Determination of dynamic contact forces for MDOF-structures

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1 Introduction

In case of coupling an active source with a passive receiver dynamic forces are transmitted between both components. For many industrial purposes considering multi degree of freedom (MDOF) systems, the knowledge of the transmitted forces for each degree of freedom is of particular interest, e.g. in order to describe the equivalent source strengths or to evaluate the most excitation directions of a given setup. However, within technical structures direct force determination often is difficult or not possible. Thus for instance, a non-reactive implementation of transducers within existing assemblies usually is not feasible due to the physical design, the functionality of the assembly and/or the influence on the contact stiffness. Furthermore, the increasing incentive for manufacturers of all types of machinery these days, to predict contributions of contact forces for virtual assemblies of existing components necessitates other approaches. This paper deals with an indirect method permitting a practical estimation of dynamic contact forces for MDOF systems solely by the use of quantities measured on separated substructures, i.e. there is no need to connect the active source and the passive receiver for measurements.

2 Theoretical background

The main idea of the applied method is to calculate dynamic contact forces $\{f_c\}$ for virtual assemblies by using characteristic quantities measured at corresponding points on its uncoupled substructures. Therefore, different sets of data are required. The first set accounts for the dynamic characteristics of both substructures by measuring the source $[Y_s]$ and receiver $[Y_r]$ mobility. A second data set is needed to include the activity of the source, for this purpose the free velocity $\{v_{sf}\}$ of the separated source operating under the same conditions as in case of coupling is measured. The resulting dynamic contact forces in the frequency domain can be written in terms of these quantities [2]:

$$\{f_c\} = \left[\, [Y_s] + [Y_r] \,\right]^{-1} \{v_{sf}\} \qquad \text{[N]} \qquad (1)$$

Since loading does affect the inner source generation mechanisms, which might be the case for technical components like motors, fans, pumps, etc., a characterization of the source activity by measuring blocked forces is more feasible. Due to the required connection to an infinitely rigid base the component in this case can be loaded, e.g. by applying a holdback torque at a motor shaft or the like. Substituting the free velocity term of equation (1) by the mobility matrix and the vector of blocked forces $\{f_{sb}\}$ of the uncoupled source, the dynamic contact force vector then is given as:

$$\{f_c\} = \left[\, [Y_S] + [Y_R] \,\right]^{-1} [Y_S]\,\{f_{sb}\} \qquad \text{[N]} \qquad (2)$$

This paper solely deals with non load-dependent, artificial excitations wherefore only the free velocity approach of equation (1) is treated.

3 Determination of dynamic forces

In the following a prediction of dynamic contact forces is demonstrated for a simple SDOF structure (Fig.1a) as well as for an electrical steering system (EPS) to represent a real technical MDOF structure (Fig.1b).

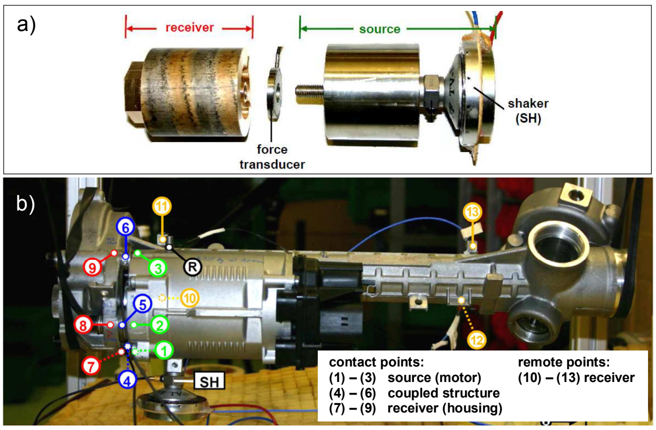

Figure 1: Test setups for prediction of contact forces: a) idealised SDOF system for validation purpose b) technical MDOF-structure (EPS) with artificial excitation

In the first case a test setup consisting of a brass cylinder as receiver and a steel cylinder attached to a mini shaker as source was employed. The components were designed to have a mass-like behaviour in the frequency range of interest (100Hz – 3000 Hz) allowing to calculate its dynamics like point mobility $Y=1/(i\omega m)$. This setup was used as a validation of equation (1) in general.

In the latter case an electrical steering system was investigated and the aim was to obtain the forces acting between the electrical motor and the steering housing. This involves 3 connection points with 3 translational forces at each point yielding 9 DOFs. The influence of moments was neglected at this stage of the investigation. Artificial shaker excitation instead of a real operating motor was chosen to prevent possible load-dependent errors.

For both cases direct contact force measurements are required to validate the predicted force spectra. To acquire proper validation data great care on direct force measurement was bestowed. Thus, in order to prevent rocking, all measurements were carried out by inserting extra thin, flat single direction Kistler force transducers. For MDOF examinations two different sensor models (axial and transversal) were used, alternating in consideration of consistent mounting and operation conditions.

3.1 Experimental results for SDOF system

Due to the ideal dynamic characteristics of the SDOF components a mathematical validation of the measured contact forces was possible. For this purpose blocked forces, induced to the system by the shaker, and the weighted masses of receiver m_r and source m_s were used to calculate back to the idealized contact forces $\{f_{c,ideal}\}$:

$$\{f_{c,ideal}\} = \left(\frac{\delta}{\delta+1}\right)\{f_{sb}\} \quad \text{with} \quad \delta = \left(\frac{m_r}{m_s}\right) \qquad \text{[N]} \qquad (3)$$

Figure 2 compares the different force determination results. The idealized forces (blue), calculated by the use of equation (3), validates the direct force measurement (red). In comparison to that the predicted contact forces (black), achieved from equation (1), are shown.

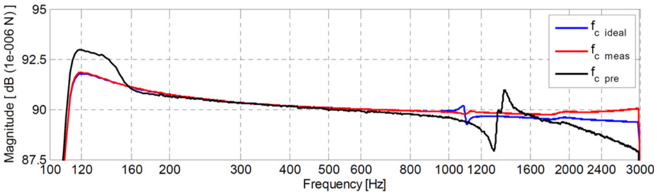

Figure 2: Idealized (blue), measured (red) and predicted (black) contact forces of the SDOF structure

Within a frequency range between 160 Hz and 1000 Hz an excellent prediction quality can be seen. Deviations at lower and higher frequencies were clearly traced back to the non-linear frequency response of the shaker (< 160 Hz) as well as its subtotal mass-like dynamic characteristics (> 1000 Hz).

3.2 Experimental results for MDOF system

For the MDOF system a validation of directly measured force data by the use of mathematical homologous models is difficult and error-prone. Therefore an indirect validation method was applied that allows estimation of operating velocities at remote points $\{v_{r,op}\}$, i.e. any point not identical to the contact points, on the coupled MDOF structure.

$$\{v_{r,op}\} = [Y_{rT}]\,\{f_{c,op}\} \qquad \text{[m/s]} \qquad (4)$$

Remote velocities are predictable if the receiver transfer mobility matrix $[Y_{rT}]$ and the in-situ measured contact force vector $\{f_{c,op}\}$ are known. The benefit of equation (4), instead of backwards calculating it to maintain a second set of predicted contact forces, is the omission of a matrix inversion, which is infamous for numerical errors. Figure 3 shows a comparison of a predicted remote velocity - that includes force measurement data (black) and the in-situ velocity data (red). At low frequencies (< 500 Hz) the remote velocity prediction is excellent. Within this range the source and receiver show pure mass-like behaviour.

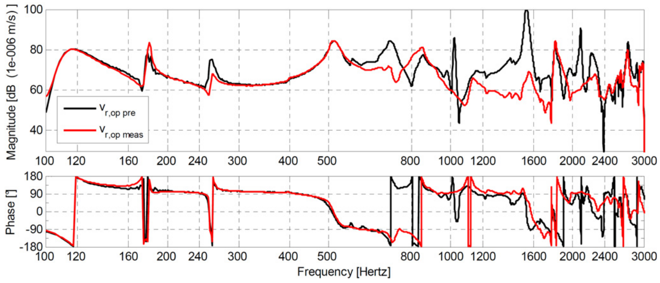

Figure 3: Measured (red) and predicted (black) remote velocities for a technical MDOF structure

At higher frequencies, where local stiffness and resonances of the substructures occur, deviations can be found that result from erroneous data set entries in the transfer mobility matrix. However due to the good agreement in the mass controlled frequency range the in-situ force measurement is assumed to be valid.

Figure 4-(a) shows the predicted contact force (black) compared to direct measurement (red) for one degree of freedom. Although there are occasionally bands with considerable errors in general clearly agreement between the shapes of both spectra was obtained. Basically the prediction includes noise at all frequencies for which defective entries in the cross terms of the mobility matrices are responsible.

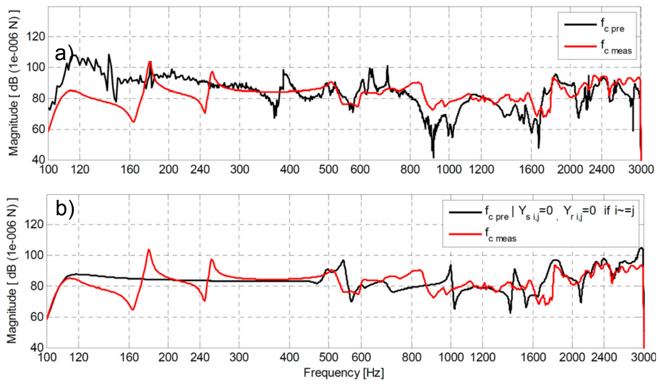

Figure 4: Measured (red) and predicted (black) contact forces for a technical MDOF structure without (top) and with (bottom) neglecting cross term entries of the mobility matrices.

Assuming that force transmission is dominated by local properties of the substructures, i.e. point mobilities, one would try to neglect defective cross terms. Thus, figure 4-(b) shows a prediction (black) where only point mobilities were regarded. In general, this method reduces noise and reduces overestimation at low frequencies. Even a more satisfying pre-diction for higher frequencies (>2 kHz) can be achieved.

Literature

[1] Moorhouse, A.T.: Measurement Of Operating Forces Of An Electric Motor. Noise-Con (2004), 64-75