Applied Soft Computing 66 (2018) 462–472

Contents lists available at ScienceDirect

Applied Soft Computing

journal homepage: www.elsevier.com/locate/asoc

Inverse problem based differential evolution for efficient structural health monitoring of trusses

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ARTICLE INFO

Article history:
Received 29 December 2016
Received in revised form
10 November 2017
Accepted 23 February 2018
Available online 27 February 2018

Keywords:
Structural health monitoring
Meta-heuristics
Inverse problem
Differential evolution
Damage detection

ABSTRACT

This paper proposes the integration of an inverse problem process using radial basis functions (RBFs) into meta-heuristics (MHs) for performance enhancement in solving structural health monitoring optimisation problems. A differential evolution (DE) algorithm is chosen as the MH for this study. In this work, RBF is integrated into the DE algorithm for generating an approximate solution rather than approximating the function value as with traditional surrogate-assisted optimisation. Four structural damage detection test problems of two trusses are used to examine the search performance of the proposed algorithms. The results obtained from using various MHs and the proposed algorithms indicate that the new algorithm is the best for all test problems. DE search performance for structural damage detection can be considerably improved by integrating RBF into its procedure.

1. Introduction

Structural damage detection is a technique used to identify the presence of structural damage, localising it, and assessing the severity [1]. Structural damage takes place due to several reasons such as defects in structures, cracks and corrosion in structural elements, and incomplete construction of the structures. Such mistakes can cause the structures to have a shortened service life and other undesirable accidents. As a result, engineers have had to develop techniques to predict and prevent it. Visual inspection of damage is one straightforward technique usually employed, however, its main disadvantage is the inability to detect internal defects and cracks. Moreover, it is difficult to check throughout a large structure and find damage locations. Therefore, a more sophisticated means should be used to detect damage locations using only one measurement.

One of the most popular damage detection techniques is the use of changes in structural modal data. The idea is that the modal data of a healthy structure is measured and used as the baseline. Once it has been found that the modal data alters from its normal values, it means structural damage may have taken place. Over several decades, researchers have investigated vibration-based damage detection of mechanical systems and structures [2–7]. The use of fuzzy logic systems [8], neural networks [4,7], and other types of soft computing has been proposed. Recently, meta-heuristics have been implemented for perform structural health monitoring based on vibration measurement. The problem of damage detection is treated as an optimisation inverse problem [6,9–12]. The advantage of this strategy is that it is easy to use, can be used to check throughout a large structure, and can locate damage positions within one measurement of modal testing. Although many researchers have demonstrated using a number of MHs for solving the optimisation problems [6,10,11,13–15], it has been found that they failed to assess the performance of MHs properly. The algorithm search convergence and usability was reported but the search consistency has never been examined. For practicality, an algorithm without the guarantee of search consistency will be always questioned, whether it can be used in reality or not. In this regards, developing MHs for optimising an inverse problem of damage detection to improve search convergence simultaneously with search consistency is an interesting topic.

Over the last few decades, development of MHs with an emphasis on improving the convergence rate and consistency can be accomplished in several ways, such as introducing new search concept MHs [16–18], using a hybridisation concept [19], using parameter adaption [20,21], or using surrogate assisted MHs [22]. The implementation of a surrogate assisted MH is usually required when the optimisation problem has computationally expensive

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https://doi.org/10.1016/j.asoc.2018.02.046
1568-4946/

Nomenclature

$[\mathbf{K}]$	Structural stiffness matrix
$[\mathbf{M}]$	Structural mass matrix
λ_j	jth mode eigenvalue
ϕ_j	jth mode eigenvector or mode shape.
n_{dof}	Size of the mass and stiffness matrices.
$[\mathbf{m}_e]$	Element mass matrices
$[\mathbf{k}_e]$	Element stiffness matrices.
n_e	Number of elements
p_i	Percentage of damage in the ith element.
n_{mode}	Number of lowest vibration modes
F	Scaling factor
$F_{\min}$	Maximum scaling factor
$F_{\max}$	Minimum scaling factor
$\mathbf{x}_{r,i}$	ith randomly selected individual
$\mathbf{x}_{old}$	Current solution (parent)
$\mathbf{x}_{new}$	New candidate solution
$rand$	Uniform random number ranged from 0 to 1
$rand(0,1)$	Random number, either 0 or 1
CR	Crossover rate
D	Number of design variables
c_k	Interpolation coefficients
φ	RBF kernel function
$\boldsymbol{\omega}_{damage}$	Natural frequencies of the damaged structure (Target vector)
$\mathbf{x}_{damage}$	Solution vector containing n_e element damage percentages

function evaluations. The simple strategy of surrogate assisted optimisation is carried out in such a way that the design of the experiment uses a technique such as Latin hypercube sampling to generate a set of training points. With those training points, actual function evaluations are performed. A surrogate model, a form of function that requires significantly less computation time, is then constructed based on the training points and their function values. Thereafter, optimisation can be performed based on using the surrogate model instead of actual function evaluations. This can greatly reduce optimisation running time. Although a surrogate model can be used to improve MHs search convergence (by reducing the number of real expensive function evaluations) and also search consistency, it is yet to find that such a model is applied to an inverse problem for structural damage detection.

Therefore, this paper presents a new, efficient MH for structural damage detection as a hybridisation of a radial basis function (RBF) interpolation and differential evolution (DE). In this work, the RBF is integrated into the main procedures of DE for approximating design solutions rather than objective functions as with traditional surrogate-assisted optimisation. Four structural damage detection and localisation test problems from two truss structures are used for performance assessment of a number of MHs and the proposed algorithm. The results obtained from the various algorithms will be statistically compared in terms of both convergence rate and consistency.

2. Natural-frequency-based damage detection and localisation

In this study, structural damage detection using changes in structural natural frequencies is considered. The detection strategy can be used for damage detection of truss elements due to corrosion, crack and yielding of members due to fatigue. This approach is based on implementing modal testing incorporated with a finite element model. Initially, the natural frequencies (usually the lowest n_{mode} natural frequencies) of the structure in a normal condition will be used as the baseline. In practice, the natural frequencies and mode shapes will be measured and the finite element model will be updated so that both measured and computed modal parameters are equivalent. The finite element model used herein is a simple linear undamped free vibration which can be expressed as:

$$[\boldsymbol{K}]\left\{\phi_j\right\} - \lambda_j[\boldsymbol{M}]\left\{\phi_j\right\} = 0 \tag{1}$$

The structural natural frequencies can be computed as

$$\omega_j = \sqrt{\lambda_j} \quad, j = 1, 2, 3, \ldots, n_{dof} \tag{2}$$

The mass and stiffness matrices can be obtained from assembling all element mass and stiffness matrices, which can be expressed as:

$$[\mathbf{M}] = \sum_{i=1}^{n_e}[\mathbf{m}_e]$$

and

$$[\boldsymbol{K}] = \sum_{i=1}^{n_e}[\boldsymbol{k}_e]. \tag{3}$$

In cases that damage in the structural element occurs, the structural natural frequencies of the structure will be different from those of the baseline structure. To localise the damage, it is assumed that the values of the structural stiffness matrix are altered, which can be written in terms of element structural damage percentage. As a result, the altered structural stiffness matrix of the damaged structure is of the form

$$[\boldsymbol{K}_d] = \sum_{i=1}^{n_e}\frac{100 - p_i}{100}[\boldsymbol{k}_e]. \tag{4}$$

The optimisation problem is then formulated by assigning all the values of element damage percentages as a design solution $\mathbf{x} = \{p_1, \ldots, p_{ne}\}^T$. The objective function is to minimise the root mean square error:

$$\text{Min}: f(\mathbf{x}) = \sqrt{\frac{\sum_{j=1}^{n_{mode}}\left(\omega_{j,damage} - \omega_{j,computed}\right)^2}{n_{mode}}} \tag{5}$$

where $\omega_{j,damage}$ is the structural natural frequency of mode j obtained from measuring a damaged structure. n_{mode} is the number of lowest vibration modes used for the damage detection. $\omega_{j,computed}$ is the structural natural frequency of mode j obtained from solving (1) using $[\mathbf{K}_d]$ instead of $[\mathbf{K}]$. The optimum solution having the objective function value close to zero gives accurate damage localisation. The values of the element damage percentage indicate where the damage takes place.

3. Test problems with trusses

To study performance assessment of a number of MHs on tackling damage detection optimisation, two truss structures are employed in this work. For the sake of simple investigation, truss damage is simulated whereas the natural frequencies of structures are computed from finite element analysis rather than measuring real structure modal data. Only truss element damages are taken into consideration. It should be noted that free vibration is simulated for all cases without considering gravity loads. The trusses are detailed as follows.