Experimental Frequency-based Substructuring Exercise Guide

PhD Course in Advanced Structural Dynamics 16-19 June 2025,
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Experimental Background

In this exercise we will measure and couple FRFs between two separate substructures, A & B, using the virtual point transformation and compare the results to an experimental reference of the assembled system AB. You will test substructure A (Figure 11a). You will carry out the test with four 3D accelerometers at the interface, and a single 3D accelerometer at an internal degree of freedom on the structure. In interest of time, we will provide you with the experimental data for substructure B and the reference AB.

Group Tasks

1) Use the BK Connect software with 3D accelerometers mounted on the test structure A to measure accelerations (automatically post-processed to FRFs). Follow the ***Carry out experiment*** - start from **Step B (Step A** is just for info)
2) Import the experimental FRFs' into the python template for further analysis
3) Compare the experimental FRFs of substructure A with the numerical FRFs of the same – what do you see? What can be the reason for discrepancies between the numerical data and the experimental
4) Couple your experimental data to a numerical counterpart substructure B and compare with the numerical reference. How does it look? What could be the reasons for discrepancies?
5) Discuss which assumptions (and thus limitations) that follow by using FRFs for coupling, and the virtual point connection
6) If you were to improve this setup, what would you do?

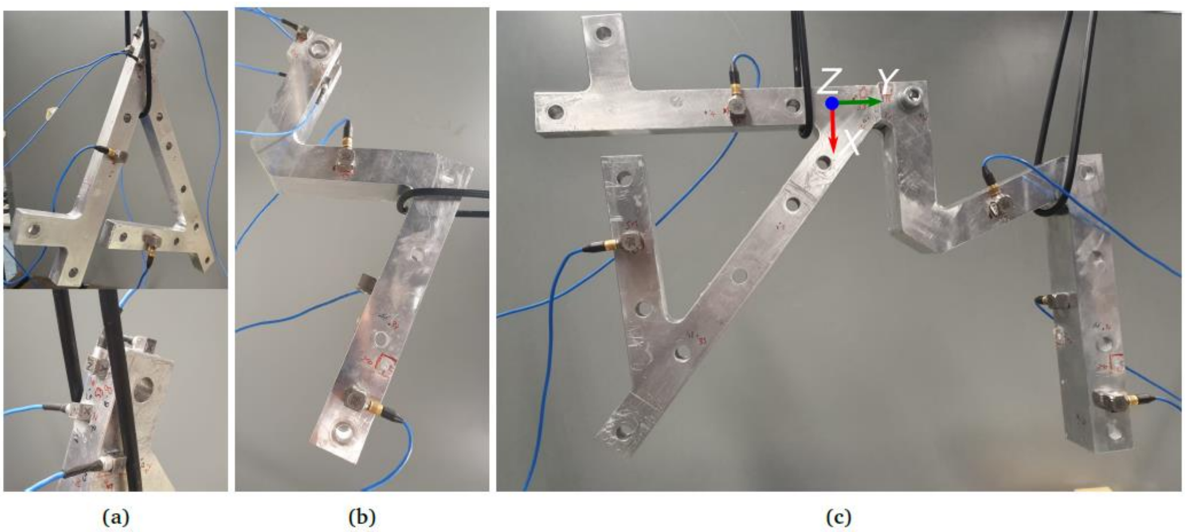

Figure 11: Experimental setup: (a) substructure A (with zoomed view of the interface) (b) substructure B, (c) A and B assembled.

Carry out the experiment

For an FBS experiment you need to go through the following. We have **prepared a template** for you so you don't have to do it all from scratch.

A. Connecting transducers
B. Setting up a new BK Connect Project
C. Model
D. Setup
E. Measure
F. Analyse
G. Import into Python and perform FBS coupling

A. Connecting Transducers

1) Figure 11a shows the experimental setup, with Substructure A hung in rubber bands (to simulate free-free boundary conditions), the impact hammer (BK 8206) used to excite a broad band of frequencies of the structure, and the accelerometers pick up the accelerations.
2) With the white nylon tip mounted on the force transducer at the hammer head, connect the cable from the force transducer to Channel 1 on the first PULSE Front-end module.
3) Mount the accelerometers at the desired positions (and directions), using super-glue, and connect the cable to Channel 2-16 on the B&K Frontend modules. Power on the frontends. Always take pictures of how the sensors are mounted on your structure and how the cables are connected.

B. Setting up a new BK Connect Project

- With the transducers connected and the Frontend powered, **Start / BK Connect App**. *After a while* the program opens, and the channel lights at the physical frontend at the lab desk table will flash briefly, indicating proper frontend connection.
- We have made a template ready for you to use. This template is called **FBS_PhDCourse**. Load this and then click "BK Connect 2024" in the upper left and "save project as" with a new name: **Group_NUMX.**
- The program requires a sequence of tasks, which are categorized in the top bar as **MODEL**, **SET UP**, **MEASURE, …**, **ANALYSE**. Clicking a task opens a menu for selecting subtasks (left bar symbols).

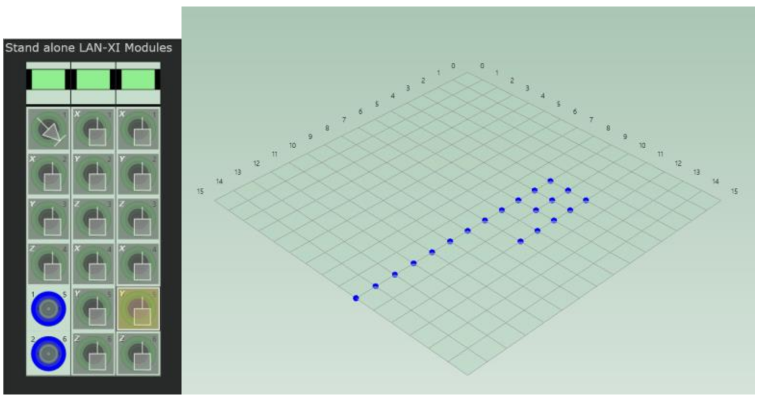

Figure 1 Left: Frontend Image. The first channel is the hammer, the next 15 channels are the 5 3D accelero-meters. Middle: Simplified geometry rep. of the 15 impacts points and 5 sensors positions.

C. Model

1) In the top bar click **MODEL / Geometry Editor.** You should see 20 blue dots. These represent the measurement points. 5 sensor positions, 3 'internal' and 12 'interface' hammer hits.

D. Setup

Transducer Manager

1) In the top bar click **SET UP / Transducer Manager**. The frontend image and hardware setup table should look like in **Error! Reference source not found.**.
2) In the drop-down menu in the HW Setup Table you can chose "Transducer Info", and in the **High-pass Filter** column see that for both signals all frequency content below 7 Hz is filtered away (this is well below the frequencies to be measured for the structure; setting lower HP filter frequencies than necessary implies unnecessarily long filter settling times, e.g. up to a minute for the 0.7 Hz setting) .

DOF Setup

1) Click **SET UP / DOF Setup**. The "blue-dot" geometry (Fig.2) should appear in the geometry window at the left.
2) In the DOF Sequence bar (below the DOFs window), we have already for you clicked **Chronological Order**, which created a list of 15 measurements to perform: The first line instructs to measure acceleration at all accelerometers in response to hammer hit 1; next line says measure (again) accelerations, but now impacting at a new position, and so forth, until all 15 DOFs have been hit. **Don't forget to save your project now and then (<Ctrl+s>).**

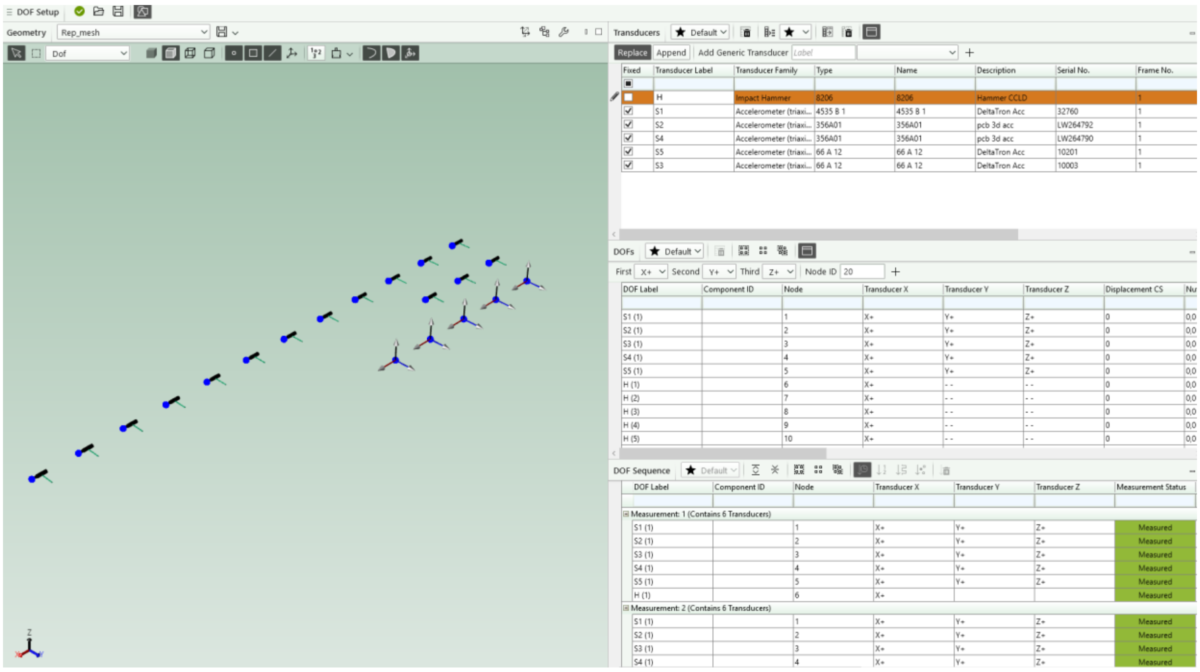

Figure 2 DOF setup. You should have 15 small hammer symbols and 5 coordinate systems representing the sensors.

Hammer Trigger Setup

1) In the left side bar click **Hammer Setup**, and click **Trigger** in the top bar to set up the *trigger level* for the hammer, i.e. the force level where the software understands the hammer has impacted something, so that it should start recording a measurement. In the Measurement Control window *deactivate* **Autoadjust**, and set **Trigger Monitor:** 10 s, and some basic frequency analysis parameters to apply for the whole modal analysis: **Analysis Mode**: Baseband, **Frequency Span**: 16000 Hz, **Record Length: 2** s. As appears in the table this gives **FFT Lines** = **Record Length** × **Frequency Span** = 16000, and **Frequency Resolution** = **Frequency Span / FFT Lines** = 1/ **Record Length** = 1 Hz. Note, the FRF output file will then be 16001 long, as it holds 0 Hz.
2) Then start the trigger setup by clicking in the Measurement Control window, and within 10 seconds (or the time set in the "Trigger Monitor" box) hit the structure repeatedly at H1,

with hit intervals of at least 1 s (or the time set in Record Length). (If no signal appears in the Recorded Trigger Window, try click , then in the new window, and in the top bar again **Trigger** and .)

3) In the Recorded Triggers window drag the dark blue square at the middle of the *upper* bar line so that the hammer peaks in the time signal are clearly above the line, and the line is also clearly above the noise floor (so that even light hammer impacts will trigger measurements, while noise and small signals like when you are moving the hammer won't). Then drag the light blue square at the middle of the *lower* bar line to a little lower than the upper line (this sets the *hysteresis* value, i.e. the value at which the trigger is *armed* to be ready for the trigger event to occur). Click Done, and you are automatically transferred to the next task, Weighting.

Hammer & Response Weighting

1) Being transferred automatically to this stage from the previous (else click **Weighting** near the top bar), you now setup the *weighting window* that will be multiplied with (i.e. "box") the input hammer time signal to improve the signal-to-noise ratio: If not starting automatically, click to start a measurement, impact the structure at H1, and then **Stop**. In the Hammer Weighting window select **Weighting Type:** Transient, and check that the hammer impulse in the Hammer Weighting window appears nicely boxed near the middle of the weighting window, and with no or only marginal visible change to the weighted hammer signal (lower window); otherwise adjust the weighting window as needed by dragging the square handles in the upper weighting signal window.
2) In the Response Weighting Setup window at the right, select **Weighting Type:** Exponential. This will multiply the output acceleration time signal with an exponentially decaying function so as to 1) improve the signal-to-noise ratio, and 2) reduce leakage and spectrum ripple caused by the discrete and finite time series (which for lightly damped system does not normally decay to zero during the recording time). Set **Suppression:** 99 %, which will reduce the weighted signal at the end of the record length to about 1 % of its max. value. Click Done. Remember to Save. Now, before proceeding, ***call your instructor*** to have your setup checked and help getting started with the measurements.

E. Measure

1) In the top bar, click MEASURE – Hammer Measurement. In the Measurement Properties window set **Number of Averages: 3** and click left of the number to lock this. In the same window click Initialize.
2) Click *Start*, and hit H1 with the hammer (they are numbered on the structure). Follow the voice instructions and add more impacts at H1, until the "Averaging complete" message appears in text, and the Average Counter window reports "Lin: 3/3". (Sometimes "Averaging Completed" is reported in text but not in voice; then just follow the text.) You can undo the latest average with .
3) Only apply hammer hits after a "Ready" message has appeared (and vibrations from the previous hit has been damped out by sliding (just quickly) your fingers along the structure surface. If relevant, delete the latest measurement by clicking . Click Done when satisfied with the measurement for this point.
4) Click *Next Measurement* & *Start* in Measurement Control, and that "Measurement # 2" is displayed in the Measurement Control window. Then apply three hammer hits at H2. If you see very bad coherence or rippled FRFs, redo the hit *(read more on coherence in Section F.4)*
5) Continue the same way with the remaining points. Click Stop after the last measurement and Done, and then **<Ctrl+s> to save the measurements with the project**.

F. Analyse

Measurement Validation

1) In the top bar click **ANALYSE** / **Measurement Validation** (left bar). In the folder structure folder at the left, browse/unfold to **Modal Analysis / Test 1 / Setup 1 / Measured Data / Hammer Measurement**, and drag the folder **Frequency Response Functions** to the graph area just at the right of the data folder tree.
2) The graphs shows all FRFs corresponding to the output accelerations (DOF 1-5 XYZ) in respons hammer hits at DOF #6, #7, ... ,#20. Scroll brieflt through the 225 FRFs and check if they look okay, with well-defined peaks and little noise noise. Click/toggle Overlay in the Functions bar to see all FRFs in the same graph.
3) Finally check the ***coherence*** **functions:** *D*eselect Overlay in the Functions bar, and drag the **Coherences folder** in the data tree to the graph area. The coherence functions show, for the same frequencies as the FRFs, the degree of linear correlation between input (here hammer impacts) and output (here acceleration of the 5 sensors). For an ideally linear and noise-free system the coherence is unity for all frequencies, while noise and/or nonlinearity gives a lower value, approaching zero for the case of no linear correlation between input and output. Coherence function values close to unity thus indicate measurements of high quality, supposing the system operates in a linear regime. Around resonances and antiresonances the the coherence typically drops below unity; this is expected and OK, since at *resonance* the input (force) is very small and thus the *force transducers* emits mostly noise, while at *anti*resonance the output (acceleration) is very small, so that the *accelerometer* emits mostly noise. So browse through the coherence functions and check they are close to unity expect at (anti)resonances. “Bad” (much lower than unity) coherence in the high-frequency end may be due to too little energy in the hammer hits at these frequency, then a harder hammer tip should be used. With piezo-based transducers (such as in this case both the accelerometer and the force transducer), bad corehence in the very low frequencies end (below 10-20 Hz) can also be expected, since anything piezo is typically weak at low frequencies, where energy $\propto$ (stroke × frequency)$^2 \approx 0$.
4) A bad measurement for a particular beam point is often easily identified by a coherence clearly lower than for the other measurements, also away from (anti-)resonances. As for the FRFs, *ripples* in only some of these could indicate undetected double hits. Ripples in all FRFs indicates that higher exponential suppression of the acceleration signal should be applied, cf. the above section **Error! Reference source not found.**. If you have any that stand out as bad –go back to *Measurement,* delete that particular point and redo it.

G. Export and analyse in Python

1) In the project browser, right click the “Frequency Response Functions” to export the FRFs. Use the “Export to Microsoft Excel” feature. A window opens – press Export. It takes a minute for it to make the excel file. It opens automatically. Save it in your Group folder on the USB with the file name “DATA_A”. Copy the data to your personal labtops.
2) Follow the instructions further in the Jupyter notebook for performing the FBS.