Chapter 11
Experimental Validation of the Use of FBS with a Pseudo Interface on a Component Replacement Procedure

Jacopo Brunetti, Walter D'Ambrogio, Annalisa Fregolent, and Miriam Ialonardi

Abstract In the field of dynamic substructuring, the choice of a suitable interface for the proper identification of a mechanical system's dynamic behavior is still an open issue in some respects. Although the coupling procedure requires the dynamics at physical interface degrees of freedom, which are often not accessible to direct measurements, in the case of decoupling, the pseudo interfaces may represent an efficient and advantageous choice. They allow overcoming the problem of expanding or reducing the system's dynamics at the physical interface by using the dynamic behavior only at internal degrees of freedom. This paper applies the coupling and decoupling procedures in one step on the round-robin structure of the Substructuring TD of the SEM, using Frequency-based substructuring with a pseudo interface, to perform the wing swap operation. Experimental results are presented to validate the proposed procedure.

Keywords Frequency-based substructuring · Pseudo Interface · Transmission Simulator · Component Replacement · Decoupling

Introduction

The dynamic behavior of a mechanical system or one of its subsystems can be successfully identified using well-established dynamic substructuring techniques. This result is obtained respectively through dynamic coupling and decoupling operations, which are based on the assumption that each part of the mechanical system, however complex, can be considered as a separate unit whose dynamics can be added to those of the other subcomponents (coupling) or subtracted from those of the entire system (decoupling) [1]. The application of the theory implies that the two conditions of compatibility (responses) and equilibrium (forces) are imposed at the interface between the involved parts. The most trivial way is to impose these conditions on the degrees of freedom (DoFs) of physical coupling shared between subsystems, which, however, are often inaccessible to direct measurement. In the case of dynamic decoupling, the effectiveness of other kinds of interfaces such as extended, mixed, or pseudo interface, which wholly or partially disregard the coupling DoFs, has already been proven [2]. In particular, the pseudo interface offers significant advantages, allowing the use of information corresponding only to internal DoFs, i.e., those which are sufficiently distant from the physical interface. On the other hand, the coupling operation requires knowledge of the dynamics at coupling DoFs, which, in the event of inaccessibility, makes it necessary to use auxiliary procedures. Examples include the well-known System Equivalent Model Mixing (SEMM) [3], Virtual Point Transformation (VPT) [4], and Singular Vector Transformation (SVT) [5], which expand or reduce the dynamics of the system at physical coupling DoFs by exploiting information about the dynamics of accessible DoFs. The problem of measuring coupling DoFs of two substructures to be coupled can also be addressed by introducing a Transmission Simulator (TS) [6]. Assuming an assembly consisting of two subsystems, the TS is a fixture that is directly measurable and physically attached to both

Jacopo Brunetti · Walter D'Ambrogio
Dipartimento di Ingegneria Industriale e dell'Informazione e di Economia
Università dell'Aquila, Via G. Gronchi, 18 - I-67100, L'Aquila (AQ), Italy
e-mail: jacopo.brunetti@univaq.it; walter.dambrogio@univaq.it

Annalisa Fregolent · Miriam Ialonardi
Dipartimento di Ingegneria Meccanica e Aerospaziale
Università di Roma La Sapienza, Via Eudossiana 18, I 00184 Rome, Italy
e-mail: annalisa.fregolent@uniroma1.it; miriam.ialonardi@uniroma1.it

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substructures, characterized by the same geometry and materials as the physical connection. The theory states that after coupling the two substructures, the TS is then decoupled from the result twice. Even though the Transmission Simulator is typically used in the modal domain, it has been extended to the frequency domain, where the present analyses have been conducted. In this study, the wing swap exercise on the round-robin structure of the Substructuring TD of the SEM [7, 8], using Frequency-based substructuring (FBS) with a pseudo interface, is performed. The novelty of the proposed approach lies in the use of a pseudo interface, either in decoupling and coupling operations, assuming that the set of internal DoFs is positioned at the same accessible locations on both wings. Furthermore, the two operations are performed in a single step, assuming that the thin wing acts as a TS, thus obviating the need to add an extra component to play the role of TS. This is particularly advantageous when two subsystems differ slightly in terms of geometry, as in the case of the two wings, which vary only in terms of thickness. In fact, since this approach relies on the usage of the same interface, systems involved must share a certain level of similarity. In this way, it is possible to effectively predict the dynamic behavior of an assembly in one case based on the dynamic behavior of another assembly. The proposed procedure is validated through both numerical and experimental results.

Background

The purpose of this study is to identify the dynamic behavior of the assembled thick-wing system in the well-known wing swap exercise. Typically, the FBS approach requires that, in a first step, the dynamics of the thin wing w be decoupled from that of the assembled thin wing Fw, resulting in the dynamics of the frame F. In a second step, the dynamics of the frame so obtained is coupled with that of the thick wing W, resulting in the identification of the dynamic behavior of the assembled thick-wing system FW, as shown in Fig. 1 and 2.

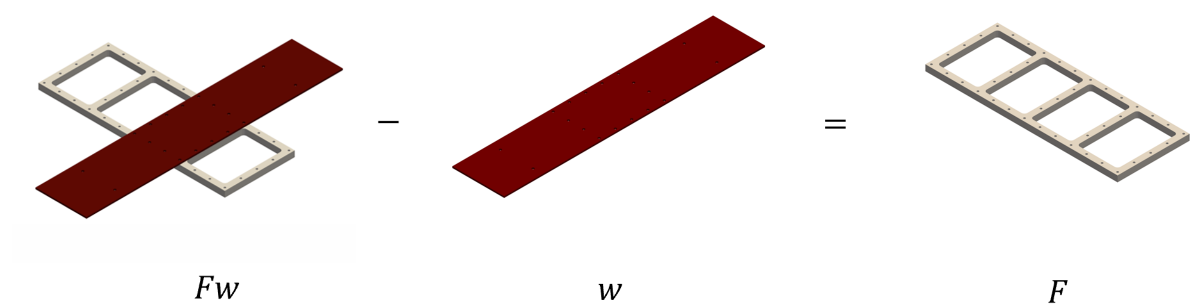

Fig. 1 First step of the (classical) wing swap exercise: decoupling of thin wing w, from the thin-wing assembly Fw.

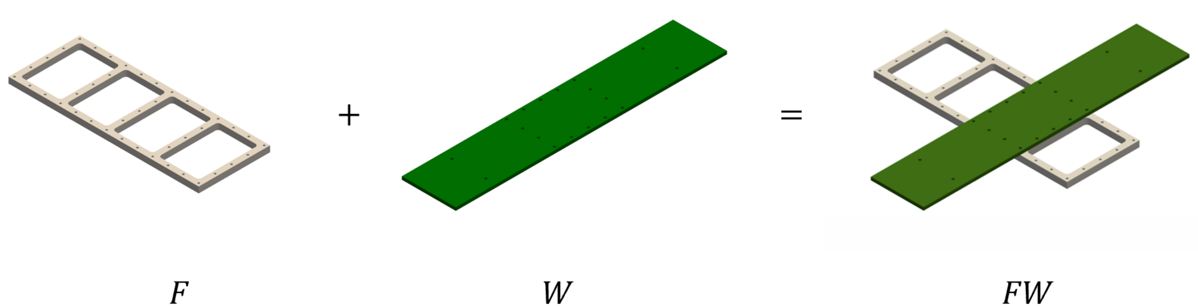

Fig. 2 Second step of the (classical) wing swap exercise: coupling between thick wing W, and frame F, obtained from decoupling in the first step.

In the frequency domain, the dynamics of the two problems are described by Eq. (1) and (2):

$$\begin{Bmatrix} \{u\}^{Fw} \\ \{u\}^{w} \end{Bmatrix} = \begin{bmatrix} [H]^{Fw} & [0] \\ [0] & -[H]^{w} \end{bmatrix} \left(\begin{Bmatrix} \{f\}^{Fw} \\ \{f\}^{w} \end{Bmatrix} + \begin{Bmatrix} \{g\}^{Fw} \\ \{g\}^{w} \end{Bmatrix} \right) \tag{1}$$

$$\begin{Bmatrix} \{u\}^F \\ \{u\}^W \end{Bmatrix} = \begin{bmatrix} [H]^F & [0] \\ [0] & [H]^W \end{bmatrix} \left(\begin{Bmatrix} \{f\}^F \\ \{f\}^W \end{Bmatrix} + \begin{Bmatrix} \{g\}^F \\ \{g\}^W \end{Bmatrix} \right) \tag{2}$$

where $\{u\}$, $\{f\}$, $\{g\}$, and $[H]$ are respectively the vector of DoFs, the vector of external forces, the vector of internal forces, and the Frequency Response Function (FRF) of the (sub)system referred to in the superscript. Performing coupling and decoupling operations requires that the compatibility and the equilibrium conditions, respectively, on responses and exchanged forces, must be imposed on shared DoFs, i.e., the interface DoFs. In the Lagrange Multiplier FBS (LM-FBS) formulation, these two conditions can be expressed in matrix form as follows:

$$\begin{cases} [B]\{u\} = \{0\} & \Longleftrightarrow \quad \text{Compatibility} \\ \{g\} = -[B]^T\{\lambda\} & \Longleftrightarrow \quad \text{Equilibrium} \end{cases} \tag{3}$$

where $[B]$ is the signed Boolean matrix and $\{\lambda\}$ the vector of the intensities of the disconnection forces. It is possible to define different types of interfaces based on the set of DoFs considered. Beyond the most intuitive interface, i.e. the standard interface which collects the physical coupling DoFs (c), it is also possible to use other types of interfaces that include them partially, as in the case of extended and mixed interfaces, or totally, as in the case of pseudo interfaces. In particular, pseudo interfaces consider only internal DoFs (i), i.e., DoFs far from the physical interface. Therefore, their use is particularly advantageous in cases where physical connections are not accessible for direct measurements. Although the effectiveness of decoupling using non-standard interfaces has already been proven, it is also a known fact that coupling requires the dynamics of physical interface DoFs (c). Finally, using Eq. (4):

$$\{u\} = \left([H] - [H][B]^T\left([B][H][B]^T\right)^{-1}[B][H]\right)\{f\} = [\tilde{H}]f \tag{4}$$

the dynamic behavior of the unknown mechanical system, as a part of $[\tilde{H}]$, is found, where $[H]$ is the block diagonal matrix collecting the FRFs of the systems involved in the coupling and decoupling operations. For reasons that will be explained later, it is worth recalling that one of the main causes of failure in the decoupling results is in the inversion of the Interface Flexibility Matrix (IFM), $([B][H][B]^T)$, which, if ill-conditioned, leads to error propagation.

The novelty of the proposed approach lies in the use of a pseudo interface in both the decoupling and coupling procedures. This is possible through an expedient which consists in considering the overall operation, $Fw - w + W$, as the decoupling from the thin wing-assembly Fw, of a Δ quantity resulting from the decoupling between the thin wing w, and the thick wing W: $Fw - (w - W) = Fw - \Delta$. In a two steps procedure, the two corresponding block diagonal matrices, $[H]^{D1}$ and $[H]^{D2}$ to be substituted in Eq. (4), together with respective signed Boolean matrices, $[B]$, would be defined by Eqs. (5) and (6).

$$\text{First decoupling :} \quad \begin{cases} [H]^{D1} = \begin{bmatrix} [H]^w & [0] \\ [0] & -[H]^W \end{bmatrix} \\ [B] = \begin{bmatrix} [I] & -[I] \end{bmatrix} \end{cases} \tag{5}$$

$$\text{Second decoupling :} \quad \begin{cases} [H]^{D2} = \begin{bmatrix} [H]^{Fw} & [0] \\ [0] & -[H]^{\Delta} \end{bmatrix} \\ [B] = \begin{bmatrix} [0] & [I] & -[I] \end{bmatrix} \end{cases} \tag{6}$$

Moreover, this paper proposes the use of a unique pseudo interface, that is valid for both wings in a comprehensive one-step operation. This suggestion arises from observing how the thin wing can play the role traditionally performed by a transmission simulator (TS). In fact, the thin wing w has the same geometry as the thick wing W, so that any set of internal DoFs can be selected on both wings as a pseudo interface. Therefore, its dynamics can be decoupled from the system's, as it would be the case for a traditional TS. It should be noted that the one-step procedure reduces the number of mathematical operations required and involves the inversion of a single IFM, thus reducing possible sources of error. In the LM-FBS, this one step can be achieved by casting the equation of motion of Fw, w and W in the frequency domain as follows:

$$\{u\} = [H](\{f\} + \{g\}) \quad \Leftrightarrow \quad \begin{Bmatrix} \{u\}^{Fw} \\ \{u\}^w \\ \{u\}^{FW} \end{Bmatrix} = \begin{bmatrix} [H]^{Fw} & [0] & [0] \\ [0] & -[H]^w & [0] \\ [0] & [0] & [H]^W \end{bmatrix} \left(\begin{Bmatrix} \{f\}^{Fw} \\ \{f\}^w \\ \{f\}^W \end{Bmatrix} + \begin{Bmatrix} \{g\}^{Fw} \\ \{g\}^w \\ \{g\}^W \end{Bmatrix} \right) \tag{7}$$

The entire operation is therefore the one shown in Fig. 3:

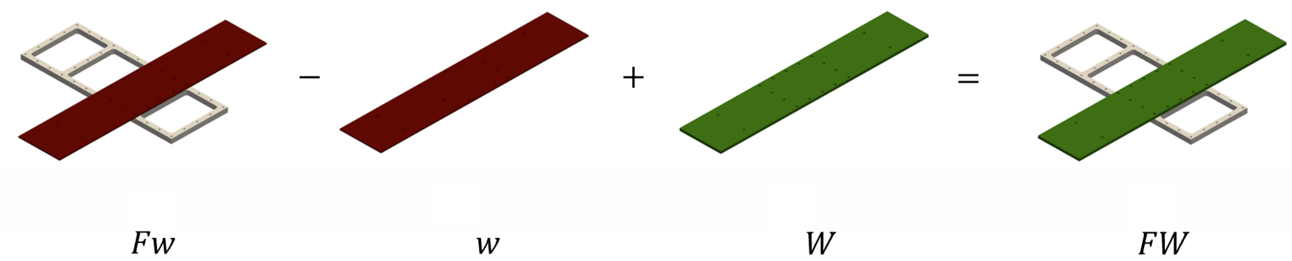

Fig. 3 The proposed approach: decoupling of thin wing w, and coupling of thick wing W, in one step.

The use of a unique pseudo interface in the one-step procedure results also in a single Boolean matrix in the form shown in Eq. (8):

$$[B] = \begin{array}{c} \begin{matrix} \{u\}_{\mathrm{v}}^{Fw} & \{u\}_{\mathrm{i}}^{Fw} & \{u\}_{\mathrm{i}}^{w} & \{u\}_{\mathrm{i}}^{W} \end{matrix} \\ \begin{bmatrix} [0] & [I] & -[I] & [0] \\ [0] & [0] & [I] & -[I] \end{bmatrix} \end{array} \quad (8)$$

where $\{u\}_i$ is the subset of internal DoFs (i), used to enforce compatibility and equilibrium conditions, that constitutes the pseudo interface, while vector $\{u\}_v$ is the subset of validation DoFs (v), i.e., a subset of DoFs not involved in the compatibility and equilibrium conditions, that are used to validate the results.

Analysis

To validate the proposed procedure, the Finite Element Models (FEMs) of the frame-thin wing Fw, the frame-thick wing assembly FW, and the two subsystems, thin wing w and thick wing W, are realized in Ansys. For each one, a modal analysis is performed to study the respective modes of vibrations. For this study, four corner connection points between frame and wings are considered in the FE models of Fw and FW, to simulate four bolted connections. The FRFs are synthesized, as required by the FBS decoupling formulation, using the Python pyFBS package through the Mode Superposition Method. Locations of pseudo interface internal DoFs (i), (yellow) exclusively on the wing, and of the validation point v, (orange) on the frame, are shown in Fig. 4. A single validation DoF v is considered, orthogonal to the wing plane.

The FRF of FW at the validation DoF v, resulting from the numerical one-step decoupling/coupling procedure with only pseudo interface, is shown in Fig. 5. The FRF obtained directly from the FE model of the frame-thick wing assembly is also reported (dashed black line) to validate the results. It can be observed that the proposed procedure allows the dynamics of the system to be correctly identified, even though it shows a softening behavior, as can be seen from the slight shift towards low frequencies, that needs to be further investigated. Probably the softening behavior can be ascribed to the choice of the number of interface DoFs. Three results are shown: the red curve $[H]_{full}^{FW,id}$ represents the result of identification using DoFs in the three directions x, y, and z, the blue curve $[H]_{Z}^{FW,id}$ is what is obtained using only DoFs along direction z orthogonal to the wing plane, and finally, the green curve $[H]_{cut}^{FW,id}$ is the result obtained by deleting some rows and columns from the full FRF matrices of all the systems involved in the decoupling procedure. The choice of what to delete is made by considering which responses (rows) and which excitations (columns) could be less relevant or provide redundant information, leading to an ineffective identification of FW. In particular, responses along x and all excitations along x and y belonging to the full set are neglected. Although $[H]_{full}^{FW,id}$ (red curve) represents the most successful outcome, it can be seen that all three curves show peaks at the same frequencies and are therefore affected by the same shift problem. However, while $[H]_{cut}^{FW,id}$ (green curve) shows a more damped trend, $[H]_{Z}^{FW,id}$ (blue curve) exhibits more pronounced peaks, also at frequencies that do not correspond to modes of vibration of the unknown system FW (spurious peaks).

To verify the proposed approach, an experimental campaign is conducted. Measurements involve the frame-thin wing assembly Fw, and the two wings w and W. Additional measurements are performed on the system to be identified FW, shown in Fig. 6, to provide a reference. It should be noted that, as predicted by this work, there's no need to conduct measurements on the frame F, which leads to a quicker experimental campaign and a reduced working time. Experimental results of the one-step decoupling/coupling operation at validation point v, are shown in Fig. 7. In particular, the results obtained

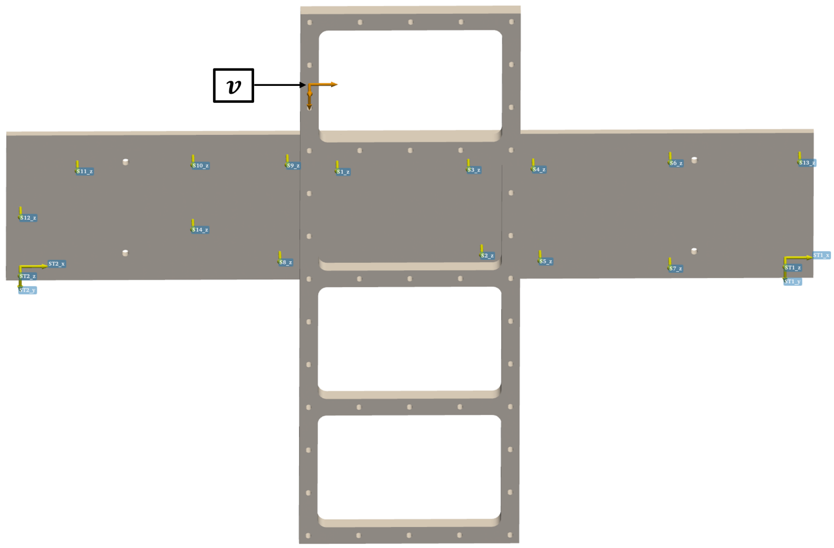

Fig. 4 The locations exclusively on the wing of pseudo interface internal DoFs (i) (yellow arrows), and on the frame of the validation point v (orange arrows).

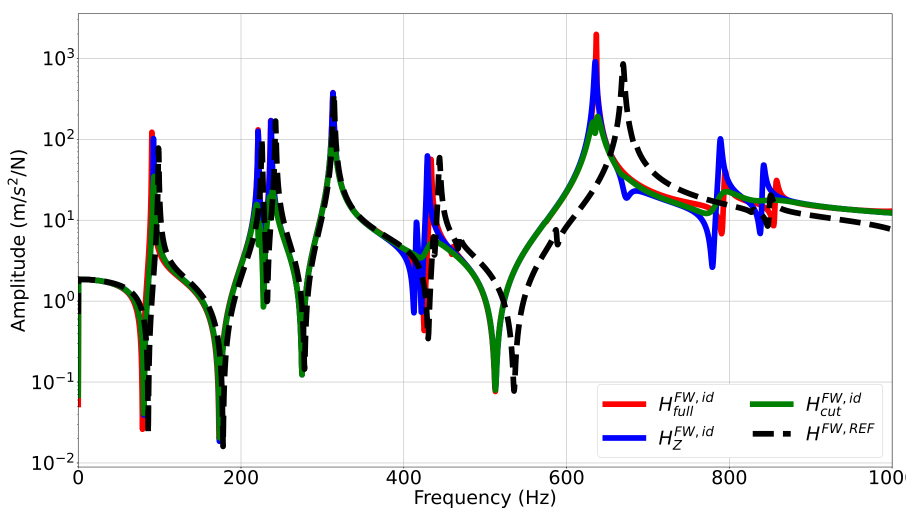

Fig. 5 Drive point accelerance FRF of the assembled system FW at validation DoF v, numerically obtained in a single step decoupling/coupling procedure through pseudo interface.

from two of the cases studied numerically are shown, i.e., identification along Z and the one performed by deleting the same response along x and the same excitations along x and y from the FRFs of all the systems involved in the procedure. Again, the reference FRF obtained from direct measurements on FW at v DoF is shown as a black-dashed line. A correspondence between the numerical and experimental results can be noted. Both results in Fig. 7 confirm the validity of the method in identifying the dynamics of the unknown system FW, while showing the softening behavior already observed. Furthermore, the FRF predicted using only DoFs along z shows peaks with more consistent amplitudes, in accordance with the numerical study.

Note that both results are a consequence of neglecting some information, although based on different considerations. This highlights the need to define solid criteria to verify the relevance and redundancy of DoFs, to determine the number and type of DoFs necessary and sufficient for an optimal system identification.

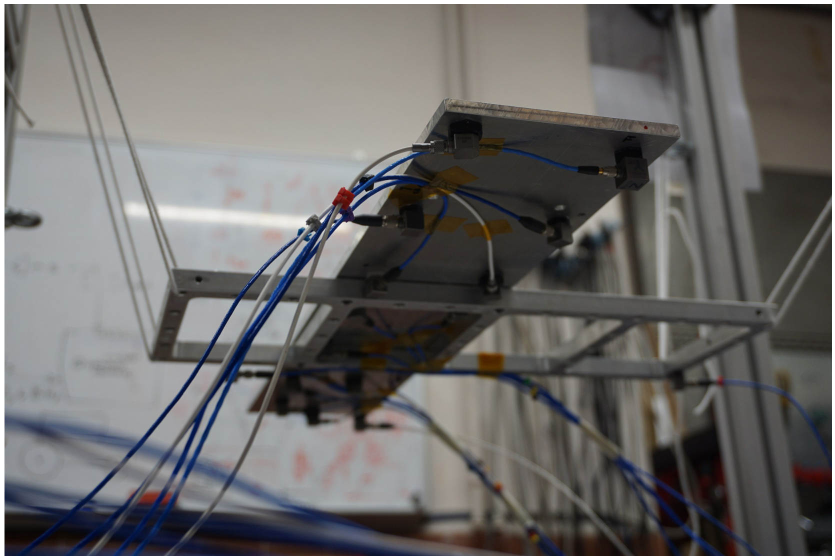

Fig. 6 A view on the pseudo interface DoFs during the experimental campaign on the frame-thick wing assembly FW.

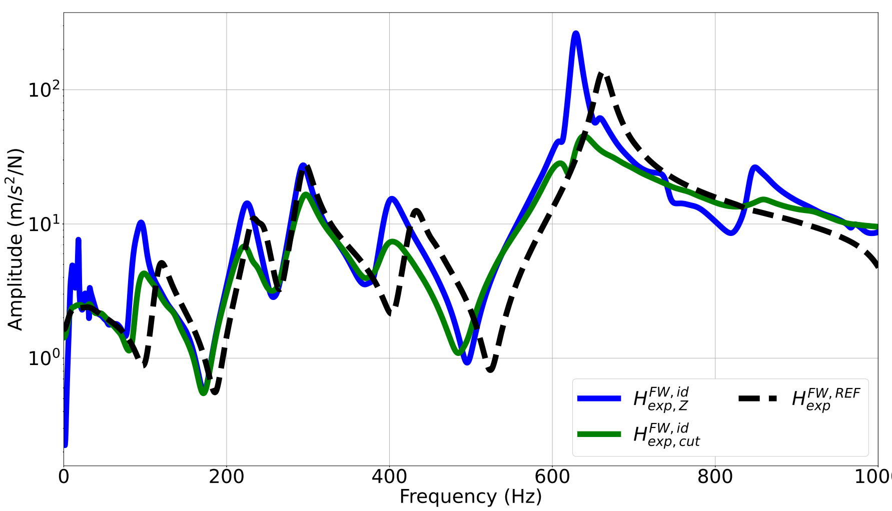

Fig. 7 Drive point accelerance FRF of the assembled system FW at validation DoF v, experimentally obtained in a single step decoupling/coupling procedure through pseudo interface.

Conclusions

In this work, the wing swap exercise on the TD testbed is carried out using the LM-FBS decoupling/coupling formulation with a pseudo interface. This choice leads to a more convenient analysis of the system's dynamics by relying on FRFs obtained from internal DoFs (i), which are directly measurable. This approach does not require FRFs at coupling DoFs (c), which are often difficult to retrieve. This achievement is possible only by considering the whole procedure as two sequential decouplings, since the coupling operation would require dynamics at DoFs (c). The procedure is also gaining value from the added benefit of being able to complete the entire operation in a single step. This possibility arises from the assumption that the thin wing w acts as a transmission simulator, being characterized by the same geometry as the physical interface that describes the frame-thick-wing assembly FW to be identified. Both numerical and experimental results show that the proposed approach successfully predicts the dynamic behavior of the frame-thick wing assembly around its resonance frequencies. Thus, it can be considered effective in predicting the dynamic behavior of mechanical systems that vary slightly from one another. In fact, the same interface is required, which means that the systems involved must share a certain level of similarity, at least in terms of geometry of the physical interface, such as the two wings that differ only in thickness. Further studies are being conducted to validate and improve the proposed procedure, as well as to establish criteria that enable the relevance and redundancy of interface DoFs to be assessed before performing the experimental campaign.

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