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Dual ant colony operational modal analysis parameter estimation method

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ABSTRACT

Operational Modal Analysis (OMA) is a common technique used to examine the dynamic properties of a system. Contrary to experimental modal analysis, the input signal is generated in object ambient environment. Operational modal analysis mainly aims at determining the number of pole pairs and at estimating modal parameters. Many methods are used for parameter identification. Some methods operate in time while others in frequency domain. The former use correlation functions, the latter - spectral density functions.

However, while some methods require the user to select poles from a stabilisation diagram, others try to automate the selection process. Dual ant colony operational modal analysis parameter estimation method (DAC-OMA) presents a new approach to the problem, avoiding issues involved in the stabilisation diagram. The presented algorithm is fully automated. It uses deterministic methods to define the interval of estimated parameters, thus reducing the problem to optimisation task which is conducted with dedicated software based on ant colony optimisation algorithm. The combination of deterministic methods restricting parameter intervals and artificial intelligence yields very good results, also for closely spaced modes and significantly varied mode shapes within one measurement point.

1. Introduction

Operational modal analysis (OMA) was first presented in [1], as Natural Excitation Technique (NExT). Instead of using artificial excitation which was measured at the same time, a way of investigating a structure's dynamic properties under its operating conditions was proposed. To this end, correlations and their spectral densities (SD) of input signals were used then as they are used now. The technique can be used to identify the dynamic properties of a system in its ambient environment. Unlike in experimental modal analysis in which excitation is generated by a shaker or an impact hammer, OMA examines all the forces interacting with a system under its normal operating conditions which has a number of advantages, since not every system can be effectively investigated using artificial excitation.

Similarly to experimental modal analysis, there are many methods of pole selection and parameter estimation. They can be divided into those which are applied to signals defined in either time or frequency domain. The former are Eigensystem Realization Algorithm (ERA) [2], Least Squares Complex Exponential (LSCE) [3] and Ibrahim Time Domain Method (ITD) [4] whereas the latter include a method of pole selection and modal parameter estimation based on peak-picking (PP) [1] and more complex methods using Singular Value Decomposition (SVD), such as Frequency Domain Decomposition (FDD) and

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Enhanced Frequency Domain Decomposition [5–10]. Other methods include stochastic subspace identification [11], maximum likelihood (ML) estimation [12] and PolyMAX [13]. A substantial number of review papers were written about the methods [14–17]. Many papers focused on their industrial applications: wind turbines [18,19], airplanes and cars [20], machining processes [21], space shuttles [22], civil engineering dynamic research on bridges [23,24], sport stadiums [25] and other buildings [26]. The methods primarily aim at proper selection of the number of physical poles, obtaining accurate values of estimated modal parameters and greater autonomy of every given method. Nowadays, methods which use stabilisation diagrams are very popular [10,13,27]. Diagrams require the user to have proper qualifications and he/she is prone to make mistakes. Diagrams which are currently in use become illegible if poles are located too close to one another. Stabilisation diagram methods are not without their disadvantages, then. The solution laid out in the present paper evades the problem as it selects an appropriate number of poles and values of estimated parameters in a system.

Operational modal analysis does not require any artificial excitation triggered by force-producing devices, such as shakers or impact hammers. Therefore, FRFs of a system cannot be directly measured. Instead, analysis is based on power spectral densities of recorded output signal. In OMA, white noise is generally understood to be the excitation signal. The same assumption was made in this study. Although in this case it is possible to determine the poles of a system, it is necessary to know noise variance and the maximum frequency that defines the noise to be able to scale mode shape vectors. The unit value of power spectral density for the white noise was predefined and as a result unscaled mode shapes were obtained which could later be scaled using one of the methods presented in [28–33].

2. Original contributions of this work

The paper offers a new approach to the problem of determining the number of poles and to parameter estimation in OMA. The presented method analyses functions in frequency domain and does not use the stabilisation diagram, thus avoiding problems its use may create. Furthermore, the method is fully autonomous. The user is not required to select poles manually. It is based on the idea of the ant colony optimisation algorithm [34]. The approach yielded good results which were presented earlier for experimental modal analysis [35].

The increasing computational power of modern computers offers new possibilities for solving problems. The presented method reduces the problem of modal parameter estimation to the task of optimisation. The solution space is deterministically defined by automated constraints assigned to estimated parameters. The values of modal parameters are found as a result of optimisation calculated by the algorithm. Additionally, the method enables to determine the number of pole pairs in a system, automatically determines its minimum number and computes successive operations increasing their number iteratively. It can efficiently detect poles which are close to one another. The autonomous character of the method is combined with high precision of parameter estimation. To obtain higher accuracy, after determination of pole pairs and preliminary estimation, the final estimation is conducted in the close neighbourhood of estimated values. The solution enables the user to obtain precise results and manage expected precision.

Below, a commonly known theory that defines the method and estimation results for generated characteristics of MIMO (multiple-input and multiple-output) systems is presented, showing its good performance in different cases.

3. Introduction to operational modal analysis

In Section 3, a theory that can be used in OMA for MIMO systems with p inputs and outputs [36] is presented. It will be used later to identify dynamic systems.

The fundamental theorem in frequency domain, describing spectral density function (SD) is described by Eq. (1):

$$\boldsymbol{G}_y(\omega) = \boldsymbol{H}(-i\omega)\boldsymbol{G}_x(\omega)\boldsymbol{H}^T(i\omega) = \boldsymbol{H}^*(i\omega)\boldsymbol{G}_x(\omega)\boldsymbol{H}^T(i\omega) \tag{1}$$

where:

$\boldsymbol{G}_x(\omega)$ – spectral density matrix of the input signal.

If the frequency response function $\boldsymbol{H}(i\omega)$ is expressed using modal parameters, Eq. (2) is obtained:

$$\boldsymbol{G}_y(\omega) = \sum_{n=1}^{N}\left(\frac{\boldsymbol{A}_n}{i\omega - \lambda_n} + \frac{\boldsymbol{A}_n^*}{i\omega - \lambda_n^*}\right)^* \boldsymbol{G}_x(\omega)\sum_{n=1}^{N}\left(\frac{\boldsymbol{A}_n}{i\omega - \lambda_n} + \frac{\boldsymbol{A}_n^*}{i\omega - \lambda_n^*}\right)^T \tag{2}$$

where:

N – number of resonances;

$\boldsymbol{A}_n$ – residue matrix of the n-th mode $[p \text{ x } p]$;

λ_n – system pole of the n-th mode.

System poles for underdamped systems are given by Eq. (3):

$$\lambda_n = \left(-\xi_n + i\sqrt{1 - \xi_n^2}\right)\Omega_n \tag{3}$$