IDENTIFICATION OF DAMAGE ON STRINGERS BY THE PSO METHOD

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Abstract

The paper employs the particle swarm optimization (PSO) method for the identification of damage to a stringer web. This method is inspired by a swarm of bees or flock of birds which look for a common solution. It is a heuristic method, that utilizes a particle as a problem-solving candidate. The location of this particle in the search space represents the configuration of all the variables to possible solutions of the problem. As the particle moves into the solution space, the values of the variables change. The particle is defined by a position vector and a velocity vector. The resulting direction of the particle is determined by three components i.e. (1) the moment or inertia, (2) autobiographical or cognitive information and (3) social interaction. The quality of the particle is evaluated by a comparison function.

In this study we tried to locate damage by using this method. The damage is represented by a rusted area on a stringer web, which was simulated as a change in the Young's modulus. We used the modal calculation of the eigenfrequencies as an evaluation function.

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Key words

- Particle swarm optimization,
- Identification of damage,
- Stringer, bridge.

1 INTRODUCTION

Due to constant increases in the frequency of traffic, emphasis is placed on monitoring the status of the main strategic transport hubs. These also include bridge structures for road or rail transport. There are various types of damage to and defects of such bridges that affect the rigidity of the structure. According to (Vičan J., 2016), the most common damage is the rusting of certain parts, the loosening of fasteners, cracks and permanent deformations.

Various methods are currently being used to detect faults. In the past, this activity was mainly performed visually. Today we are assisted in this activity by a non-destructive method called ambient vibration monitoring (AVM) (Farrar C.R. et al., 1997). It is a method where the common or ambient loads of the structure,

such as traffic, wind, etc., are used for the long-term measurement of natural frequencies and the monitoring of their changes. Based on changes in frequency, it is possible to locate damage on a structure. The set of all these activities is called structural health monitoring (SHM) (Sohn, H. et al., 2001).

The particle swarm optimization (PSO) method (Kennedy, J. et al., 1995) is an approach which can be applied to locate damage on parts of a bridge based on changes in eigenfrequencies. In this article we will deal with corrosion damage to parts of a stringer web. A numerical model of a bridge over the river Váh near Strečno, Slovakia was used for this analysis (Marton, M., 2019; Marton, M. et al., 2020). The numerical model was created in ANSYS. The PSO method was programmed in MATLAB. With the combined use of these programs, we achieved the results presented in this article.

2 PARTICLE SWARM OPTIMIZATION METHOD

The PSO method is a relatively new technique that was first described by Kennedy and Eberhart in 1995 (Kennedy, J. et al., 1995). It is a metaheuristic method from the group of optimization techniques. This method was inspired by a flock of birds or a swarm of bees that follow certain rules when searching for food. A given set of individual particles communicate with each other and thus help each other in the search.

The whole algorithm takes place in iterative steps. First, the system is initialized, which means that the particles are randomly distributed in the search space, the edges or boundaries of which are determined by the user. The quality of each particle is assessed using the evaluation function, and the position of the best particle becomes a global optimum. Equation (1) is used to determine the direction and velocity of the movement:

$$v_{ij}(t+1) = w \times v_{ij}(t) + c1 \times r1 \times [p_{ij}(t) - x_{ij}(t)] + c2 \times r2 \times [p_{gj}(t) - x_{ij}(t)] \quad (1)$$

The next particle position is calculated from formula (2), using the position from the previous iteration and the velocity calculated in the current iteration:

$$x_{ij}(t+1) = x_{ij}(t) + v_{ij}(t+1) \quad (2)$$

The motion of the particle is best expressed in Fig. 1. The resulting movement (direction and velocity) of the particle is determined by the three components. The first one is the moment or inertia component. In Fig. 1a it is symbolized by the initial velocity arrow. The second it is the autobiographical or cognitive component, which means that the particle is attracted to the previous best location. The third component is the social interaction which means that the particle is attracted to the best located particle of the swarm.

2.1 Implementation of the PSO method for detecting of damage

The PSO method had to be adapted to our needs, which means that we had to adjust the basic settings of the algorithm param-

eters. These included the number of particles, which is the size of the population (PopSize) and, in our case, equals 49 particles; the lower and upper limit setting for the search space boundary, the number of iterations (MaxIter), and the number of runs. We kept the weighting factor w at the standard setting. Also, the social and cognitive components equalled 2 for all the calculations. The maximum and minimum velocities were determined from the boundary conditions.

The code is structured as follows: initialization takes place at the beginning; then using iterations the quality of the position of each particle in the objective function is evaluated. This means that in one iteration, the calculation and output of the frequencies from ANSYS must be started as many times as the number of particles. This is followed by an update of the position and velocity at which the two components are updated (see Fig. 2). First, the current best solution of an individual particle is updated, which means that if the particle has a better solution in the current iteration than in the previous iterations, the position of the particle is updated in the 'particle best position' (partBestP) of the autobiographical component. Afterwards, the second component is updated. If the given particle has a better solution than has been written in the best swarm solution (swarmBestP), then this social component is updated to a new value. At the end of the cycle the new position and speed are updated for the next iteration, and the whole procedure is repeated.

3 PREPARATION OF A NUMERICAL MODEL

As mentioned in the introduction, a numerical model of a truss arch railway bridge (Fig. 3) over the river Váh near Strečno, Slovakia, was used for this analysis (Marton, M., 2019). We focused on the stringer in the second segment of the bridge (Fig. 4). To speed up the calculations, we replaced the effect of the overall action of the bridge by supporting the stringer with flexible supports. In the end we decided to continue with fixed articulated supports at the points of connection of the stringer to the crossbar (Fig. 5), as it is not necessary to have real bridge eigenfrequencies for a local study of the stringer.

Fig. 1 Particle motion scheme a) descriptive, b) mathematical (Kavicky, L., 2010)

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FOR i = 1 to PopSize
    To initialize P(i) random
    V(i) = 0
END FOR
DO t = 1 to MaxIter
    Evaluate P(i)
    IF P(i) new position is better than partBestP(i)
        partBestP(i) = P(i)
    IF partBestP(i) is better than SwarmBestP
        SwarmBestP = partBestP(i)
    ENDIF
    ENDIF
    Upgrade velocity of particles by formula (1)
    Recalculate position of particles by formula (2)
    IF particle is out of search space THEN
        return particle back to previous position
    ENDIF
ENDDO

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!!! PopSize - population size
 !!! P - Position of particle
 !!! V - Initial velocity
 !!! MaxIter - Number of iterations
 !!! Evaluate position of particle

Fig. 2 Pseudocode of the PSO algorithm

Fig. 3 Arch bridge over the river Váh near Strečno [5]

Fig. 4 Model of the truss arch railway bridge near Strečno [5]

3.1 Damaged stringer model

The numerical model of the stringer, which was elaborated in ANSYS, is shown in Fig. 5. The web of the stringer was modelled using shell planar elements (SHELL63). The upper and lower flanges are BEAM4 beam elements. The damage (rusted area) was modelled by changing the modulus of elasticity at a certain point on the web of the stringer. We used the MPCHG command to change the material properties. The location of the damage, i.e. the coordinates x and z on the web of the stringer, are numbered from 0 to 1, each of which was subsequently multiplied by the length or height of the stringer respectively.

4 SOLUTION OF THE SEARCH FOR DAMAGE TO THE STRINGER BY THE PSO METHOD

For an easier interpretation of the results, we chose to apply the MS Excel program. The graph in Figs. 6, 7 and 8 shows the elements of the stringer web. The coloured squares represent the particles and thus the individual damage. The evaluation function was performed for each particle individually. The damage points on the side member (see Fig. 7) do not show damage at all the points at the same time. There is always only one damaged element.

Fig. 5 Stringer with damage

The original position of the particle is given in Fig. 6, with the colour scale symbolizing the damage rate index. The interval from which the program looks for damage is 0.001-0.00001. The numbers on the colour scale show the upper limit of a given colour interval (e.g., dark green is in the range between 0.00001-0.000165; red is in the 0.000825-0.001 range). The rate index of the introduced damage was chosen approximately in the middle of the specified interval with a value of 0.0005.

The other two parameters are relative coordinates, i.e., $x = 0.5$ and $z = 0.1$. It is $X_s = x \cdot l_s$, in the specific coordinates,

Fig. 6 Original damage location–

FIG. 7 PARTICLE INITIALIZATION BY RANDOM DISTRIBUTION AND DAMAGE INTENSITY (COLOR)

Fig. 8 Selected iteration steps (1st, 3rd, 5th, 7th, 9th)

where l_s is the length of the stringer, so that $X = 0.5 \cdot 4.8\text{m} = 2.4\text{m}$ and similarly $Z_s = z \cdot h_s$, where h_s is the height of the stringer, so that $Z = 0.1 \cdot 0.8\text{m} = 0.08\text{m}$.

The initialization of the particles is shown in Fig. 7. At the beginning of each search run of the PSO method, a random placement of particles is performed in the search space. This is called initialization. As the placement of the particles is random it is different during each run. Therefore, multiple runs are important as different initial positions of the particles and the subsequent course of the method will cover the search space better. Also, if the algorithm tends to slip into a local optimum (Salehizadeh S.M. et al., 2001), then we can evaluate the correct solution statistically using multiple runs.

Selected iteration steps (1, 3, 5, 7, 9) are presented in Fig. 8. The particle with the best solution has the parameters of $x = 0.496$, $z = 0.109$, and $IP = 0.000267$. The results of the three parameters are compared in Tab. 1. The second column ('original') has the values we defined as a simulation of the real damage. The third column ('found') contains the values of the damage parameters that the program identified. The last column indicates the difference to the introduced state. It is obvious that the largest deviation is in the third parameter, i.e., the damage index. Although this difference is almost 50%, the coordinates of the location of the damage were found relatively accurately. This means we can localize the damage rather well, but without determining the exact extent of the damage.

Tab. 1 Table of results for the three parameters of the rectangle

RESULTS – STRINGER 3 parameters			
Parameters	Original	Found	Deviation
Position X	0.5	0.496	0.8%
Position Z	0.1	0.109	9.1%
Damage Index	0.0005	0.000267	47%

The first ten eigenfrequencies are compared in Tab. 2. The 'FreqMeasured' column contains frequencies that are calculated from the damage values introduced (i.e., from the values in the 'original' column of Tab. 1). In the 'FreqResults' column, the eigenfrequencies are calculated from the parameters found by the program (i.e., from the values in the 'found' column in Tab. 1). The deviation from the exact solution is presented in the last column in terms of absolute values. Below is the average deviation of the calculated and measured eigenfrequencies.

In practice the sensitivity of the measurements and measuring devices is limited. The difference in the eigenfrequencies is very small (see Tab. 2). Thus, small differences in the frequencies due to damage will not be detectable. Such a small amount of damage as we described above will not be detected in real conditions by comparing eigenfrequencies. However, since the PSO method is very variable, it is possible to define the objective function using any other measured value, such as the stresses at different locations or displacements.

5 CONCLUSION

In conclusion, we can state that the PSO method can be used to identify the position and index of damage to the steel structure

Tab. 2 Comparison of frequencies of the three parameters of the stringer

STRINGER Mode shape	FreqMeasured [Hz]	FreqResults [Hz]	Deviation
1.	12.277426	12.277425	0.000008%
2.	22.508822	22.508821	0.000004%
3.	42.585907	42.585907	0.000000%
4.	50.409989	50.409987	0.000004%
5.	76.557735	76.557735	0.000000%
6.	82.523564	82.523563	0.000001%
7.	84.920035	84.920013	0.000026%
8.	93.626763	93.626763	0.000000%
9.	108.615528	108.615527	0.000001%
10.	113.515571	113.515564	0.000006%
	Average deviation		0.000007%

of a bridge. We determined that the method could also be used in practice with properly chosen search parameters and boundaries of the search space.

It can be difficult to prepare the method for a specific use in advance. In order to save computational time, the repeated reloading of the model must be as simple as possible. In this case, we prepared this method to search for damage to the stringer web of a steel bridge.

We know from previous experience that the PSO method has a problem finding a solution on symmetrical structures. If the damage is located in a part with symmetry, it is possible that the method will identify damage in the symmetrical part of the structure with no damage. For this reason the simulated damage was chosen to be located centrally.

The calculation time depends on many factors. The first one is the size of the model, i.e., the mesh size and the number and type of elements. The next important factor is the settings of the method such as the number of particles, the number of iterations, and the number of runs. The computing capacity also significantly influences the run time.

The PSO method is very sensitive to input parameters such as the number of particles for a given size of the search space, and the particle velocity must be chosen suitably. It is also important to adjust the number of iteration cycles to a given model size and to define the size of the search space on the structure. The method is mostly stable as it almost always converges to a solution. However, it is important to assess whether the calculations do not slip into a local optimum. One possibility to eliminate the problem of local optima is running the cycle several times over. Another option is to set the search space to only one part of the symmetry.

The advantage of this optimization technique is its modifiability and broad variability in the search for a solution. It is widely applicable in various industries, easily programmable, and not demanding on computing capacity. Another advantage is its rapid convergence.

A disadvantage may be its tendency to find seemingly correct local solutions. Thus, the results may often be unreliable, and the user must correctly verify the resulting data.

Moreover, it is important to test the method in real conditions. As any real physical structure has material and geometric imperfections, its eigenfrequencies will not perfectly match the eigenfrequencies of the numerical model. With a small change in stiffness due to damage, the changes in eigenfrequencies might not be significant enough for the method to detect them. Therefore, further research by testing the method on a real structure is needed.

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