RELIABILITY OF DYNAMIC AND HYBRID TESTS IN THE PRESENCE OF CONTROL ERRORS

Francisco Javier Molina[1], Pierre Pegon[2], and Georges Magonette[3]

ABSTRACT

The deleterious effect of control errors in the obtained response for shaking-table, pseudo-dynamic and hybrid tests can be quantified in a standard way by assessing the frequency and damping distortion in the obtained response as identified from equivalent linear models. The identified linear models are based only on the measurements done during the experiment, which increases the generality and applicability of the proposed strategy.

INTRODUCTION

Dynamic simulation experiments on structures are normally based on the use of hydraulic actuators that can apply large loads, displacements and velocities. However, this actuation system is subject to systematic control errors that can significantly modify the obtained response producing alterations in the apparent frequencies and damping. These effects, which are not predictable just by looking at the magnitude of the control errors, have been observed for pseudo-dynamic (PsD) and hybrid tests (Shing and Mahin 1987, Thewalt and Roman 1994, Molina et al. 2002, Mosqueda et al. 2007) as well as for shaking-table (ST) tests (Molina et al. 2008) and different specific strategies have been proposed for their assessment. The possibility of developing common reliability assessment criteria for all those different kinds of test would offer tools for increasing the credibility of test results by means of standard quality control parameters. A first step in that direction has been done regarding PsD and ST tests (Molina et al. 2009) and based on the comparison of the obtained experimental eigenfrequencies and damping ratios with the ones of the ideal prototype structure. Those frequencies and damping ratios are estimated by means of linear models that approximate both the experimental system and the prototype one and are always identified exclusively from the results of the test in question, assuming that all the excitations really acting on the specimen during the test are properly measured. In this paper, such assessment strategy is extended to PsD tests with substructuring and to real-time hybrid tests.

Within that general approach, it is considered that the testing set-up models a prototype structure under certain conditions, ideally represented by the equation

$$o(t) = F\left\{i(t)\right\} \qquad (1)$$

where $i(t)$ is the specified input (excitation) as a function of time t, $o(t)$ is the corresponding output (response) and $F\{\}$ is ideally the functional operator of the prototype system that produces the output function when applied to the input function. The performed response during

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[1] *European Laboratory for Structural Assessment (ELSA), IPSC, JRC, European Commission, Ispra, Italy*
[2] *European Laboratory for Structural Assessment (ELSA), IPSC, JRC, European Commission, Ispra, Italy*
[3] *European Laboratory for Structural Assessment (ELSA), IPSC, JRC, European Commission, Ispra, Italy*

the test $o^{perf}(t)$ will be different to the ideal prototype one, so that, for the experimental model, expression (1) is transformed into

$$o^{perf}(t) = F^{exp}\left\{i^{perf}(t)\right\} \tag{2}$$

where the operator of the prototype system has been substituted by the one of the experimental system. Even though the test can be performed in a different scale regarding the time or other magnitudes, the variables in expressions (1) and (2) are all referred to the original prototype scale. Then, the reliability of the test will be assessed by the fidelity in the reproduction of the ideal response by the performed response or, preferably, by the fidelity in the reproduction of the ideal operator of the prototype system by the experimental system operator

When a test is executed, the performed input and output in (2) are part of the test results, but normally the entities appearing in expression (1) are not known and the reliability of the test is not assessed. In the following sections, we will propose methods for assessing the test reliability based on the estimation and comparison of the functional operators for the prototype and for the experimental systems by using linear-equivalent models identified from the measurements. Then, the reliability of the test will be assessed by comparing some characteristic values, such as eigenfrequencies and damping ratios, for both systems. It is worth to mention that a similar technique is done for example when analysing the accuracy of discrete-time integration methods for the equation of motion as compared to the continuous ideal solution. As it is done also there, those characteristic values are obtained for linear systems that are expected to suffer the same kind of error consequences as the real non-linear structures (Hilber et al., 1977). As a difference with respect to that case, the current assessment is proposed here to be applied to every executed simulation and not to the method itself.

PSEUDO-DYNAMIC TEST

The object of a PsD test is solving a seismic problem for a N-DoF structure, for which the input is the specified accelerogram $\mathbf{a_g}(t)$ and the output is the relative displacements $\mathbf{d}(t)$. The functional operator in (1) is defined as the one that solves the equation of motion, which for the purpose of the proposed assessment is approximated by a linear one and expressed in the Laplace domain as

$$\mathbf{M}s^2\mathbf{D}(s) + \mathbf{R}(s) = \mathbf{M}s^2\mathbf{D}(s) + \mathbf{C}s\mathbf{D}(s) + \mathbf{K}\mathbf{D}(s) = -\mathbf{MJA_g}(s) \tag{3}$$

where $\mathbf{M}$ is the mass matrix that multiplies the relative accelerations, $\mathbf{R}(s)$ are the restoring forces that depend non-linearly on the history of displacements and velocities and $\mathbf{J}$ is the matrix of influence for the ground acceleration components on the DoFs.

Expression (3) can also be rewritten as

$$\mathbf{D}(s) = \left[\mathbf{M}s^2\right]^{-1}\left[-\mathbf{MJA_g}(s) - \mathbf{R}(s)\right] \tag{4}$$

Corresponding to the diagram of Fig. 1

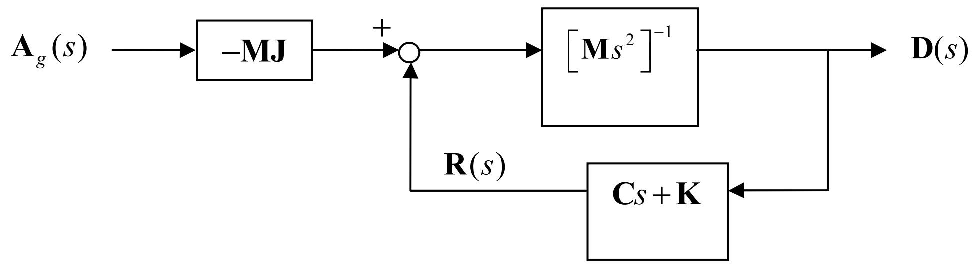

Fig. 1. Prototype system for a linear seismic problem.

Working with linear systems in the Laplace domain, the application of the operator to give the solution of the equation consists of a multiplication of the excitation by the transfer function between the input and the output

$$\mathbf{D}(s) = \mathbf{F}(s)\mathbf{A}_{\mathbf{g}}(s) \quad (5)$$

which substitutes (1). The poles of this transfer function can be obtained by solving the eigenvalue problem (Ewins, 1984)

$$s\begin{bmatrix} \mathbf{C} & \mathbf{M} \\ \mathbf{M} & \mathbf{0} \end{bmatrix}\boldsymbol{\varphi} + \begin{bmatrix} \mathbf{K} & \mathbf{0} \\ \mathbf{0} & -\mathbf{M} \end{bmatrix}\boldsymbol{\varphi} = \mathbf{0} \quad (6)$$

which complex conjugate eigenvalue couples can then be expressed in the form

$$s_i, s_i^* = \omega_i(-\zeta_i \pm j\sqrt{1-\zeta_i^2}) \quad (7)$$

where ω_i is the natural frequency and ζ_i the damping ratio of the i^{th} mode.

In this section we will consider the case of a PsD test on a global specimen (that contains all the elements of the system) and we will try to analyse the discrepancies in the response introduced exclusively by the control errors. Thus, we will not consider here other aberrations such as the ones introduced by the application of a discrete number of DoFs (mass concentration) or by neglecting the strain-rate effect. Also the alterations in the response introduced by the discrete-time integration method will not be considered. In fact, the latter alterations are completely negligible when using the continuous PsD technique that uses extremely small integration time steps (Pegon et al. 2008).

Within such assumptions, the linear-equivalent system of the prototype structure can be represented as in the diagram of Fig. 1, while the one of the PsD experiment can be represented as in Fig. 2. In both diagrams, the time and the Laplace variable are in the scale of the prototype in order to facilitate the comparison, independently of the fact that the PsD test is done slower than the reality.

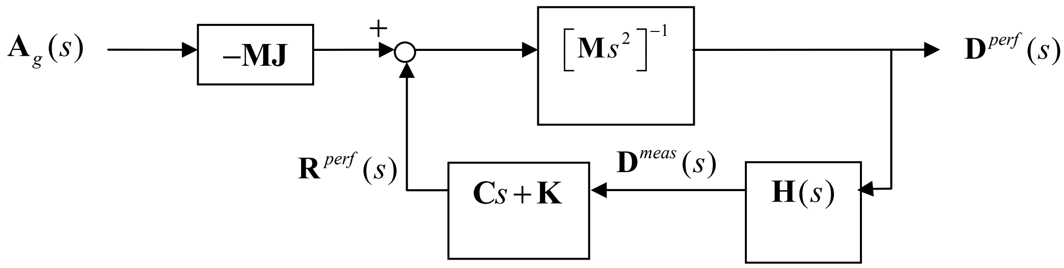

Fig. 2. Linear-equivalent experimental system for a PsD test.

According to the definition (2), the solution of the PsD equation of motion will be called performed displacement

$$\mathbf{D}^{perf}(s) = \mathbf{F}^{exp}(s)\mathbf{A}_{\mathbf{g}}(s) \tag{8}$$

in order to distinguish it from the one of the prototype system (5). However, the physic displacements that are measured during the test are

$$\mathbf{D}^{meas}(s) = \mathbf{H}(s)\mathbf{D}^{perf}(s) \tag{9}$$

where $\mathbf{H}(s)$ is the transfer function of the control system that imposes the displacements to the specimen normally by hydraulic actuators. This transfer function depends on the controller type and parameters, on the actuators, on the specimen and also on the testing speed (Molina et al. 2002). Because the physic displacement of the specimen are different from the solved ones, the physic restoring forces which are measured and introduced in the PsD equation obey to the relationship

$$\mathbf{R}^{perf}(s) = \mathbf{C}s\mathbf{D}^{meas}(s) + \mathbf{K}\mathbf{D}^{meas}(s) = \left[\mathbf{C}\mathbf{H}(s)s + \mathbf{K}\mathbf{H}(s)\right]\mathbf{D}^{perf}(s) \tag{10}$$

However, in order to simplify this formulation, we will substitute expression (10) by the approximation

$$\mathbf{R}^{perf}(s) = \left[\mathbf{C}^{perf}s + \mathbf{K}^{perf}\right]\mathbf{D}^{perf}(s) \tag{11}$$

And then, approximately, the diagram in Fig. 2 will be substituted by the one in Fig. 3, corresponding to the equation

$$\mathbf{M}s^2\mathbf{D}^{perf}(s) + \mathbf{R}^{perf}(s) = \left[\mathbf{M}s^2 + \mathbf{C}^{perf}s + \mathbf{K}^{perf}\right]\mathbf{D}^{perf}(s) = -\mathbf{MJA}_{\mathbf{g}}(s) \tag{12}$$

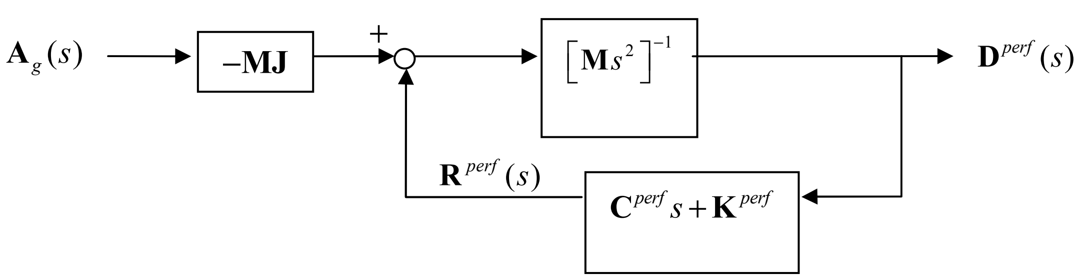

Fig. 3. Approximation of the experimental system based on the performed damping and stiffness matrices.

The assessment of the test reliability will be done by comparing the characteristics of the experimental transfer function with the ones of the prototype transfer function. To do so, the method that we propose consists of making estimations of the matrices entering in these formulae by using the results of the performed test without introducing any analytical model for the structure or for the control system. In fact, just using the variables that are available during the test (Fig. 2), we can establish the relationship

$$\mathbf{R}^{perf}(s) = \left[\mathbf{C}s + \mathbf{K}\right]\mathbf{D}^{meas}(s) \tag{13}$$

That we use in the time domain as

$$\mathbf{r}^{perf}(t) = \mathbf{C}\,\dot{d}^{meas}(t) + \mathbf{K}d^{meas}(t) \tag{14}$$

In order to identify the damping and stiffness matrices of the prototype $\mathbf{C}$ and $\mathbf{K}$ by means of the spatial model method (Molina et al. 1999). The eigenvalue problem (6) is applied to such identified matrices in order to solve the frequencies and damping ratios of the prototype (7). Then, by using always only variables accessible during the test, from the established relationship (11), working again with the time domain spatial model identification, the performed damping and stiffness matrices of the experimental model $\mathbf{C}^{perf}$ and $\mathbf{K}^{perf}$ are identified from

$$\mathbf{r}^{perf}(t) = \mathbf{C}^{perf}\,\dot{d}^{perf}(t) + \mathbf{K}^{perf}d^{perf}(t) \tag{15}$$

and with them the eigenvalue problem

$$s\begin{bmatrix}\mathbf{C}^{perf} & \mathbf{M}\\ \mathbf{M} & \mathbf{0}\end{bmatrix}\boldsymbol{\varphi} + \begin{bmatrix}\mathbf{K}^{perf} & \mathbf{0}\\ \mathbf{0} & -\mathbf{M}\end{bmatrix}\boldsymbol{\varphi} = \mathbf{0} \tag{16}$$

is formulated, and its solution

$$s_i^{exp}, s_i^{exp*} = \omega_i^{exp}(-\zeta_i^{exp} \pm j\sqrt{1-\zeta_i^{exp2}}) \tag{17}$$

gives the experimental frequency and damping values. Finally, the reliability of the experiment is assessed by comparing these experimental values (17) with the ones estimated for the prototype (15). This assessment has been regularly applied to the PsD tests performed in the ELSA laboratory for several years (Molina and Geradin 2007).

PSEUDO-DYNAMIC TEST WITH SUBSTRUCTURING

When the PsD test is performed for a system of substructures, if we consider only the errors introduced by the control system as in the previous section, for the linear-equivalent modelling, equation (3) and Fig. 1 can still describe the global prototype system. In the same way, Fig. 2 can describe the global experimental system that will be approximated by (12) and Fig. 3.

In order to fix ideas, we will assume that the prototype system is made of a first substructure called A and a second substructure called B. Thus, from the solved global vector of displacement $\mathbf{D}(s)$, the respective displacements of the substructures $\mathbf{D}_A(s)$ and $\mathbf{D}_B(s)$ are derived by compatibility. Then, for the first substructure, we have that the respective restoring force is given by

$$\mathbf{R}_A(s) = [\mathbf{C}_A s + \mathbf{K}_A]\mathbf{D}_A(s) \tag{18}$$

And for the second substructure

$$\mathbf{R}_B(s) = [\mathbf{C}_B s + \mathbf{K}_B]\mathbf{D}_B(s) \tag{19}$$

The global vector of restoring forces $\mathbf{R}(s)$ is then assembled from $\mathbf{R}_A(s)$ and $\mathbf{R}_B(s)$ by equilibrium. Also the global matrices of damping and stiffness can be assembled from the ones of the substructures by compatibility and equilibrium and we will symbolically represent this by

$$\mathbf{C} = \mathbf{C}_A \oplus \mathbf{C}_B \; ; \; \mathbf{K} = \mathbf{K}_A \oplus \mathbf{K}_B \tag{20}$$

We will assume that in the PsD test the first substructure A is experimental, while the second one B is numerical. Thus, similarly to the previous section (Fig. 2), the displacements solved for the experimental substructure will be applied to it through the control system that will introduce a distortion producing the measured displacements

$$\mathbf{D}_A^{meas}(s) = \mathbf{H}_A(s)\mathbf{D}_A^{perf}(s) \tag{21}$$

and then, similarly to (10)

$$\mathbf{R}_A^{perf}(s) = \mathbf{C}_A s\mathbf{D}_A^{meas}(s) + \mathbf{K}_A\mathbf{D}_A^{meas}(s) = \left[\mathbf{C}_A\mathbf{H}_A(s)s + \mathbf{K}_A\mathbf{H}_A(s)\right]\mathbf{D}_A^{perf}(s) \tag{22}$$

This means that the submatrices of damping and stiffness relative to the experimental substructure can be identified from the time domain expression containing the results of the test

$$\mathbf{r}_A^{perf}(t) = \mathbf{C}_A \dot{d}_A^{meas}(t) + \mathbf{K}_A d_A^{meas}(t) \tag{23}$$

Because in the numerical substructure there are no control errors, we do not need to distinguish between performed and measured displacements and so

$$\mathbf{R}_B^{perf}(s) = \mathbf{C}_B s\mathbf{D}_B^{perf}(s) + \mathbf{K}_B\mathbf{D}_B^{perf}(s) \tag{24}$$

Then, if the numerical substructure is linear, its relative matrices of damping and stiffness are already known. Otherwise, they can be identified analogously from the time domain expression containing the test results as

$$\mathbf{r}_B^{perf}(t) = \mathbf{C}_B \dot{d}_B^{perf}(t) + \mathbf{K}_B d_B^{perf}(t) \tag{25}$$

Using the identified matrices from (23) and (25), the global matrices are assembled according to (20). Then, by formulating the eigenvalue problem (6), the natural frequencies of the prototype system (7) are solved

On the other hand, regarding the experimental system, according to Fig. 3 and similarly to (11), we will approximate (22) by

$$\mathbf{R}_A^{perf}(s) = \left[\mathbf{C}_A^{perf} s + \mathbf{K}_A^{perf}\right]\mathbf{D}_A^{perf}(s) \tag{26}$$

so that the performed matrices for the experimental substructure will be identified in the time domain using the relationship

$$\mathbf{r}_A^{perf}(t) = \mathbf{C}_A^{perf}\,\dot{d}_A^{perf}(t) + \mathbf{K}_A^{perf}\,d_A^{perf}(t) \tag{27}$$

Then, the already identified matrices for the numerical substructure from (25) can be considered to be the performed ones since no experimental errors distort the behaviour of this part of the structure. That is to say,

$$\mathbf{C}_B^{perf} = \mathbf{C}_B \quad ; \quad \mathbf{K}_B^{perf} = \mathbf{K}_B \tag{28}$$

and it is possible now to assemble, like in (20), the global performed matrices of the test

$$\mathbf{C}^{perf} = \mathbf{C}_A^{perf} \oplus \mathbf{C}_B^{perf} \;;\; \mathbf{K}^{perf} = \mathbf{K}_A^{perf} \oplus \mathbf{K}_B^{perf} \tag{29}$$

That allows formulating the eigenvalue problem (16), which solution are the natural frequencies and damping ratios of the experimental system (17). Then, by comparison of these values (17) with the ones of the prototype system (7), the reliability of the performed test is assessed.

REAL-TIME HYBRID TEST

When the test is performed at real-time speed, the term PsD is not used anymore and it is simply called real-time hybrid test. Even though for this kind of test, the numerical errors introduced by the integration algorithm can be significant and represent a major issue depending on the type of algorithm (Shing 2008). We will consider that those errors are assessed separately by other techniques and shown to be negligible, so that our error assessment will continue to be limited to the control errors effects.

As in the previous subsection, we will consider that, for the linear equivalent modelling, equation (3) and Fig. 1 describe the global prototype system. However, with respect to the previous sections, we will introduce two novelties that may be relevant for real-time tests. Firstly, testing at real time, the physical mass of the specimen $\mathbf{M}^{phy}$ produces inertial forces that modify the measurement of the restoring forces, so that, instead of (10),

$$\mathbf{R}^{meas}(s) = \mathbf{M}^{phy} s^2 \mathbf{D}^{meas}(s) + \mathbf{C}s\mathbf{D}^{meas}(s) + \mathbf{K}\mathbf{D}^{meas}(s) \tag{30}$$

And this is also the reason for which, in the hybrid equation of motion

$$\mathbf{M}^{an} s^2 \mathbf{D}^{perf}(s) + \mathbf{R}^{meas}(s) = -\mathbf{MJA_g}(s) \tag{31}$$

a reduced analytical mass $\mathbf{M}^{an}$ is used instead of the total presumed mass $\mathbf{M}$. Ideally, the analytical mass should be

$$\mathbf{M}^{an} = \mathbf{M} - \mathbf{M}^{phy} \tag{32}$$

however the exact value of $\mathbf{M}^{phy}$ is not known.

Secondly, because the effects of the control errors in real-time tests can be very severe, typically, the target sent to the controller is not the solved displacement $\mathbf{D}^{perf}(s)$ from the equation of motion (31), but a modification of it obtained by applying a compensation numerical filter

$\mathbf{H}^{comp}(s)$ that should, at least partially, neutralise the distortion that will be introduced afterwards by the control (e.g. Hiuruchi et al. 1999). Thus, the target displacement is computed as

$$\mathbf{D}^{targ}(s) = \mathbf{H}^{comp}(s)\mathbf{D}^{perf}(s) \tag{33}$$

And then, because of the control errors, the obtained measured displacement is

$$\mathbf{D}^{meas}(s) = \mathbf{H}(s)\mathbf{D}^{targ}(s) \tag{34}$$

where $\mathbf{H}(s)$ is the transfer function of the control system.

Thus, the flux diagram for this type of text, after equations (30) to (34), can be the one shown in Fig. 4.

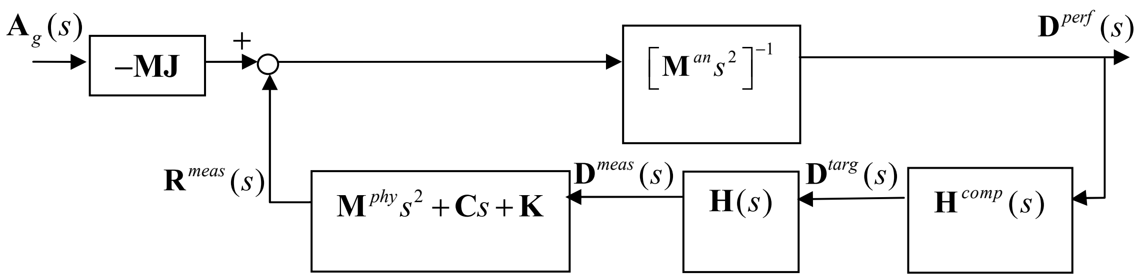

Fig. 4. Linear-equivalent experimental system for a real-time hybrid test.

The measured restoring forces, by combining (30), (33) and (34), can be expressed as

$$\mathbf{R}^{meas}(s) = \left[\mathbf{M}^{phy}s^2 + \mathbf{C}s + \mathbf{K}\right]\mathbf{H}(s)\mathbf{H}^{comp}(s)\mathbf{D}^{perf}(s) \tag{35}$$

However, as in the previous sections, we will introduce an approximation of the type

$$\mathbf{R}^{meas}(s) = \left[\mathbf{M}^{meas}s^2 + \mathbf{C}^{perf}s + \mathbf{K}^{perf}\right]\mathbf{D}^{perf}(s) \tag{36}$$

so that, equation (31) becomes

$$\left[\left(\mathbf{M}^{an} + \mathbf{M}^{meas}\right)s^2 + \mathbf{C}^{perf}s + \mathbf{K}^{perf}\right]\mathbf{D}^{perf}(s) = -\mathbf{MJA_g}(s) \tag{37}$$

that can be represented by the diagram in Fig. 5, where we define

$$\mathbf{M}^{perf} = \mathbf{M}^{an} + \mathbf{M}^{meas} \tag{38}$$

and

$$\mathbf{R}^{perf}(s) = \left[\mathbf{C}^{perf}s + \mathbf{K}^{perf}\right]\mathbf{D}^{perf}(s) \tag{39}$$

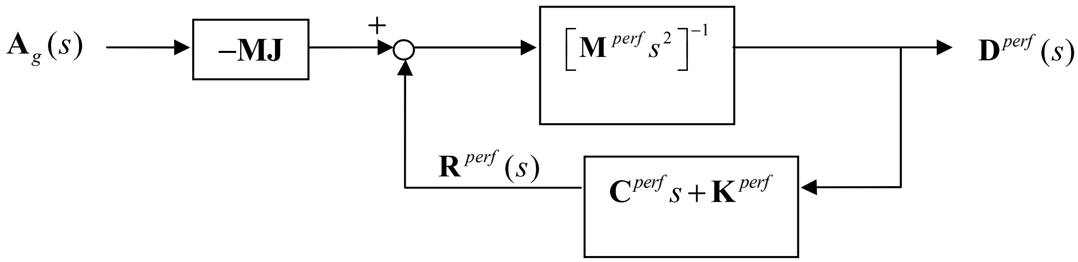

Fig. 5. Approximation of the experimental system based on the performed matrices of mass, damping and stiffness.

As in the previous section, we will consider that the structure is divided into two substructures of which A is the experimental one and B is the analytical one. Then, the required matrices for the linear approximation of the prototype and of the experimental systems will be estimated separately for each substructure also here. Thus, from the time domain version of (30) for the experimental substructure,

$$\mathbf{r}_A^{meas}(t) = \mathbf{M}_A^{phy}\ddot{d}_A^{meas}(t) + \mathbf{C}_A\dot{d}_A^{meas}(t) + \mathbf{K}_A d_A^{meas}(t) \tag{40}$$

The associated ideal matrices $\mathbf{M}_A^{phy}$, $\mathbf{C}_A$ and $\mathbf{K}_A$ can be estimated, whereas, for the analytical substructure, the physical mass is null and the damping and stiffness matrices, if necessary, can be estimated from

$$\mathbf{r}_B^{perf}(t) = \mathbf{C}_B\dot{d}_B^{perf}(t) + \mathbf{K}_B d_B^{perf}(t) \tag{41}$$

Since for this substructure there is no difference between performed, target and measured displacements. The global matrices are then obtained by assembling (20) and

$$\mathbf{M}^{phy} = \mathbf{M}_A^{phy} \oplus \mathbf{M}_B^{phy} \tag{42}$$

where

$$\mathbf{M}_B^{phy} = \mathbf{0} \tag{43}$$

Note that this estimated value of the physical mass (42) may eventually be used for updating the adopted value of the analytical mass as (32) for successive executions of the test with the same specimen. With the assembled matrices of damping and stiffness, plus the theoretical mass matrix, the prototype eigenvalue problem (6) can be formulated and solved as (7).

Now, regarding the experimental system, the time domain version of equation (36)

$$\mathbf{r}_A^{meas}(t) = \mathbf{M}_A^{meas}\ddot{d}_A^{perf}(t) + \mathbf{C}_A^{perf}\dot{d}_A^{perf}(t) + \mathbf{K}_A^{perf} d_A^{perf}(t) \tag{44}$$

Allows to estimate the involved matrices for the specimen substructure, whereas for the numerical substructure, we have (28) and

$$\mathbf{M}_B^{meas} = \mathbf{0} \tag{45}$$

Thus, the global matrices are assembled following (29) and

$$\mathbf{M}^{meas} = \mathbf{M}_A^{meas} \oplus \mathbf{M}_B^{meas} \tag{46}$$

And the global performed mass is given by (38). This allows formulating the eigenvalue problem associated to the experimental system of Fig. 5 as

$$s\begin{bmatrix} \mathbf{C}^{perf} & \mathbf{M}^{perf} \\ \mathbf{M}^{perf} & \mathbf{0} \end{bmatrix}\boldsymbol{\varphi} + \begin{bmatrix} \mathbf{K}^{perf} & \mathbf{0} \\ \mathbf{0} & -\mathbf{M}^{perf} \end{bmatrix}\boldsymbol{\varphi} = \mathbf{0} \tag{47}$$

Again, the reliability of the performed experiment is assessed by comparing these experimental eigenfrequencies and damping ratios with the estimated ones for the prototype system.

CONCLUSIONS

This paper is a contribution to the definition of a general approach for the assessment of reliability in PsD, dynamic and hybrid tests regarding the disturbances of the ideal response of the specimens due to the presence of control errors. The assessment is done through the comparison of the experimental response eigenfrequencies and damping ratios with the ones of the prototype structure. All the required parameters are estimated using exclusively experimental information from the test. The systematic application of this type of assessment to structural experiments would increase the reliability of their results.

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