结论: 1. 和声搜索算法具有程序实现简单和搜索能力较强的优点, 本研究得到了其参数的合理取值范围, 提高了其优化搜索的能力; 2. 研究得到了较为理想的测点位置和合理的传感器数目; 3. 根据起重机结构的动力特性, 考虑其空间模态可得到更为理想的优化方案和识别能力。

关键词: 和声搜索算法; 优化传感器布置; 门式起重机; 模态置信度准则; 结构健康监测