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Modal screening of vibrating systems with local modes

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Abstract. This paper reports experience in using several Mode Indicator Functions for structures with local higher modes and heavy damping. The failure to locate all the modes of vibration for heavily damped structures is emphasized using a 15 degrees of freedom lumped parameter system.

Keywords: Mode Indicator Functions, CMIF, ImMIF, MMIF, CoMIF, QCoMIF.

1. Introduction

Modal screening is common in the first stages of a modal survey. Mode Indicator Functions (MIFs) and stability diagrams are used to detect the active modes in a given frequency band [1]. It is useful to assess the suitability of various MIFs in examining systems with various degrees of modal density, damping levels, and presence of local modes.

Some singular value and eigenvalue based MIFs use rectangular Frequency Response Function (FRF) matrices calculated in turn at each excitation frequency.

The *Complex Mode Indicator Function* (CMIF) is defined [2] by the singular values of the FRF matrix plotted as a function of frequency. It has peaks at the damped natural frequencies. In the *Imaginary Mode Indicator Function* (ImMIF), use of the singular values of the imaginary part instead of the complex FRF matrix has obvious advantages in the location of resonances.

The *Multivariate Mode Indicator Function* (MMIF) is defined [3] by the eigenvalues of a generalized problem involving the real and the imaginary parts of the FRF matrix plotted against frequency. There are as many curves in a plot as the number of references. They exhibit troughs at the undamped natural frequencies.

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The *Componentwise Mode Indicator Function* (CoMIF) is defined [4] by vectors computed as the difference between a column vector of ones and the element-by-element product of the left singular vectors of a compound FRF (CFRF) matrix having the FRFs as columns. The number of curves is equal to the effective rank of the CFRF matrix. The CoMIF has dips at the damped natural frequencies. The format with subplots of the individual CoMIFs is often preferred to the format with overlaid curves. The deepest trough in each subplot locates a mode of vibration.
The *Q-Vector Componentwise Mode Indicator Function* (QCoMIF) is defined [5] by vectors computed as the difference between a column vector of ones and the Hadamard product of the Q-vectors obtained from the pivoted QLP decomposition of the CFRF matrix. The QCoMIF has troughs at the damped natural frequencies.
All these MIFs work well for lightly damped structures.
This paper compares their performance in the case of a heavily damped system and reveals their failure to pinpoint all the resonances of systems with local modes.

2. Tested structure

The data used in this paper have been generated for the 15 degrees of freedom (DOF) system (Fig.1) analyzed by Yang and Brown [6], then by Li, Fladung, Phillips and Brown [7]. The small masses simulate the higher frequency mode phenomena that exist in physical systems.

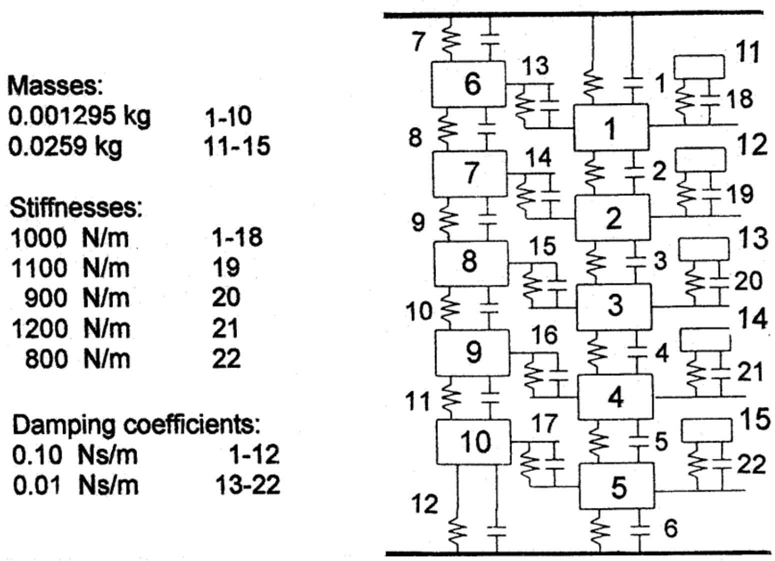

Fig. 1. 15 DOF system.

The five masses located on the right (numbered 11 to 15) are one order of magnitude (about 20 times) smaller than the others. This produces a cluster of five higher natural frequencies.

3. Natural frequencies and mode shapes

The damped natural frequencies and modal damping ratios are given in Table 1.

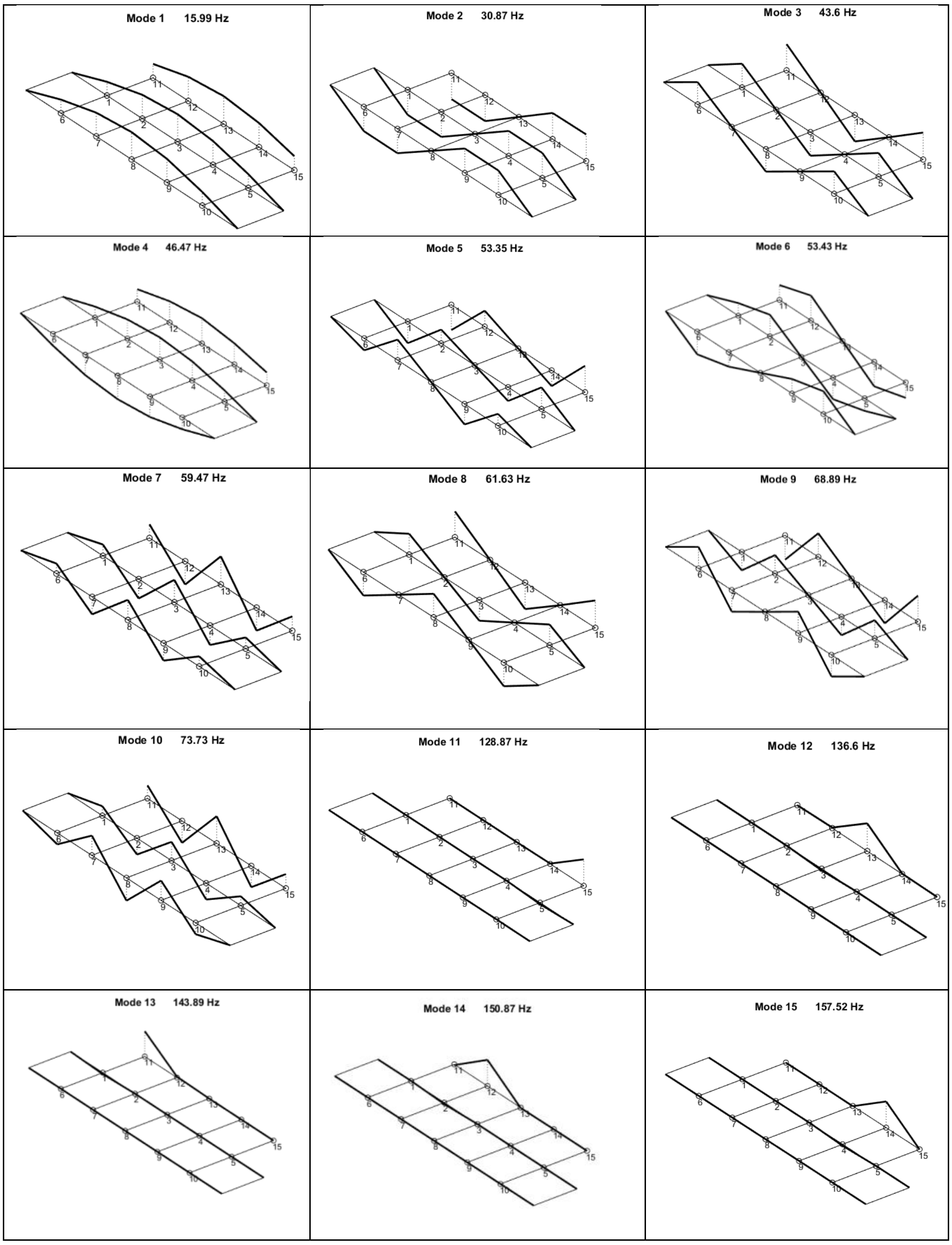

Fig. 2. Mode shapes of the 15 DOF system.

The analytical data set is constructed such that there are 10 modes of vibration in the frequency range 10-80 Hz and 5 modes between 120-160 Hz, with a quasi-repeated mode at about 53.4 Hz. The mode shapes are presented in Fig. 2.

Table 1. Eigenfrequencies and damping ratios of the lightly damped system

Mode	Natural frequency, Hz	Damping ratio, %	Mode	Natural frequency, Hz	Damping ratio, %
1	15.98	0.50	9	68.88	1.38
2	30.86	0.97	10	73.72	1.58
3	43.60	1.36	11	128.87	0.54
4	46.47	0.30	12	136.59	0.51
5	53.35	1.67	13	143.89	0.48
6	53.42	0.67	14	150.87	0.46
7	59.45	1.85	15	157.52	0.44
8	61.62	1.06			

The five high frequency modes, which are well separated from the main system modes, are the local modes.

4. Frequency response functions

MIFs are based on Frequency Response Functions. Complex receptance frequency response functions $FRFjk$ were computed for displacement at mass j produced by excitation at the mass k. Figure 3 shows the noise-free FRFs for excitation applied on mass 14 and response measured at masses 1 to 15, represented as magnitude (log scale) versus frequency (linear scale) plots.

5. MIFs for the lightly damped system

For the construction of MIFs, a simulated test data set was generated assuming that the system is excited on masses 11 and 14, and the response at all fifteen masses is “measured” at frequencies between 1-180 Hz, with 0.1 Hz frequency resolution.

Excitation in at least two points is required by the existence of the double-mode at about 53.4 Hz. Response “measurement” at all 15 masses is necessary to ensure the adequate definition of the mode shapes.

Excitation at masses 11 and 14 was selected based on the comparison of MIFs calculated for different pairs of points. It is obvious that construction of MIFs based on FRFs generated with excitation at more than two points enables a better location of resonances.

Generally, in all structural testing procedures, it is important to determine the modes that should be included in the analysis. A decision has to be made if it is necessary to locate all modes of vibration active in a frequency band, or only a few modes with dominant contribution to the response.

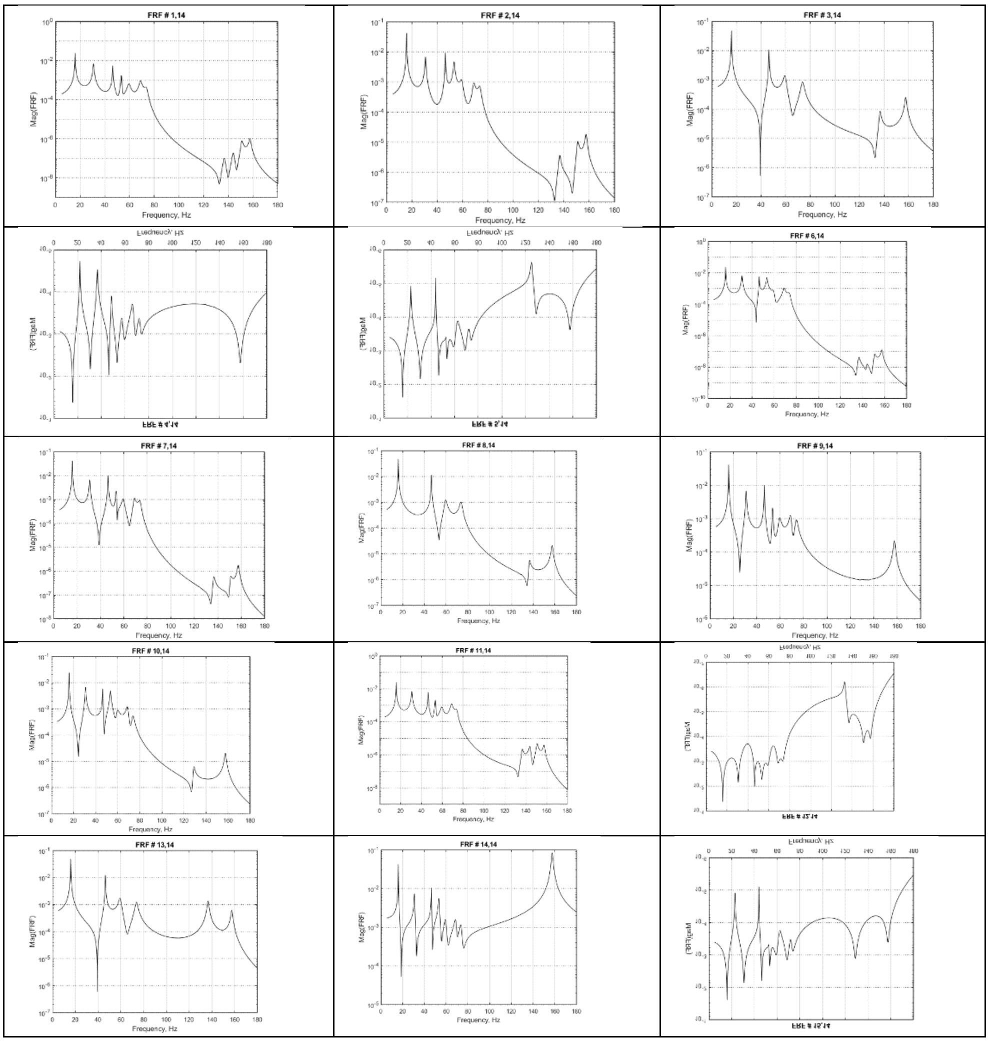

Fig. 3. FRF curves for excitation in 14.

Consider the 15 DOF system with damping coefficients as given in Fig.1, having modal damping ratios between 0.4-1.85 percent.

The Complex Mode Indicator Function (CMIF) of the 15x2 FRF matrix, with input in 11 and 14, and output in 1 to 15 is shown in Fig.4. The CMIF fails to locate three local modes, but reveals the double mode at about 53.4 Hz.

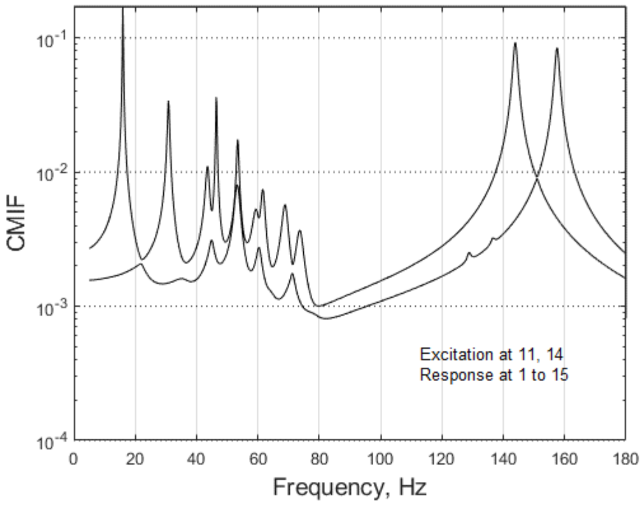

Fig. 4. CMIF plot for the lightly damped system.

The ImMIF plot, based on the SVD of the imaginary part of the FRF matrix, is shown in Fig.5. It outperforms the CMIF, locating all 15 resonances.

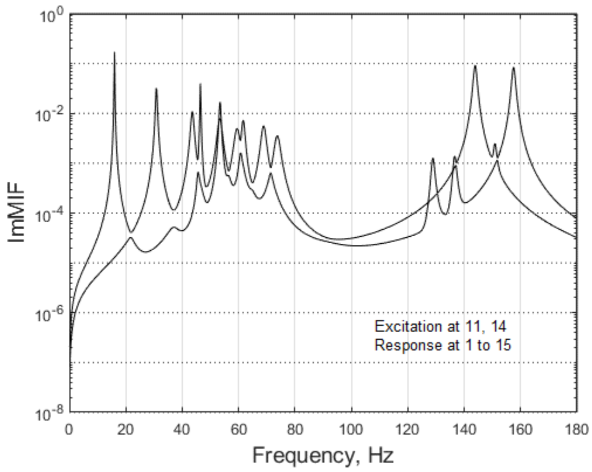

Fig. 5. ImMIF plot for the lightly damped system.

The MMIF plot is presented in Fig.6. It locates all 15 resonances. At about 53.4 Hz both curves have a minimum, indicating two closely coupled modes.

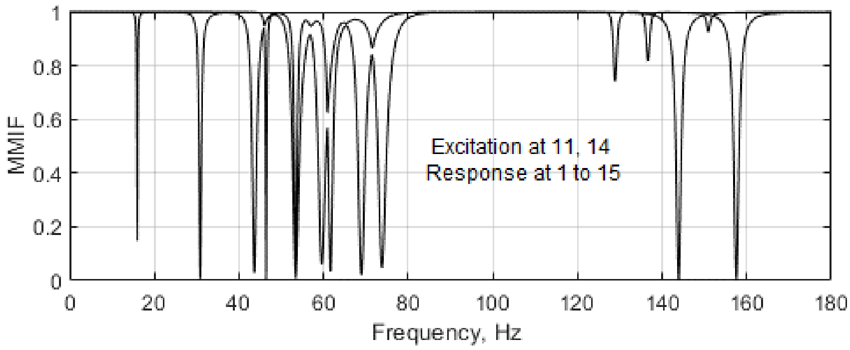

Fig. 6. MMIF plot for the lightly damped system.

The CoMIF with subplots is given in Fig.7. It locates all 15 resonances, but requires some skill to be interpreted.

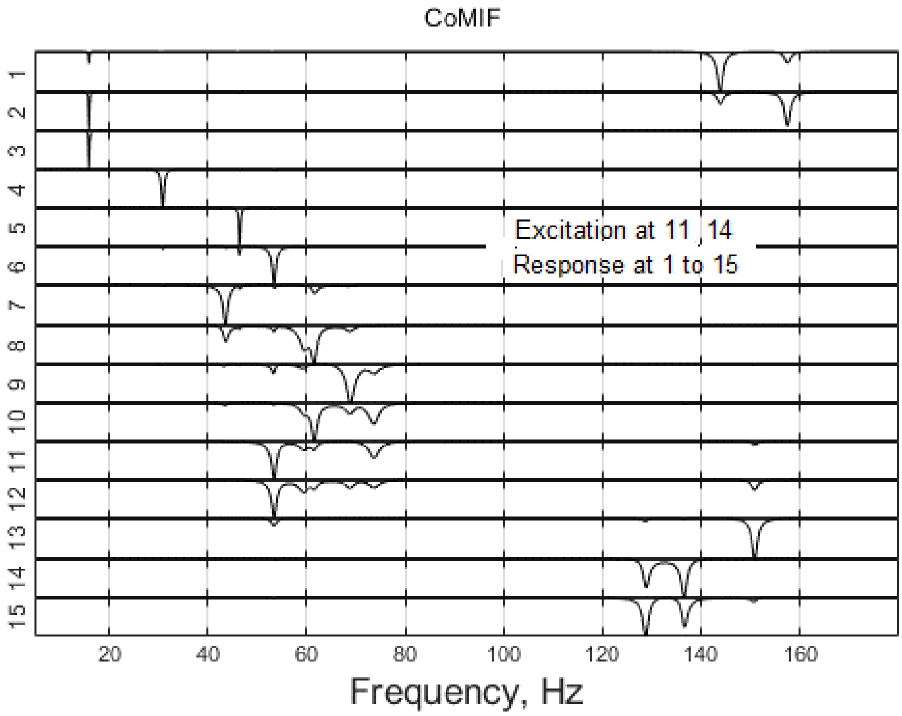

Fig. 7. CoMIF plot for the lightly damped system.

The QCoMIF plot is depicted in Fig.8. It locates all 15 resonances, but again requires some experience and a cursor to locate the resonance frequencies at dips.

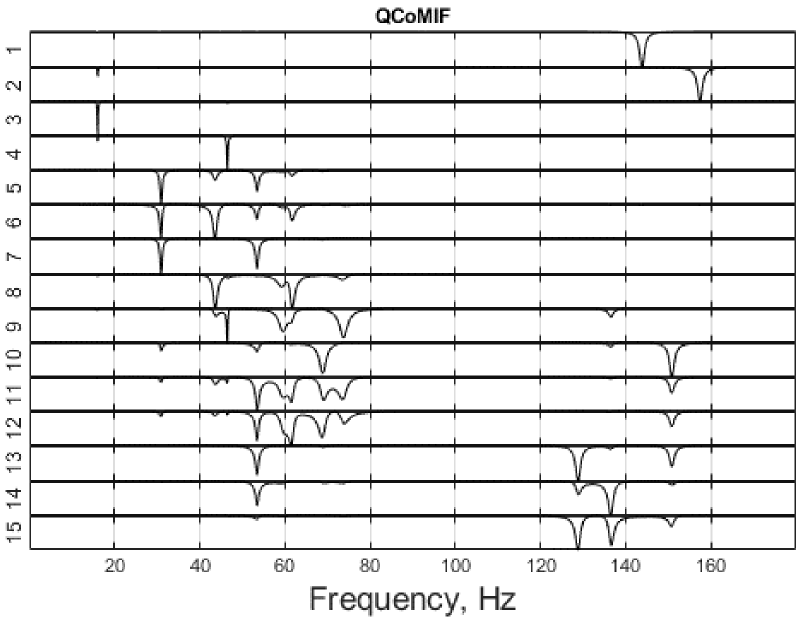

Fig. 8. QCoMIF plot for the lightly damped system and excitation in 11 and 14.

6. MIFs for the heavily damped system

Consider the 15 DOF system from Fig.1 in which the damping was increased by seven times [6]. As for the lightly damped system, FRFs have been generated assuming that the system is excited on masses 11 and 14, and the response is calculated at all fifteen masses. This amounts to a total of 30 FRFs calculated at frequencies between 1-180 Hz with 0.1 Hz frequency resolution.

Table 2. Eigenfrequencies and damping ratios of the heavily damped system.

Mode	Natural frequency, Hz	Damping ratio, %	Mode	Natural frequency, Hz	Damping ratio, %
1	15.98	3.51	9	68.57	9.67
2	30.79	6.78	10	73.28	11.05
3	43.41	9.55	11	128.75	3.76
4	46.49	2.11	12	136.49	3.54
5	53.00	11.67	13	14379	3.34
6	53.36	4.69	14	150.76	3.20
7	58.98	12.98	15	157.42	3.06
8	61.46	7.42			

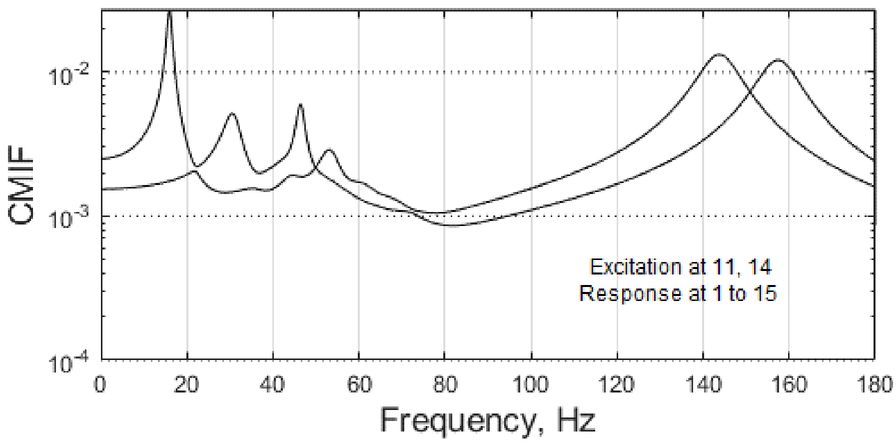

Fig. 9. CMIF plot for the heavily damped system.

The CMIF plot is shown in Fig.9. It locates only four global modes and two local modes, so it cannot be used as a reliable mode indicator.

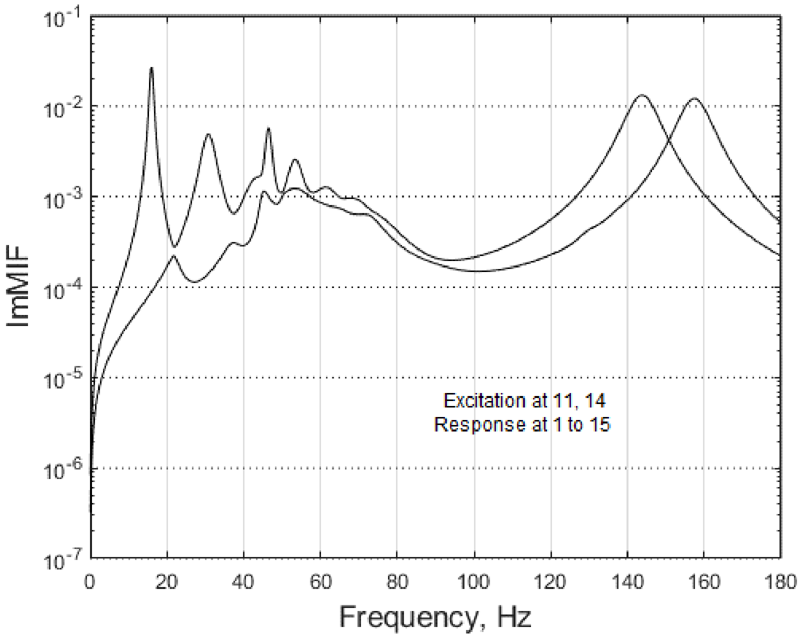

Fig. 10. ImMIF plot for the heavily damped system.

The ImMIF plot is presented in Fig.10. It locates only nine modes.

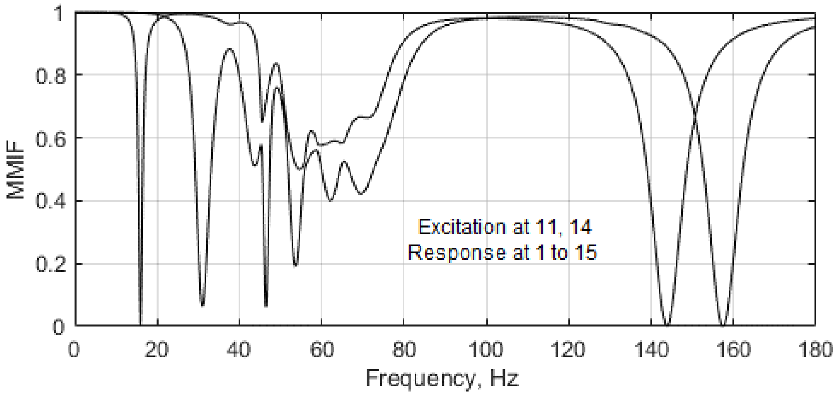

Fig. 11. MMIF plot for the heavily damped system.

The MMIF plot is depicted in Fig.11. It locates eight global modes, including the double mode at 53.4 Hz, and two local modes.

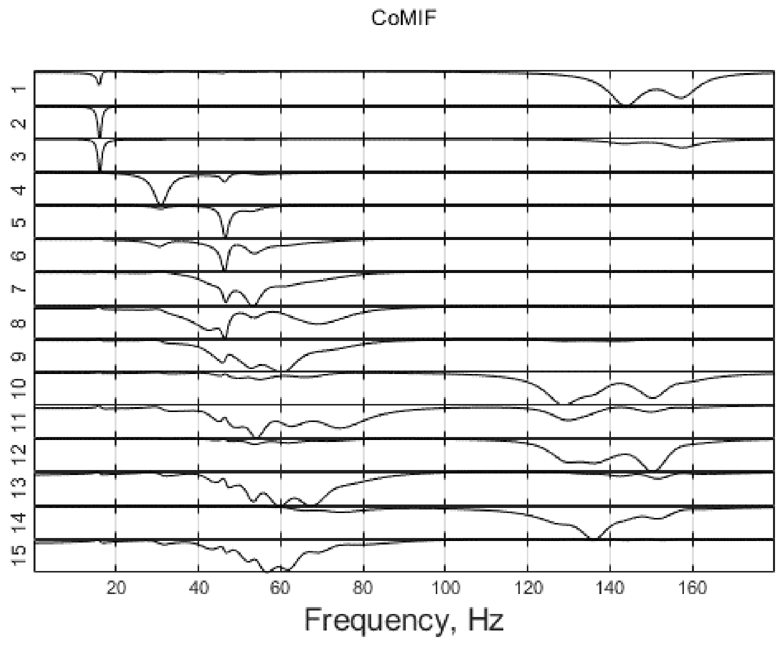

Fig. 12. CoMIF plot for the heavily damped system and excitation in 11 and 14.

The CoMIF with subplots is shown in Fig.12. It locates all 15 modes, but they are difficult to determine due to the existence of several dips at the same frequency even for the same mode.

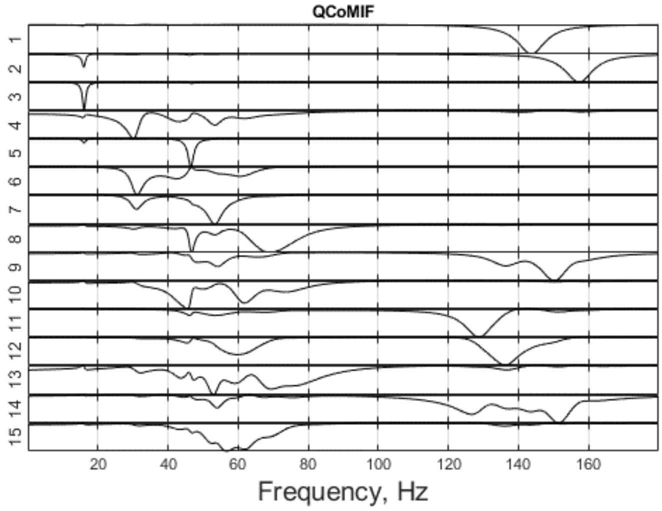

Fig. 13. QCoMIF plot for the heavily damped system and excitation in 11 and 14.

The same can be said about the QCoMIF plot presented in Fig.13. Modes have to be located looking for the deepest through in each subplot.

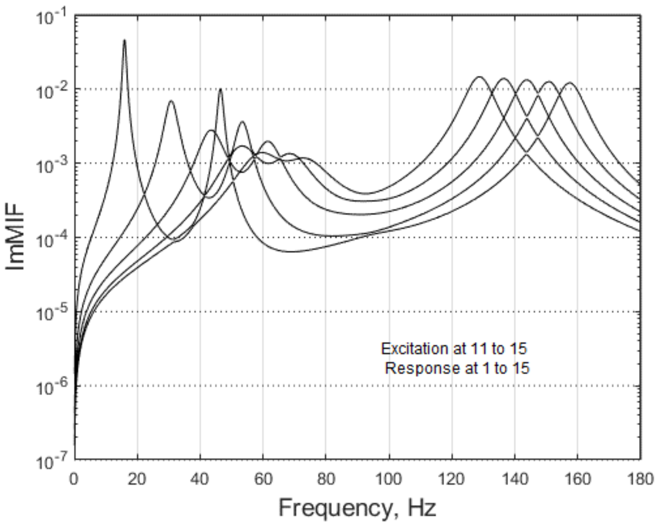

Fig. 14. ImMIF plot for the heavily damped system and excitation in five points.

Best results can be obtained using more excitation points The ImMIF plot based on the 5x15 FRF matrix for excitation on masses 11 to 15 is shown in Fig.14. It locates all five higher modes and nine global modes.

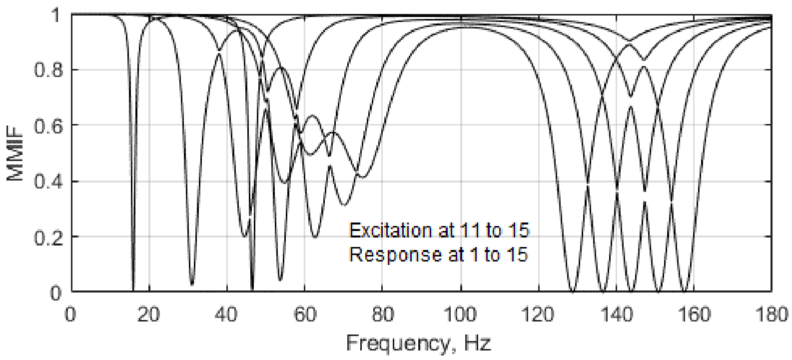

Fig. 15. MMIF plot for the heavily damped system and excitation in five points.

The MMIF plot based on the 5x15 FRF matrix, for excitation on masses 11 to 15, is shown in Fig.15. It locates 14 modes, including the double mode at about 53 Hz.

7. Concluding remarks

The aim of this paper was to document the ability of some MIFs to locate the resonances of a lightly damped system, in contrast with the failure of the same MIFs to locate the modes of a system with local modes and high damping. Their usefulness depends on the selection of the number and location of the input points.
The performance of all analyzed MIFs declines with high damping levels, especially in the presence of local modes of vibration. The only obvious way to improve their suitability is to use more excitation points, especially on the small masses responsible of the higher local modes.

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