An application of operational modal analysis in modal filtering

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Abstract. Modal filtration in the field of damage detection has many advantages, including: its autonomous operation (without the interaction of qualified staff), low computational cost and low sensitivity to changes in external conditions. However, the main drawback of this group of damage detection methods is its limited applicability to operational data. In this paper a method of modal filter formulation from the in-operational data is described. The basis for this approach is FRFs synthesis using knowledge of the operational modal model. For that purpose a method of operational mode shape scaling is described. This is based on the measurements of several FRFs of the object. The method is then applied to the construction of modal filters and modal filtration. Additionally, the study presents verification of the method using data obtained from simulation and laboratory experiments. Verification consisted of comparing the results of modal filtering based on classical experimental modal analysis with the results of the approach proposed in the work.

1. Introduction

The applicability of modal models to a wide-ranging class of issues related to diagnosis, damage detection or structural health monitoring, has been discussed and verified in various publications. An overview of such an algorithms one can find in [21, 22]. In recent years, several teams of researchers have developed the use of modal models for the implementation of modal filters, and have applied the results of such analyses in the tasks of Structural Health Monitoring (SHM) [23,24,25,26,27]. Generally speaking, the modal filter extracts the modal coordinates of each individual mode from a system's output. This is achieved by mapping the response vector from the physical space - the network of measurement points - to the modal space. It was first introduced by Baruh and Meirovitch in 1982 [28] with the aim of overcoming the spill-over problem encountered while controlling distributed parameter systems. Spill-over is a phenomenon in which the energy addressed to the controlled mode is pumped into the uncontrolled modes. Since then, the modal filter has been applied to: active vibration reduction, the correlation of experimental modal models with theoretical models obtained by Finite Element Method (FEM), the identification of operational forces and finally to damage detection. This latter group of applications is the main interest of the authors. Modal filtration in the field of damage detection has many advantages, including: its autonomous operation (without the interaction of qualified staff), low computational cost and low sensitivity to changes in external conditions [27]. However, the main drawback of this group of damage detection methods is its limited applicability to operational data. In the literature, the modal filtration of the pure responses spectra
(instead of Frequency Response Functions FRFs) has been proposed [26]. However, this approach frequently does not provide the desired results, as it only works properly for excitations in the form of white noise, or an ideal impulse. In this paper a different approach is described. The basis for the modal filter application are FRFs synthesized using knowledge of the operational modal model. A method of operational mode shape scaling is also described. This is based on the measurements of several FRFs of the object. Such an approach is much more complex and less computationally efficient but it has the advantage that its results are proper for any kind of excitation signal.

2. Modal filter theory
The modal filter is a tool to extract the modal coordinates of each individual mode from the system outputs by mapping the response vector from the physical space to the modal space [29]. The construction of the r-th modal filter, which corresponds to r-th pole of the transfer function $H(\omega)$, starts with the assumption that the modal residue $R_{pp}$ is in the imaginary form:

$$R_{pp} = j \cdot 1$$  \hspace{1cm} (1)

Next, the 1 DOF frequency response function $H_{pp}(\omega)$ is determined as follows:

$$H_{pp}(\omega) = \frac{R_{pp}}{j \omega + \lambda_r} + \frac{R^*_pp}{j \omega + \lambda^*_r}$$  \hspace{1cm} (2)

where: $\lambda_r$ - r-th pole of the system.

For the given frequency range, the above FRF is determined by the $k$ values:

$$H_{pp}(\omega) = \begin{bmatrix} H_{pp}(\omega_1) & H_{pp}(\omega_2) & \cdots & H_{pp}(\omega_k) \end{bmatrix}^T$$  \hspace{1cm} (3)

Assuming that a single excitation was used and the response signals were measured in $N$ points, the experimental frequency response function matrix can be presented as the $k \times N$ matrix:

$$H_{kN}(\omega) = \begin{bmatrix} H_1(\omega_1) & H_2(\omega_1) & H_N(\omega_1) \\ H_1(\omega_2) & H_2(\omega_2) & H_N(\omega_2) \\ \vdots \\ H_1(\omega_k) & H_2(\omega_k) & H_N(\omega_k) \end{bmatrix}$$  \hspace{1cm} (4)

The FRF matrix formed in this way is used to determine the reciprocal modal vector matrix $\Psi_p$:

$$\Psi_p = H_{kN}^+ \cdot H_{pp}$$  \hspace{1cm} (5)

where: $^+$ denotes a pseudo-inverse of the matrix

Reciprocal modal vectors should be orthogonal with respect to all the modal vectors except the one to which the filter is tuned, and, thanks to that, are applied to the decomposition of the system responses to the modal coordinates $\eta_r$. 


\[ \eta_r(\omega) = \Psi_p^T \cdot x(\omega) = \begin{pmatrix} \phi_r^T \\ j\omega - \lambda_r \end{pmatrix} + \psi_r^* \phi_r^* \begin{pmatrix} \phi_r^T \\ j\omega - \lambda_r^* \end{pmatrix} \]

(6)

where:
- \( \phi_r \) – \( r \)-th modal vector
- \( x(\omega) \) – vector of system responses.

It is clear that for such a formulation of the modal filter, the FRF matrix is required for the filter construction. Additionally, as mentioned above, it is better to use FRFs as a modal filter input. Therefore the authors decided to use the following procedure for in-operational modal filter definition:
- Measurement of system responses,
- In-operational modal analysis,
- Measurement of FRFs at a limited number of points,
- Scaling the operational mode shapes,
- Synthesis of FRFs from a scaled operational modal model,
- Construction of the modal filter.

3. Operational mode shape scaling

Scaling operational mode shapes can be performed in several different ways. The general assumption is that it is necessary to acquire additional knowledge concerning the tested object. This knowledge can be gained through use of:
- an analytical model of the tested object, e.g. the finite element model,
- methods for investigating the sensitivity of modal parameters to the known changes in the parameters of the tested structure,
- additional measurement characteristics collected during testing,
- cepstral analysis.

Using the first group of methods appears to be quite obvious. The idea behind the use of the analytical model parameters (e.g. mass or stiffness matrix) for the tested object seems to be fairly simple. The difficulty is, however, to create a suitably tuned analytical model describing the dynamics of the tested object. Necessary knowledge related to the parameters of material resources and detailed geometric modeling are often too limited for the application of this method. The successful application of this kind of scale in the study of bridge constructions is shown in [20]. The techniques used in this example have enabled the use of FEM (finite element method) for the scaling of operational mode shape.

The second group of methods based on the study of the sensitivity of modal parameters to controlled changes to the tested object are the most frequently used. In most cases, a modified parameter of the object is a matrix of the masses. The change is mostly at one [1,5] or more [2] measurement points. The techniques used to determine the scaling coefficients are based on different assumptions. The most important of the assumptions adopted for each of the methods discussed in this group is the need to at least double the implementation of the modal experiment. The first test is performed on the unmodified object, second after the introduction or removal of a known mass or set of the masses. Both experiments are performed on the same network points and assume similar operating conditions to force the object. In the simplest case [1,2,5,7,8] it is assumed that a slight modification of the mass at a point disturbs only the natural frequencies and does not change the mode shape. The formulation according to scaling in this case can be performed independently for each identified mode shape. Another concept was concluded in [11]. In this case, it is assumed that the mass modification can affect both the pole change of the object and also be reflected in the local shape modification. In this case, the issue of estimating scaling factors, however, requires a global approach and the designation of all the factors in a single optimization.

The third group of methods is the least discussed in the literature. This approach assumes the estimation of scaling factors based on an additionally performed set of transfer function characteristics.
measurements. This method was first successfully applied to determine the scaling coefficients of the model obtained on the basis of the acoustic excitation [4,19]. Its idea is based on the operational measurement of the points in the defined network. In addition to the selected point network, it is necessary to measure the point characteristics using pulsed excitation (with measured excitation force). On the basis of the operational modal model parameters, the point characteristics are reconstructed at the points where the measured point characteristics were known. Realization of a comparison of characteristics allows the estimation of missing scaling factors.

The fourth group consists of the methods proposed in [17,18]. These works were conducted by a team led by Prof. B. Randall. The method involves the reconstruction of the frequency response function using cepstrum analysis. The method allows the reconstruction of FRF force structure functions, assuming a single impulse of force at a given location. In [18] the method is extended by the additional possibility of a broadband noise signal in addition to the excitation.

The presented methods show that the issue of scaling can be solved in at least a couple of ways. Taking into account the fact that the creation of the updated FEM models is very difficult, the first group of methods appears to be of limited use for the case of operational measurements. A similar impression applies to the methods of cepstral analysis. Very complex mathematical apparatus associated with the intensive use of nonlinear optimization methods makes these methods less relevant to the determination of a scaling factor derived modal model based on operational measurements. Accordingly, for further analysis, methods based on the sensitivity of modal parameters to changes in the parameters of the mass of the tested structures, and methods to estimate the scaling factors based on additional measurements of the transfer characteristics in the selected measurement points network, were selected.

3.1. Scaling of a classical modal model

The formulation of a classical modal model is often described by the equation, which is represented in the frequency domain [12], as follows:

\[
H(\omega) = \sum_{r=1}^{N} \left( \frac{Q_r \psi_r \psi_r'}{j\omega - \lambda_r} + \frac{Q_r \psi_r' \psi_r''}{j\omega - \lambda_r'} \right)
\]  

(7)

where:

- \(H(\omega)\) - spectral transfer function matrix
- \(\psi_r\) - mode shapes vector corresponding to the pole \(r\)
- \(Q_r\) - scaling factor of the \(r\)-th mode shape
- \(\lambda_r\) - \(r\)-th system pole
- \(N\) - number of system poles

One of the steps occurring in the majority of algorithms for the estimation of modal parameters of the modal model is to extract the matrix of residuals. This matrix follows directly from Formula (7) and is equal to:

\[
A_r = Q_r \psi_r \psi_r' = Q_r \begin{bmatrix}
\psi_1' \\
\psi_2' \\
\vdots \\
\psi_M'
\end{bmatrix} = \begin{bmatrix}
\psi_1 & \psi_2 & \cdots & \psi_M \\
\psi_1' & \psi_2' & \cdots & \psi_M' \\
\vdots & \vdots & \ddots & \vdots \\
\psi_M' & \psi_M' & \cdots & \psi_M'
\end{bmatrix}_r
\]  

(8)

where:

- \(M\) - number of points which determines the mode shape
The modal residue matrix is constant for a given pole. It is the basis for the mode shape estimation. Values of the individual elements of the residue matrix are:

\[ A_{pq} = Q_r \psi_{pr} \psi_{qr} \]  \hspace{1cm} (9)

It should be noted that, in the case of classical modal analysis, the point characteristic plays a vital role. It describes the point (position on the geometry of the tested object), in which the tested system is both provided with force and measured response. In a point characteristic modal residue reaches the value:

\[ A_{pp} = Q_r \psi_{pr} \psi_{pr} \]  \hspace{1cm} (10)

which can be recalculated as:

\[ Q_r = \frac{A_{pp}}{\psi_{pr} \psi_{pr}} \]  \hspace{1cm} (11)

Accordingly, the following assumptions are most often made with a view to obtaining the correct value of the estimated mode shape:

- unity modal \([a]\) matrix – which gives:
  - \( Q_r = 1 \)
  - \( \psi_{qr} = \sqrt{A_{qqr}} \)
  - \( \psi_{pr} = \frac{A_{pq}}{A_{qqr}} \)

- unity modal coefficient \( \psi_{ir} = 1 \)

- \( Q_r = \frac{A_{pq}}{\psi_{pr} \psi_{qr}} \)

- \( \psi_{qr} = \frac{A_{pq}}{A_{pr}} \)

- \( \psi_{pr} = \frac{A_{pq}}{A_{qr}} \)

- unity modal vector length

- \( Q_r = \frac{A_{pq}}{\sqrt{A_{pr} A_{qr}}} \)

- \( \psi_{qr} = \sqrt{\sum_{i=1}^{n} A_{qir} A_{ir}^*} \)

- \( \psi_{pr} = \frac{A_{pq}}{\sqrt{A_{qpr} A_{pr}}} \)

- unity modal mass \( m_r = 1 \)

- \( Q_r = \frac{1}{j2\omega} \)

- \( \psi_{qr} = \frac{A_{qqr}}{Q_r} \)
\[ \Psi_{qr} = \frac{A_{qr}}{Q_{r}^*} \]

In practice, for the estimation of modal parameters of the model, in most cases the use of scaling the last schema which sets up a vibration unit modal mass is assumed.

3.2. Determination of scaling for measurement of additional characteristics

In the case of the use of additional measurement characteristics for scaling the estimated mode shape we assume the existence of modal model parameters in advance. These parameters are:
- \( \lambda_r \) – system poles obtained on the basis of operational data
- \( \varphi_r \) - unscaled mode shapes obtained on the basis of operational data.

Equation (7) shows that, in the case of an additional transfer characteristic, the equation will take the form:

\[
H_{pp}(\omega) = \sum_{r=1}^{N} \left( \frac{Q_{r}\Psi_{pr}^*\Psi_{pr}^*}{j\omega - \lambda_r^*} + \frac{Q_{r}^*\varphi_{pr}^*\varphi_{pr}}{j\omega - \lambda_r} \right)
\]

(12)

Assuming \( \overline{Q_r}\varphi_r^*\varphi_r = Q_{r}^*\Psi_{pr}^*\Psi_{pr}^* \) we obtain:

\[
H_{pp}(\omega) = \sum_{r=1}^{N} \frac{\overline{Q_r}\varphi_r^*\varphi_r}{j\omega - \lambda_r^*} + \frac{\overline{Q_r}^*\varphi_r^*\varphi_r}{j\omega - \lambda_r}
\]

(13)

Scaling coefficients can be determined by the least squares formulation of the task. Estimation of the scale factor can be improved by choosing a set of points on the tested structure and the appointment of several transfer characteristics at these points.

The method assumes that the operating model and the one built in classical circumstances converge. In the case of non-linear objects, it may be possible that differences in the operational and classical modal model are large enough to prevent it from obtaining the correct scaling factors.

3.3. Scaling an operational mode shape algorithm for the measurement of additional transfer characteristics

In the case of determining the scaling factor for operational mode shapes, the additional measurement of the transient measurements at only a few points on the tested structure is required, which significantly simplifies the implementation of the experiment. In the case of other methods, such as use of the additional mass, scaling is necessary to repeat the whole measurement process at all points of the assumed measurement network. Knowledge of additional transfer characteristics is required at a minimum of one pair of points. In this case, the designation of a scaling algorithm is as follows:

- operational performance of the modal test in a defined network of measurement points,
- additional measurement of the transient behavior for at least one pair of points contained in the previously established network of measurement points,
- performance of the modal parameter estimation model for the operational data set,
- based on estimated modal parameters of the model and additional collected transfer characteristics, formulation of the least-squares problem,
- solution to the problem of least squares, providing the scaling coefficients sought.

4. Experimental verification

The laboratory stand used for experimental validation of the proposed structural health monitoring procedure consists of a steel frame excited with an electrodynamic shaker. Vibrations were measured by accelerometers placed on the frame. A photo of the test setup without sensors and measuring equipment is presented in Figure 1, and the network of measuring points is presented in Figure 2.
In the course of experiment, time histories of the excitation force and accelerations of vibrations at each measuring point were recorded. As was established in the procedure, the data from the test were used to estimate both FRFs and cross-spectral densities (CSD). Both experimental and operational modal analyses were carried out. Table 1 presents the obtained modal parameters.

Table 6. Modal parameters of the laboratory stand

| MS no | EMA | OMA |
|------|-----|-----|
|      | N. f. [Hz] | Modal d. c. % | N. f. [Hz] | Modal d. c. % |
| 1    | 10.82 | 7.01 | 11.03 | 3.35 |
| 2    | 43.63 | 1.53 | 43.34 | 1.29 |
| 3    | 54.52 | 1.99 | 60.39 | 2.49 |
| 4    | 120.74 | 1 | 119.49 | 0.75 |
| 5    | 161.7 | 0.7 | 159.69 | 0.49 |
| 6    | 227.73 | 1.23 | 228.91 | 1.23 |

Next, 3 of the FRFs were used for operational modal model scaling. Scaled modal model was next used for FRFs synthesis and these FRFs were used for modal filter coefficients estimation. The results of such an operational modal filtration were compared with classical modal filtering. In Figure 3 comparison between FRFs measured and synthesized with use of described procedure is placed.

Figure 1. The Test Setup (photograph)  
Figure 2. Tested Structure Scheme – Laboratory Model of a Frame

Figure 3. Comparison of measured and synthesized FRFs
As is visible from the examples in Figure 3, the convergence between the measured and synthesized FRFs is acceptable except in the region of 2nd natural frequency. There is some problem in the data which means that the pole of the system does not stabilize for the same frequency – probably due to the sensor mass influence. The authors decided not to repeat the test while such a situation could happen during measurements for damage detection purposes and the method should be robust for such a phenomena. In Figure 4 the results of modal filtration with use of a classical modal filter and with use of an operational modal filter are compared.

![Figure 4](image.png)

**Figure 4.** Comparison of modal filtration with the use of classical and operational approaches

As is visible from the presented examples, the synthesized FRFs from a scaled operational modal model can be easily applied for modal filtration. Obtained results are almost identical to the ones from a classical modal filter. There are, of course, some differences in mode shape no. 3, but they do not disqualify the method, since the reason for that is in the measurements.

5. Final conclusions

The paper presents an attempt to construct an application for modal filtration with the use of output only data. The method is based on the replacement of originally measured FRFs (for which the excitation signal is required) with FRFs synthesized from the scaled operational modal model. The presented experimental verification showed that, with use of in-operational data and only one impulse FRF, there is a possibility of a modal filter construction with comparable results to the classical one. Since the modal filter can be applied in many fields (see Section 1), thanks to the proposed innovation all these applications will have a wider range.

In future work, the authors will test the applicability of an operational modal filter to damage detection and localization according to the procedure described in [27, 30].

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