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METHODICAL SUPPORT FOR THE DIMENSIONING OF VARIANT LIGHTWEIGHT STRUCTURES UNDER DYNAMIC EXCITATIONS

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Keywords: methodical dimensioning, consistent interface modelling, dynamic excitation

1. Introduction

The megatrend of individualization can also be found in the cabin interior of passenger aircraft. It applies all the more as the individual cabin look and layout is one of the few measures an airline has to distinguish itself from its competitor because every airline has to buy from the same few aircraft manufacturers. Therefore, airlines often have special demands towards design, layout and extra comfort when ordering a new cabin. The variety of simple partitions or class dividers can be seen when looking at some selected examples of partitions from the product range of a medium sized cabin interior supplier in Figure 1. The interior suppliers and the aircraft manufacturers are thereby faced with the challenge of dimensioning all these variants when in development.

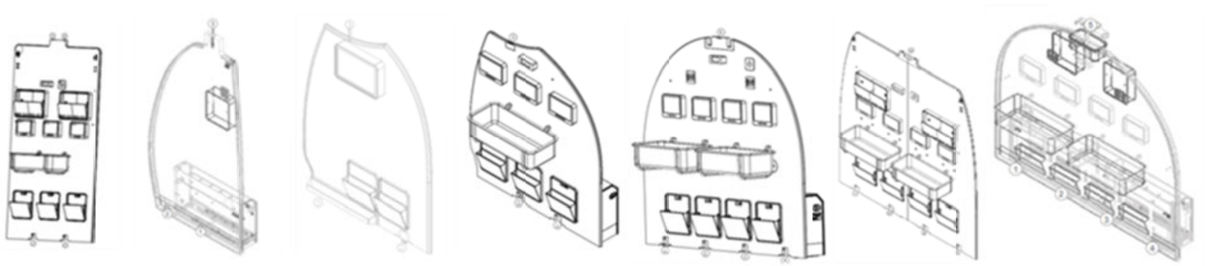

Figure 1. Different product variants of aircraft cabin partitions (source: Diehl Service Modules GmbH)

As cabin interior monuments stay within the vicinity of passengers they are subject to strict aviation safety regulations. Furthermore, larger cabin monuments exert high interface loads at their fixations which often run directly to primary aircraft structures and therefore affect the safety assessment of primary structures.

Usually, a good mechanical design in aviation needs several iterations to find a suitable optimum in design with low weight and just enough safety margin. The cabin interior suppliers, sometimes small and medium sized companies, can often not afford the tremendous effort to model, simulate and dimension each and every variant in all detail over several design loops. In case precise values for the needed model parameters for simulations of the many variants are missing, the dimensioning can only be based on engineering judgement from experience. This is leaving a lot of optimization potential unused. The problem becomes worse for the challenging and time consuming dimensioning under dynamic loads. In dynamic analysis a lot of interdependencies between mass, stiffness and damping affect the vibrational behaviour. Rough estimation and simplifications as in static design are often not

valid and good dimensioning using a detailed analysis is only possible when the necessary model parameters have been gathered from testing.
In particular the variety challenge is targeted in this paper, followed by an approach for support.
The problems of current dimensioning of variant structures under dynamic load are analysed in section 2. Based on this in-depth analysis a 3-step approach to support a lightweight dimensioning under dynamic excitations with a detailed mechanical analysis for highly variant products is presented in section 3. Section 4 further focusses on the methodical model preparation step of the approach. The preliminary application evaluation of the approach is shortly presented in Section 5.

2. The problem and current means of action

The following analysis provided the basis for the development of the supporting approach.
Generally, if no special care is taken to handle the variants' multiplication effect, all the effort of dimensioning under dynamic loads is multiplied by the number of variants making the dimensioning of variant aircraft cabin interior very challenging.
When looking at the production of a medium sized cabin monument supplier, the variety is not only high but also the produced numbers per variant are very low. The data collected in the study [Jonas et al. 2012] clearly shows the difficult situation for the supplier: Between the years 2009 and 2010 the number of produced variants of partitions and class dividers (Figure 1) increased by 50% to an absolute 3-digit number. In the same time frame the produced stock number per variant lowered by 20% to only 3.7 produced units per variant. Therefore, the monetary effort of dimensioning is divided by less produced units lowering the spread of each variant if costs are not handed on to the customer.
The multiplier effect can be further fragmented into the three combinatorial factors "load case", "geometry" and "material" as shown in Figure 2. The total combinatorial variety is the product of these three factors. Variants are usually reflected in dimensioning by variations of load cases and geometry. Different load cases arise from different use cases and different geometries arise from aesthetic or functional design requirements. For dimensioning, each set of a load case and an external geometry requirement makes up one variant.
The combinatorial problem becomes worse because in dimensioning not only the number of variants multiply dimensioning efforts but also internal parameter variations in the design process. When looking for a design optimum in dimensioning, the design engineers will use iteration loops and vary the internal geometry (space that is not restricted) as well as the material. These parameter variations will stay within the dimensioning design phase and not cause the generation of different variants.

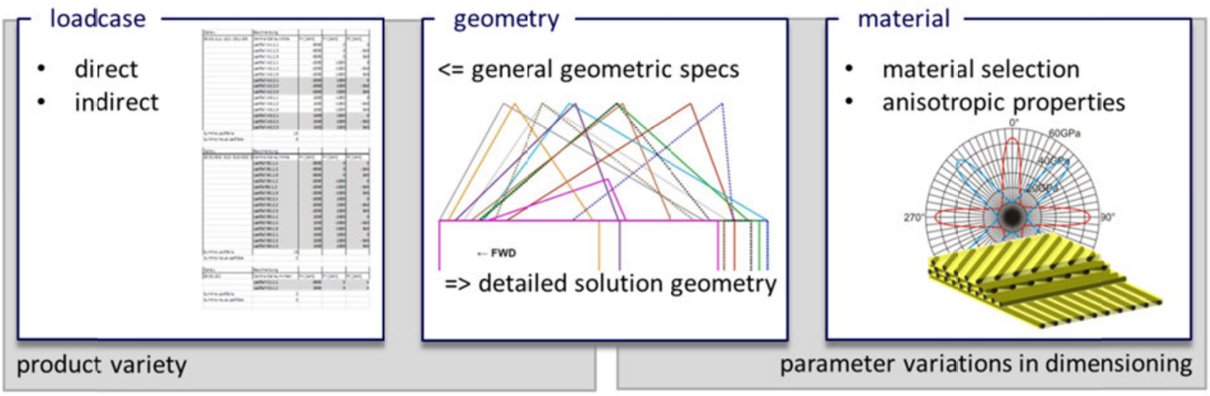

Figure 2. The multiplication factors of combinatorial variety in dimensioning with a detailed mechanical analysis

This variety or specifically the combinatorial variety of a system and its states can be described with the word complexity [Malik 1977]. As shown in [Brosch and Krause 2011], the term complexity is used differently in various sciences and other, sometimes contradicting, definitions are used. This paper will focus on the combinatorial variety, which contributes to the complexity of a system.

Many authors have presented and dealt with methods in product development to handle complexity in product development. A general and comprehensive overview is given in [Lindemann et al. 2009], where three strategies to deal with complexity in product development are presented:

- assimilation and evaluation of complex systems as the basis for the following two strategies
- avoidance and reduction of complexity
- management and control of complexity

The methods presented and used in [Lindemann et al. 2009] focus on the early phases of product development and generally remain too general to be applied to the specific task of structural dynamics dimensioning. However, the specific approach developed in the following can be assigned to the management and control strategy. The combinatorial variety - contributing to complexity as defined before - cannot be reduced anymore in the later stage of dimensioning a product.

2.1 The current stiffening approach

The state of the art in industry is that if a resonance frequency of the structure lies within the frequency band of the excitation, the structure is stiffened so that the resonance frequency is pushed out of the excitation band, see Figure 3. This simple approach does not need detailed information on the damping behaviour as resonances can be calculated from stiffness and mass information.
However, the stiffening approach comes with severe restrictions because weight gain of the structure plays a critical role in aerospace engineering.
For a lightweight design, the supporting structure of these cabin monuments is made of an aramid honeycomb core with layers of fibre reinforced face sheets on both sides. As the core thickness normally has been already increased to the design limits, the sandwich is equipped with thicker and stronger sheets of fibre reinforced plastics. Unfortunately, this adds mass. As the resonance frequency is determined by the square root out of stiffness over mass, the frequency push effect is severely limited. To make it work nonetheless, the stiffness needs to be increased a lot more than the inherently following mass increase. The result is a heavy structure with an often inferior mechanical design and acoustical problems as the resonance frequency may have moved above the hearing threshold.

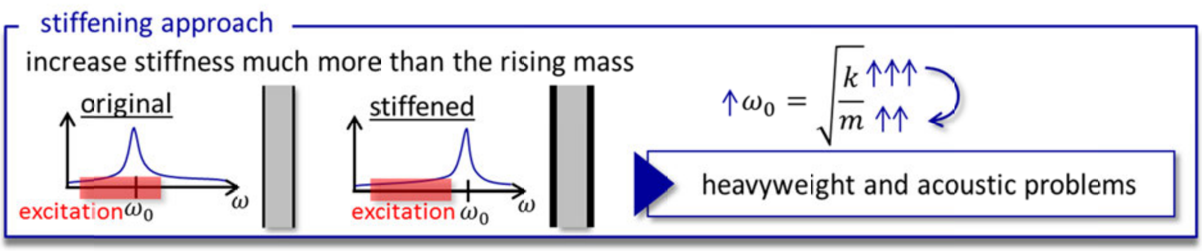

Figure 3. Stiffening in order to push resonance frequencies out of the excitation range

Even though the stiffening approach usually works out in the end, a stiffening without adding too much weight can only be achieved in single dimensioning solutions for one or only very few variants. Furthermore it needs precise stiffness and mass properties for accurate predictions of the resonance frequency in simulation, which are often missing. In the end, the stiffening approach appears as a purely technical cure for a complexity problem with an application limit for small sets of variants only. The resulting general overdimensioning over all variants contradicts the lightweight aim of all aerospace engineering but is often used nonetheless.

2.2 A methodical approach

The high variety of cabin interior as demanded the airline customers for their individualization can be handled well using a modular product structure. With such a modular structure a high external variety can be produced using only a small internal variety. [Krause and Eilmus 2011]
The integrated PKT approach for the development of modular product families is a workshop-based modularization approach that helps to identify modules as sets of components over the different product life phases to generate variants by an individual combination of modules, see Figure 4.

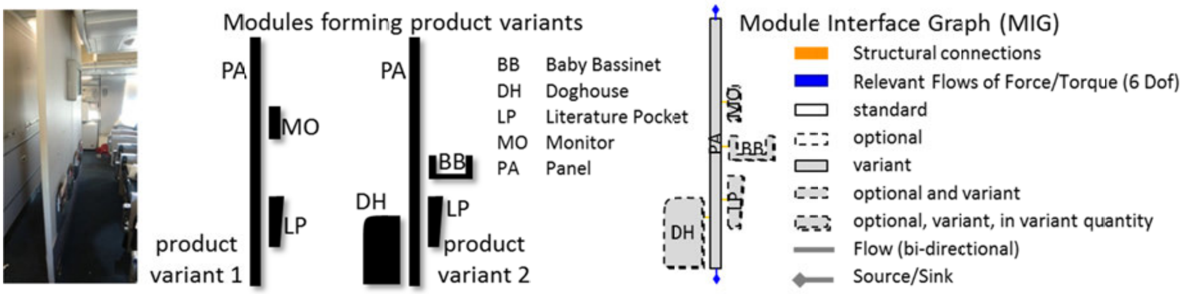

Figure 4. A combination of modules to form different variants of a partition/class divider cumulated in MIG

The Module Interface Graph, MIG, [Blees et al. 2010] is a 2D sketch with media flows between the relevant components in the product structure for all variants. The various components can then be accumulated to modules in the further process as described in [Blees et al. 2010]. The type of interfaces is specified by a colour coding. In the dimensioning context only potentially load carrying interfaces are of interest. As the approach in this paper is localized after a successful modularization, a MIG is used here (see Figure 4) that only consists of the defined modules and does not depict the components anymore. Since the substructure boundaries for a technical analysis are defined according to the modules' system boundaries, internal interfaces of modules are not subjected to variety and are therefore not in the focus of combinatorial dimensioning. This is called a black box model [Pintelon and Schoukens 2001], where only the behaviour at the interfaces is of interest.
The integrated PKT-approach [Krause et al. 2013] as a set of methods for successful modularization and variant-specific design has been used in many research and industry projects from varying branches like aviation, special purpose machinery, safety and food. However, the application of the PKT approach has been primarily focused on the earlier design phases and not been applied to dimensioning for the vibrational behaviour with a detailed mechanical analysis, the scope of this paper. The idea of using only a few well defined modules to combine in order to generate a vast set of different variants will therefore be transferred into structural dynamic dimensioning.

3. Better dimensioning with detailed mechanical analysis

For a sophisticated lightweight design with structures made out of fibre reinforced plastics (FRPs) a detailed mechanical analysis as described in [Schürmann 2005] is usually compulsory. With the use of simulations based on the Finite Element Method (FEM) as described in [Bathe 2007], the structural behaviour can be predicted and the relevant mechanical requirements, such as load cases, can be substantiated. In the following, an approach will be presented that supports the dimensioning under stationary dynamic loads of variant lightweight structures by enabling a simulation- and test-based detailed mechanical analysis of modules. The dynamic models of the modules can be combined to form a full system product variant and hence the vibrational behaviour of that variant for further optimisation is calculated from the coupled models of the modules.

3.1 The dynamic substructuring method

In literature, the term "dynamic substructuring" refers to the coupling of models in structural dynamic analysis. By using coupling and decoupling algorithms the technical implementation of the modular substructure in dimensioning is possible. It also makes the interchangeable use of substructure models from simulation or real test data possible. Using dynamic substructuring, the detailed mechanical analysis can use test data where a simulation will not yield acceptable results. Because of the possibility to use test data without the reduction to simplified one-degree-of-freedom-models in the modal domain, the Frequency Based Assembly (FBA) is chosen over the Component-Mode-Synthesis (CMS) in this context. For further reading on the technical implementation side of the approach presented, please refer to [Plaumann et al. 2013] and [Plaumann and Krause 2014].
A first presentation of the frequency based substructuring can be found in [Jetmundsen et al. 1988]. The authors describe the vibrational analysis of a helicopter that is segmented into five substructures.

The dynamic models are defined separately for each substructure. The substructures are then coupled together. However, the authors do not mention the possible application to improve variety handling among the advantages of the approach. A more recent source describing the current state of dynamic substructuring is [de Klerk et al. 2008]. Here only the benefit of having different groups working on the same complex system is mentioned regarding aspects of variety. The use in a modular substructure is not targeted in these and other publications investigated except for [Sellgren and Drogou 1998], which will be covered in the next section. The lack of methodical support regarding variety aspects shows best in typical descriptions of the formulation of the coupling matrix. The coupling matrix defines which substructure is coupled to another as well as which degrees of freedom (dofs) are coupled at the interface nodes. In the given literature the coupling matrix simply appears without any hints to the derivation process. But a consistent interface definition for all possible combinations of modules is crucial for a dynamic substructuring calculation in dimensioning. Therefore a methodical derivation guideline is needed to support the application towards dimensioning of variant product families.

3.2 An approach for combinatorial dynamic dimensioning

The only source found in a literature study that deals with dynamic substructuring in the context of product development are publications like [Sellgren and Drogou 1998] and [Blackenfelt and Sellgren 2000] forming the cumulative dissertation of Sellgren. Unfortunately, there are several mismatches between their approach and the application background presented in this paper. Firstly, these sources deal with component-mode-synthesis only, a state-of-the-art feature of today's commercial FEM-tools, which cannot cover the complex behaviour of assembled cabin interior monuments properly as shown in [Plaumann et al. 2013]. Secondly, their approach of modularization differs significantly from the idea of life phase modularization in the early phases of product development as they modularize after detailed design aspects have been targeted like the definition of interfaces as unique geometric entities. The modularization step in the integrated PKT approach occurs in the early phases of product development by bringing together the design expertise from all relevant product life phases at an early stage. Requirements towards the modularization will be formulated following certain module drivers of each life phase [Blees et al. 2010].

In order to support the dimensioning of highly variant structures like aircraft cabin interior regarding its vibrational behaviour, a three step approach is under development at the institute PKT. It is based on the idea to handle many variants with only a few modules, which are defined earlier in a life phase modularization. In order to use dynamic substructuring, a transfer from modules to the technical dynamic substructures is necessary, providing interfaces and system boundaries clearly defined to the specific technical needs. Dynamic substructures can have a much more detailed definition of single parts contained and degrees of freedom to be coupled. Modules are defined at an earlier step in product development where the design is not detailed to every interface screw and nut. In this context, a consistency of interface definitions for all used combinations of modules is crucial for calculation. The process is depicted in Figure 5 with the localization of transfer steps from variants to modules, from modules to substructures as well as back again to modules and variants.

Step 3 in Figure 5 mainly consists of the coupling of dynamic substructure models according to the combination in each variant. This process step makes use of the Frequency Based Assembly (FBA) approach [de Klerk et al. 2008], [Jetmundsen et al. 1988]. The technical aspects towards the application with the presented background are given in [Plaumann et al. 2013], which also contributes the test data of completely assembled systems as benchmarks for the technical validation of the support. The evaluation and validation will be further detailed in [Plaumann and Krause 2014] using an aircraft galley partially loaded with sliding masses.

The second step generates the dynamic models for each substructure in a reduction process based on system identification. The dynamic behaviour of each substructure is reduced to the behaviour at its interfaces and relevant inner nodes in the frequency domain and described in a Frequency Response Functions (FRFs). The use of the Frequency Based Assembly method in the last step keeps the dynamic models more accurate regarding possible non-linearities, which would have been linearized when using classical component-mode-synthesis as in [Sellgren and Drogou 1998]. Test and

simulation results from the Institute PKT contribute dynamic substructure models of cabin interior to this step. The system identification process pursued for this special application as well as some results are presented in [Plaumann et al. 2013].
The first step of the model preparation delivers a suitable model template for the system identification with model consistency for all used combinations of different modules in a product family. The methodical guideline of this step to support the models' consistency will be presented in the next section. To further increase the benefit of the presented support, a software implementation is under development that covers some parts of the approach which have not been implemented in commercial software in a useful manner so far.
First development studies of the approach as presented in section 5 have provided well sufficient results for cases with a well conducted model preparation. The approach is therefore technical feasible but requires a methodical model preparation that ensures reliable results with reproducible models.

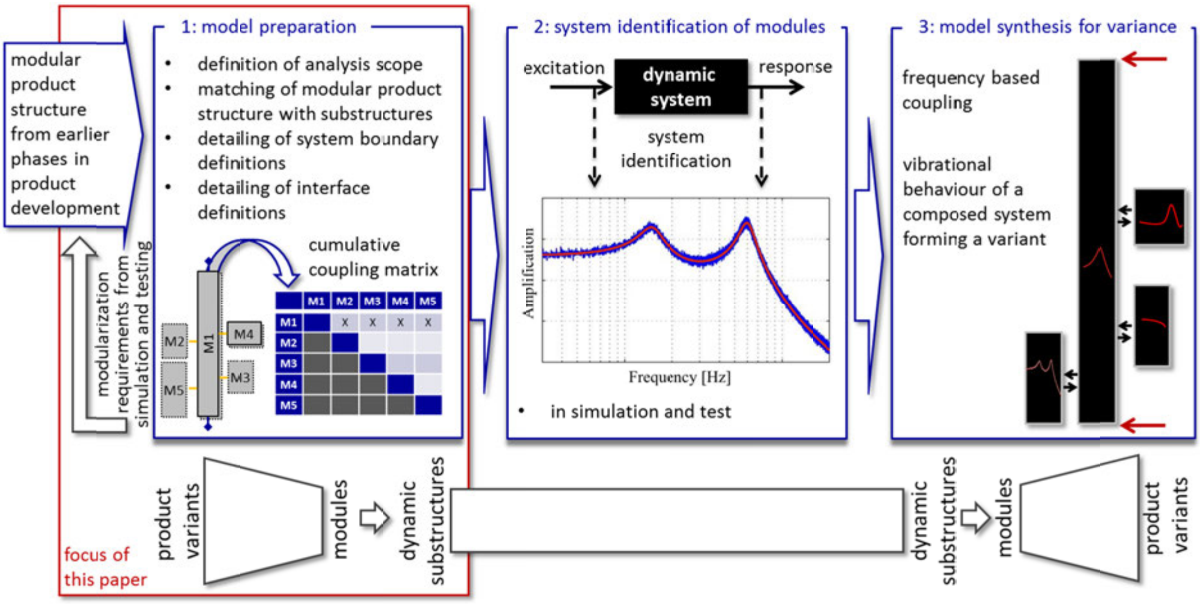

Figure 5. Overview of the presented approach to support dimensioning of variant structures under dynamic loading by combination of a few handled individually modules to many variants

4. Methodical model preparation for combinatorial dynamic analysis

The requirements for model preparation arise from technical necessities in order to get the calculations running and the results right as well as from methodical necessities to be able to handle many variants easier. As this paper contribution deals primarily with the first step in Figure 5 on the methodical model preparation, the corresponding sub steps will be described.
Prior to the execution of the substructuring process a few requirements have to be implemented into the modularization to enable a smooth matching of modules and technical substructures at the later stage of the approach presented here.

4.1 Requirements for a transfer from a modular product structure to dynamic substructures

The matching between modules from a product-strategic modularization in the early phases of product development and technical substructures is a critical aspect of the approach. The modularization in the integrated PKT approach accounts for different module drivers from the various relevant product life phases in specifically suitable modularizations. At a later stage these modularizations will be combined to one modularization per life phase which are then further streamlined to have a minimum of changes between the modularizations of different life phases.
For the presented combinatorial dynamic dimensioning approach the following generic factors are given to enable a smooth matching between modules and substructures. They can be attributed to a new module driver "modular simulation and testing" of the product development life phase.

Table 1. Modularization requirements from simulation and testing in dynamic substructuring

Requirements of the simulation	Requirements of testing
• Keep in mind the modelling and calculation effort (trade-off between accuracy and costs) • Keep in mind, that often model reductions to simple mechanical elements have to be possible for simplified dimensioning calculations	• Ensure measurability of the necessary variables at module interfaces and surrounding environment • Ensure that a test-specific fixation of each module as well as of the entire product is techn. feasible • Keep module weight within the testing capabilities • Keep module size within the testing capabilities

Especially the technical aspects of testing demands are likely to generate detailed technical requirements specific to the product and the manufacturer's capabilities (as for example test rigs). To foster the consequent implementation of modules over all life phases and stake holders the integrated PKT approach recommends the invitation of appropriate representatives, which are in this case familiar with the requirements of dimensioning and substantiation in simulation and testing, to the modularization process.
After a successful modularization the actual process as depicted in Figure 5 can be started. This paper focusses on the first step of model preparation which will be detailed in the following. Certain sub steps dealing with organizational and technical necessities, will not be covered in detail here. They manage the jumping to process sub steps under certain process boundaries as well as the definition of coupling variables, target variables, frequency range and global coordinate system. The main point of this technical sub step is that it is generally advisable to define what you expect from an analysis before starting with the actual work. The two sub steps presented in detail here cover the methodical proceeding of detailing the system boundary and interface definition.

4.2 Detailed definition of the system boundaries (part assignment)

The detailing of the system boundaries mainly consists of an assignment of the structural parts to one of the module-matching substructures. The assignment starts with the system boundary definition coming from the modularization, which usually is not yet defined on the hierarchical level of single parts. As test results depend on a clear definition of which parts of interfaces belong to which module, a clear definition is needed here. The level of detail has to be defined in a way that is as simple as possible and yet yields sufficiently accurate results for dimensioning. In order to establish this level of accuracy, parameter studies in simulations and simple development tests may be necessary.
The further detailed boundary definition is based on a first analysis of the dominant flows described by [Stone 1997] as part of the method of module heuristics. In structural analysis the dominant flow is usually the transfer of force and torque.
If this is not yielding sufficiently detailed boundary definitions, a segmentation and analysis of the boundary regions using the concept of working surfaces [Roth 1982] is proposed here. A more recent development well suited for this subtask is the contact and channel approach, as presented in [Albers et al. 2008]. The deployment of a certain function is of minor interest in the context presented here as the focus lies on the detailed analysis and definition of subsystem boundaries. It has been used in the following example of the contact between a literature pocket and a partition wall in Figure 6.

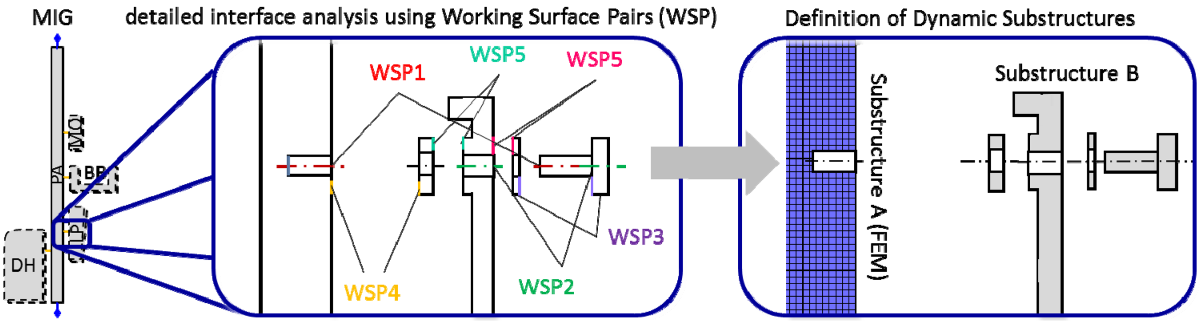

Figure 6. Detailed boundary definition using the analysis of working surface pairs

The assignment of interface elements like screws is normally dominated by the technical feasibility of the test setup as some parts cannot be separated during testing. Being the main reason for the further detailing of the module boundaries to technical substructure definitions, the level of detail should not exceed the technically necessary level. A generalization of the technical necessities can be found in Table 1 above.

4.3 Detailed interface definition

The first source describing dynamic substructuring using frequency based assembly by [Jetmundsen et al. 1988] presents a five point method, which already mentions the drawing of a "symbolic map" of the subassemblies and interfaces involved. It further mentions the construction of a mapping matrix. Unfortunately the method does not go into much more detail and - even though presenting a good starting point - is not specific to the need of an application to the variety challenge with interface consistency of different modules which attach to the same interface. As described above, a mapping matrix or coupling matrix needs to be consistent if one interface can accommodate for the connection to different modules or variants of the module attached.

In the following, the Module Interface Graph (see section 2.2) is used as a simple symbolic depiction of the modules and its interfaces. As the combinatorial dynamic dimensioning approach is conducted after a successful modularization, the MIG depicts only the modules, no components. A black box model is sufficient, where only the behaviour at the interfaces is of interest. Figure 7 shows that several levels of detail are necessary to define a proper mechanical coupling at the interfaces in a technical analysis. Each possible interface connection between two modules is localized to one or more interface nodes. At theses nodes the coupled degrees of freedom (dofs) have to be defined with at least one coupled dof and a maximum of all dofs (3 translatoric + 3 rotational).

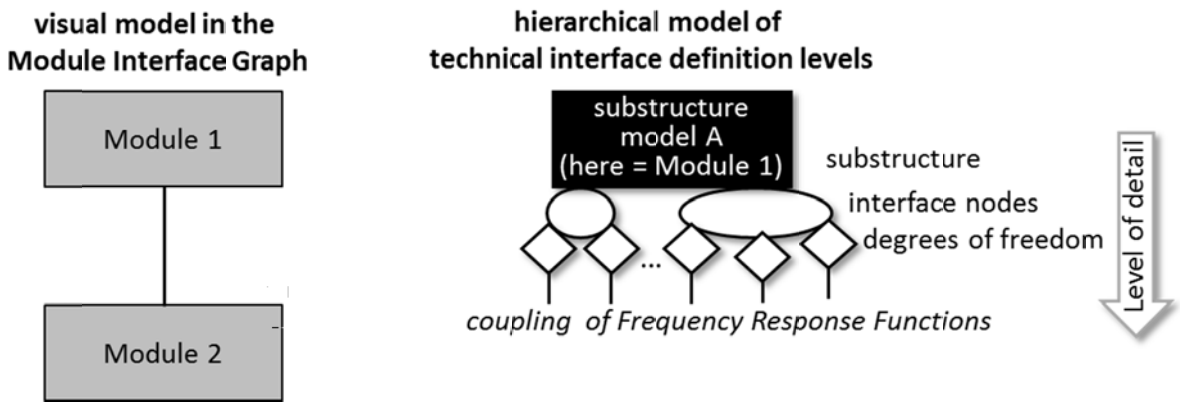

Figure 7. From MIG to technical interface definitions levels

Therefore detailing in three steps is defined, that starts on the level of the matching modules and substructures to further detail the technical interface coupling definition. The first step is the derivation of the cumulative coupling matrix from the MIG, which resides on a level of general interfaces of modules being coupled together in at least one product variant of the product family. Each possible localized structural interface connection is assigned a name tag (in the example in Figure 8 represented by the letters A,B,C,D). Here the interface A in the MIG connects the modules LP and PA. The respective entry in the symmetric matrix bears the name tag of the interface. The cumulative coupling matrix contains all possible couplings over the whole product family. The cumulative coupling matrix can also be derived using a Design Structure Matrix (DSM, [Lindemann et al. 2009]) which can be seen as precursor to the technical coupling matrix in dynamic substructuring.

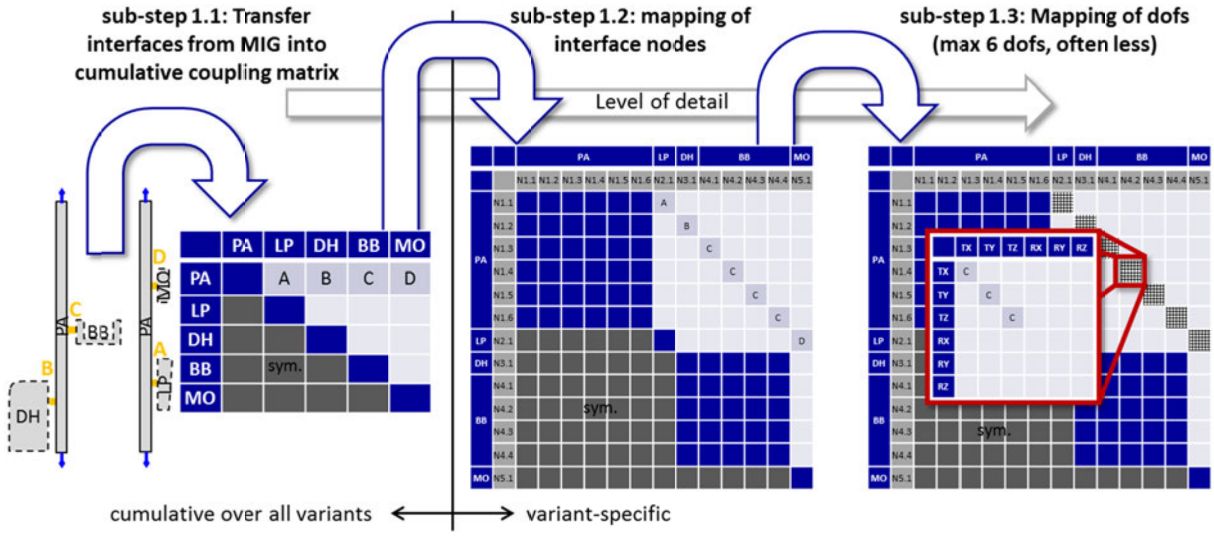

Figure 8. Transfer steps in detailed interface definitions

The further sub-steps 1.2 and 1.3 in Figure 8 then define the more detailed coupling definitions for each variant. The variant specific coupling may also happen at a later stage.

In the example of Figure 8 the baby bassinet (BB) is connected to the partition panel (PA) at four model nodes instead of one. By spreading the interface over more nodes, one can often neglect hard to measure rotatory dofs or obtain a higher local prediction resolution. Here, the necessary level of prediction resolution, the area covered by the interface and the amount of mass added to the main structure are the most relevant factors indicating that more than one node is needed for modelling. If uncertain about the necessary interface node number, parameter studies have to be performed. The technical characteristics to be defined for each different interface are node numbers, coupling dofs, modelling of local force distribution at the interface and dimensions to be coupled.

5. Preliminary evaluation in a development study

The approach has been developed to a level to be applied in a real application of a simple partition panel with different literature pockets to be added on, thereby forming different product variants. This preliminary application evaluation showed a prediction quality well suited for the application background. In Figure 9 a hybrid dynamic substructuring model of a simulated partition panel coupled together with a literature pocket model from a small shaker test resembles the measured transmissibility curve of the complete assembled system on the Hexapod vibration test rig very well.

A good coincidence of prediction and benchmark as shown in Figure 9 needs a clear model definition and a guideline as described in this contribution. A more detailed evaluation and validation study on an aircraft galley will be presented in [Plaumann and Krause 2014]. In general, good results are obtained if a good data base is used, which renders the approach feasible for the application.

Having some requirements as 1) a general understanding of variant-specific product development and modularization, 2) an adequately modularized product structure and 3) a consistent use of interface definitions, the approach presented here gives many benefits to the dimensioning of variant lightweight structures - not necessarily restricted to cabin interior - under stationary dynamic loads:

It supports the dimensioning by using a few modules to generate the combinatorial variety of many variants. This reduces the modelling effort as well as the calculation of new combinatorial variants and thereby helps to save time for more parameter variations in optimization. It further reduces the testing effort by using smaller and simpler test setups of a few modules instead of full scale tests for each variant. By offering the choice between test and simulation for the generation of the dynamic substructure models according to capabilities and needs in a hybrid calucalation approach it helps to increase prediction accuracy and reduces the modelling effort.

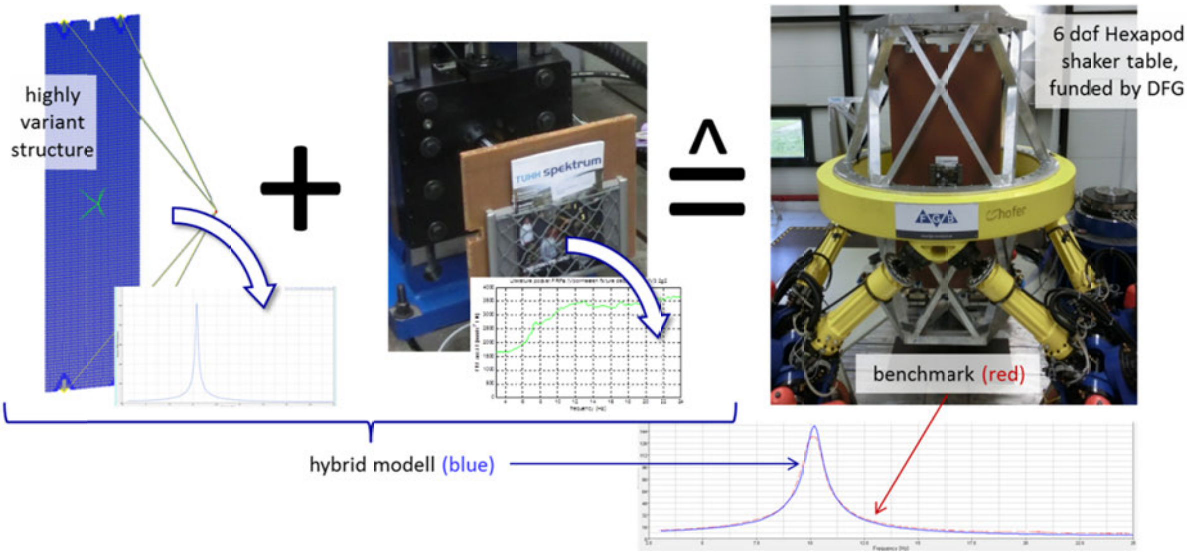

Figure 9. The hybrid dynamic substructuring model coincides with real test data of the assembled system

6. Summary

In industrial context of vibrational analysis and dimensioning of highly variant product families the design engineers are faced with tremendous simulation and testing efforts if each variant is optimized on its own. This often renders an individual optimization of each variant with current measures impossible. As a consequence this frequently results in inferior mechanical design solutions which are chosen because they are estimated to produce the least problems in critical safety tests. As a better solution to this problem an approach proposed that uses modules from a modular product structure in a dynamic substructuring procedure to calculate many variants by the combination of a few modules. The approach presented targets these problems with a systematic model preparation over all variants and the consequent use of a modular product structure matched to dynamic substructures in vibrational system identification. The approach supports dynamic dimensioning by giving methodical and technical guidelines as well as offering a software implementation.

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