Scanning Laser Doppler Vibrometry Exercise

PhD Course in Advanced Structural Dynamics 16-19 June 2025, Marie Brøns

Experimental Background

You will test a thin plate, clamped in a frame fixture approximating simply supported boundary conditions. This is done by cutting the plate almost through its thickness all along the clamped edges, which provides only very little resisting bending moment along the plate boundary (recall that an ideal simple support provides infinite translation stiffness and zero rotation stiffness at the boundary). The plate is rectangular with dimensions **a×b×h = 150×120×1 mm** and is made of steel with Young's modulus **2.08×10^{11} Pa**, Poisson ratio **0.3**, and density **7850 kg/m^3.**

The plate is excited by a voltage-driven piezoceramic disk glued to the back of the plate. When oscillating, the piezoceramic disc exerts a local surface force and thus bending moment to the plate, which will then vibrate transversely.

You are to use an SLDV to measure the velocities of the plate surface, and use modal analysis to estimate natural frequencies, mode shapes and damping. Finally, you will compare the results to Kirchhoff plate theory and discuss the results.

Group Tasks

1) Use the SLDV to measure velocities on the plate surface, apply the modal software tool MEScope to obtain experimental estimated natural frequencies, mode shapes and damping by following Carry.out.experiment - start from **Step D** (Step A-C is just for info)
2) Calculate the theoretical frequencies and mode shapes (using eq. 1-3)
3) Calculate the deviation (in %) between experimental and theoretical natural frequencies. Discuss what reasons could explain the deviations?
4) Qualitatively compare theoretical and experimental mode shapes. Discuss how a quantitative comparison could be performed.
5) Discuss the experimentally obtained damping ratios
6) Would a FEM model, in this case, bring more insights than the theoretical model?
7) Discuss the pros and cons of an SLDV, when would you use it, when would you use another tool. List other possible ways of estimating experimental mode shapes.
8) Look at the average coherence function of your data – what does it tell you about the setup?
9) What is the difference between an operational deflection mode and a fitted mode shape?

Figure 1 Polytec PSV-500 scanning laser Doppler vibrometer

Kirchhoff Plate Theory

For a simply supported rectangular thin plate with sides a and b in a plane (x,y), thickness h, Young's modulus E, Poisson ratio ν, and density ρ, the natural frequencies f_{ij} for transverse vibrations are given by:

$$f_{ij} = \frac{\pi}{4\sqrt{3}}\sqrt{\frac{Eh^2}{\rho(1-\nu^2)}}\left(\left(\frac{i}{a}\right)^2 + \left(\frac{j}{b}\right)^2\right) \quad \text{(Hz)}, \quad i, j = 1, 2, 3, \cdots. \tag{1}$$

The corresponding mode shapes $\varphi(x,y)$ describing transverse deformations are:

$$\varphi_{ij}(x,y) = \sin\left(\frac{i\pi x}{a}\right)\sin\left(\frac{j\pi y}{b}\right), \quad x \in [0, a], \quad y \in [0, b], \tag{2}$$

with nodal lines (i.e. points at rest, $\varphi = 0$) given by:

$$\begin{aligned} x &= \frac{p}{i}a, \quad p = 0, 1, \cdots, i \quad ((i-1) \text{ internal nodal lines in total}), \\ y &= \frac{q}{j}b, \quad q = 0, 1, \cdots, j \quad ((j-1) \quad \text{ – " – } \quad). \end{aligned} \tag{3}$$

Carry out the experiment

You will now go through the following

A. Check the hardware is ready and calibrated
B. Define you scanning points on your plate
C. Check the parameter settings (frequency resolution and range, etc)
D. Measure a single point to see that the setup works
E. Perform the scan
F. Look at operational deflection shapes in the PSV Presentation Software
G. Export FRFs and use MEScope modal analysis software to fit natural frequencies, mode shapes and damping ratios.

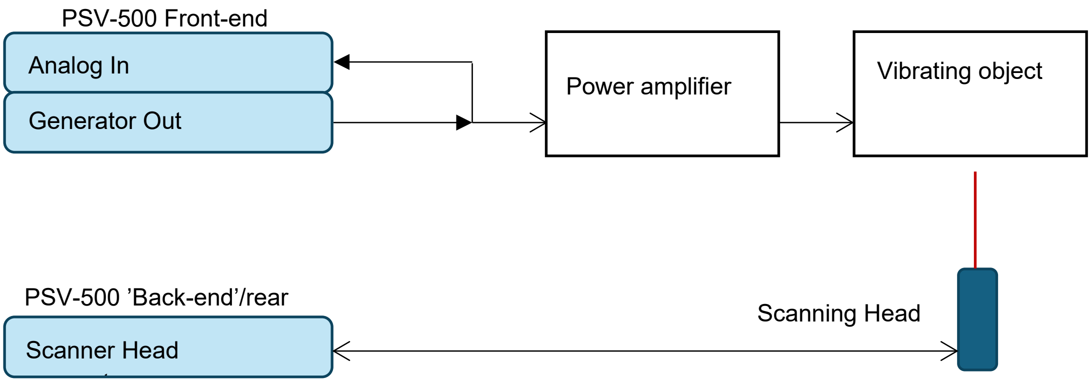

Figure 2 Experimental setup flow.

A. Check hardware setup

1) Figure 2 shows an overview of the wiring. Check that wires are connected as shown, e.g., that the piezo ceramic disk is connected to the Power Amplifier output, and the Power amplifier is connected to the PSV Frontend.
2) Check that the Power Amplifier is set **'Current Limit' to 5 A**, **'Attenuator' to 20 dB,** and **'Gain Control' to zero** (all the way counterclockwise).
3) Double-click the PSV desktop icon to start the Polytec software in Acquisition Mode (or use Window's start menu).
4) Check that the scanning head points at the object. For the best signal-to-noise ratio the distance from the laser beam exit in the camera to the object should be approximately an integer number of the laser's *resonator length* (20.4 cm for this HeNe laser).
5) Zoom in the video camera so that the object appears as large as possible in the video window: Use the slider **Zoom** in the field **Camera** or roll the mouse wheel (centre click and drag to move).
6) Now focus the video camera: First uncheck the **Laser** checkbox, since otherwise the laser beam prevents the video camera from focusing automatically. Then click **Autofocus** in the field **Camera**.
7) Switch the laser beam on again, and focus the laser beam into a small spot, either using the icons N and F, or automatically using the AF-icon.
8) Align the positions on the live video image with the position of the laser at the measurement surface, distributing alignment points over the surface:
    a. Click or in the top menu select **Setup / 2D Alignment**. The software will maximize the video window.
    b. Delete existing alignment points if any, either by right-clicking a point on the image (not an alignment point) and selecting **Delete All**, or by right-clicking and deleting individual points.
    c. In the toolbar of the video window, click . The High-Contrast Laser Display is activated.
    d. Move the laser beam with the left mouse button to the wanted position. The software searches for the laser beam and defines an alignment point at this position. Repeat this step, defining at least 3 alignment points. More points give more accurate positioning of the laser beam. For a rectangular plate 3×3 points evenly distributed will be fine.
    e. Once you have aligned all points, click again or select **Setup / 2D Alignment**.

B. Define Scan Points

1) Go to scan point definition: In the toolbar of the application window, click , or click **Setup / Define Scan Points**.
2) First delete all scan points which may already be defined: **Edit / Select All** and then **Edit / Delete**. If there are no scan points the fields are inactive.
3) Click in the graphics toolbar and draw the largest possible rectangle on the object, close to the boundary. A rectangle with a red edge and white squares marks the edges, and scan points appear in blue inside. Adjust as necessary by pulling the edges.
4) Click the first icon under **Object** and under **Grid** to display the scan points and the grid type. Set 'Density X' and 'Density Y' to 30 (or higher for a finer grid).
5) Pointing the mouse at the grid, the mouse pointer becomes a cross, and you can move the grid with the scan points by clicking the grid and moving it using the mouse.
6) You have now finished defining scan points. In the toolbar of the application window, click again (or **Setup / Define Scan Points**) to quit scan point definition.

7) Now point at the live video image and click a scan point; the laser beam moves to this point on the object. Click additional scan points to check and see if the laser beam is positioned precisely at the scan points. If some points fail on this test, try re-align using more points, as described above.
8) Now it's time to save your settings so far: **File / Save Current Settings As...**, assign the settings file a sensible name, and save it in *the data folder* D:\SLDVdata\Team-<*n*>

C. Check parameter settings

1) In the toolbar of the application window, click A/D, or select **Acquisition / Settings** in the menu bar; the dialog Acquisition Settings appears.
2) Display the tab pages in the dialog from left to right and set the parameters in each. The suitable settings depend on the object. For our plate with piezo-electric excitation set up as follows:

- **General** tab: Click FFT; Set 'Averaging' to 'Magnitude' with 3 samples per average; Check "Remeasure" + "Automatically adapt ..overrange (AutoRange)" (⇒ bad measurements are repeated after the first scan).
- **Channels** tab: Check Active for 'Vibrometer' (this is the signal for measured velocity); Direction=+Z; Check Active for 'Reference 1' (this is the input signal to the power amplifier driving the piezo ceramic disk); Direction=+Z; Range=10 V; Coupling=DC; Quantity=Voltage; Factor=1.
- **Filters** tab: Set all to 'No Filter'
- **Frequency** tab: **Bandwidth=3 kHz; From=0 kHz; To=3 kHz; FFT Lines=3200**. (These parameters affect the level of detail / accuracy of frequency spectra, as expressed by the frequency resolution displayed in Hz in the setup window.)
- **Window** tab: Set all to 'Rectangle'.
- **Trigger** tab: Source= 'Off'.
- **SE** tab (this is Signal Enhancement and Speckle Tracking): Check 'Vibrometer'; Check 'Speckle Tracking'; Set the Slider to 'Fast'.
- **Vibrometer** tab: Velocity=2 mm/s (max. velocity to be expected); Tracking Filter='Off'.
- **Generator** tab (signal to the power amplifier driving the piezo ceramic disk): Check 'Active'; Waveform='Pseudo Random'; Amplitude=1.5 V; Offset= 0 V.

3) Click **OK**.

D. Check all is in order using a Single Point measurement

1) Start output from the function generator: In the toolbar of the application window, click , or select **Acquisition / Generator** in the menu bar.
2) Turn on the **Power Amplifier**, initially turn up the 'Gain Control' knob up to about the **14 o'clock position**.
3) Start a continuous (in time) measurement: In the toolbar of the application window, click , or select **Acquisition / Continuous** in the menu bar. The analyzer displays the measurement signal on the vibrometer channel in the Analyzer window. If necessary autoscale the y-axis: Click in the analyzer toolbar, or **Analyzer / Autoscale** in the main menu bar (when the analyzer window is active).
4) If a time trace of the velocity appears, you can show the corresponding frequency spectrum by clicking - "FFT" in the Analyzer window and then RI AΦ - 'Magnitude [dB]'.
5) Click at a new scan point in the video window. The software will position the laser beam at that point and display the measured velocity there. Check if the measurement range is suitable: The 'Vib' bar (vibrometer signal) in the scanning head control (the rightmost panel) should be as far to the right as possible without overloading, i.e. without turning red. In case of overload either turn down the gain on the power amplifier, or increase the measurement

range: Click again, in the **Vibrometer** tab select the next higher measurement range under 'Velocity', click **OK**, and recheck the 'Vib' bar.

6) Stop the continuous measurement by clicking in the toolbar of the application window (or selecting **Acquisition / Stop**).

E. Perform the scan

1) In the toolbar of the application window, click . The dialog Save As appears. Navigate to the data folder, enter a suitable file name and click Save.
2) The scan starts. Leave the object and camera undisturbed. The scan takes some minutes.
3) In the video window you can follow the progress of the scan. Each scan (except maybe a very few) points should appear as 'Valid' or 'Optimal', cf. the color code left of the live video window. If you are unhappy with the test, you can interrupt the scan by clicking .
4) After ended test - turn off the generator and the BK amplifier.

F. View the Operational Deflection Modes

1) Select **View / Presentation**, and use **File / Open** to find and load the saved scan file (file extension .svd) from you data folder.
2) In the PSV Presentation program, click **Window / Tile Horizontally** in the main menu; then in the lower window, showing a spectrum (cf. Figure 3), click the 'Autoscale' icon. (If there is no spectrum click **Presentation / View /Average Spectrum**.) Click and select 'Magnitude [dB]'.
3) To check the quality and linearity of measurements you can display the *coherence function*[1] (but only if 'Averaging' > 1 was set under **Acquisition** / **Settings** / **General**): Click in the spectrum window and select 'Vib & Ref1'; then click and select 'Coherence'. To return to displaying the velocity-FRF: click and select 'FRF Velocity / Voltage.
4) Click or select **Setup / Frequency Bands** in the main menu, and the Frequency Band Definition window appears. It should hold a template for at table of frequency bands, if it doesn't then click in the toolbar of the window to display the Frequency Band Editor.
5) In the spectrum window, click each frequency of interest (typically that's the peaks, i.e. the resonance frequencies). In the Frequency Band Editor, you see a new row entering the table for each frequency you click. To delete rows, select one or more and click or press <Del>.
6) When finished selecting frequencies, in the Frequency Band window, click the 'Save Frequency Band' icon , click **Save**, browse to your data folder, and close the Frequency Band window while clicking 'Yes' to the 'recalculate frequency band?' question.
7) Now you can display the vibration pattern corresponding to each of the selected frequencies (cf. Figure 4): In the upper window use the drop-down button just right of the icon to select. Click the zoom icon to adjust to proper display size.

G. Perform modal analysis – estimate phi, omega and zeta

1) *Export:* While still in the PSV software, select **File / Export / ME'scope**, browse to your data folder, and click **Save**. In the window popping up check the 'Display Objects (Elements)' box. Expand the 'Points' list (*don't* check the box itself!) and thereafter the 'FFT' box (without

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[1] The *coherence function* is a measure of the amount of uncorrelated noise and / or nonlinearity in the measured input-output relation. It attains a number between *unity* (if the input-output relation for the system at a given frequency is linear and noise-free) and *zero* (pure noise or strong nonlinearity). The coherence function should be reasonably close to one in the frequency range of interest. However, drops in coherence usually appear, and are acceptable, at resonances (where the input signal is weak and the input sensor thus measures mostly noise), and at anti-resonances (where the output signal is weak and the output sensor(s) thus measures mostly noise).

checking it). Under the 'Vib & Ref1' list, check (only) the 'FRF Velocity / Voltage' box (this signal holds the measured velocity-FRFs), and click **OK**. Then you can close the PSV Acquisition and PSV Presentation program windows.

2) *Import:* Start the ME'scopeVES (64 bit) software. On the Start Page opening window, click **Create a new Project...**, using the same file location and root name as for the PSV project you saved earlier. Import the measured data from the PSV: Click **File / Import / Structure** to import the geometry (.str) file and then **File / Import / Data Block** to import the scan measurement (.blk) file. When asked for a file name for saving, just confirm using the same root name as for the project. Answer **OK** to questions.
3) Arrange the display: Click **Windows / Arrange Windows / For Animation** and widen the spectrum window so that you can clearly see the peaks.
4) Next use ME'scope to estimate the modal properties of the measured system, i.e. the natural frequencies, damping ratios, and mode shapes for the scanned frequency range.
5) Click the Block Data window (BLK:). Click **Format / Y-Axis**, check 'dBs' and adjust the 'Decades' number until you see both the peaks and valleys in the spectrum.
6) Select a range of frequency for the estimation of modal parameters: click **Cursor / Band Cursor**, and use the mouse to position the vertical red lines marking the frequency (cf. the example shown in Figure 5, upper left).
7) Click **Modes / Curve Fitting** and press.the **Count Peaks** button on the **Mode Indicator** tab to count the number of modes (resonance peaks) in a cursor band; answer 'Yes' to the "Warning! Traces are selected.. " question, and select 'Magnitude' / OK in the popup box. The graph below the spectrum then displays the modes counted as red dots, and the **Modes** box on the **Mode Indicator** tab shows the number of peaks (cf. Figure 5, lower left and upper right). Only modes with a peak above the *noise threshold* are counted (horizontal line; change by pulling slider bar at the right).
8) Check the red dots to see that all peaks in the selected band are identified. If not try repeat from step c), selecting 'Real Part' instead of 'Magnitude'. Or repeat from step b), using a smaller or larger frequency range. Or count the number of peaks yourself and enter the number manually in the **Peaks** box.
9) Now estimate the natural frequencies and damping ratios: On the on the **Frequency & Damping** tab check that **Global Polynomial** method is selected. Then click the **Frequency & Damping** button, answering 'Yes' to the 'Method ... continue?' question. New frequency & damping estimates are now added to the Modal Parameters spreadsheet (Figure 5, lower right).
10) Check that the frequencies appear to agree with the spectrum peaks, and that there are no missing or extraneous frequencies. To redo one or more estimations, just select and delete the corresponding rows in the Modal Parameters spreadsheet: click the icon or select **Curve Fit / Delete Selected Modes**.
11) *Note:* In many cases (especially with noisy data), it is better to build up a list of modal frequencies & damping by curve fitting in small cursor bands, using few modes or even only a single peak each time.
12) To estimate mode shapes, under **Residues - Save Shapes** click the **Residues** tab (answer 'Yes'), and the frequency response plots will be overlaid by red curves showing the corresponding curve fitted FRFs. Click **Save Shapes / New File / OK**, and a new spreadsheet will appear, listing shape numbers and corresponding estimated natural frequencies and damping ratios.
13) To animate mode shapes: Click **Windows / Arrange Windows / For Animation**, and then **Animate / Animate Shapes** in the main menu; answer **Yes** / **OK** to the series of questions popping up. Select any shape number in the Shape Table (turns green) to animate the corresponding mode shape. Adjust the display to your liking:
    - To display click with the animation window activated or **Animate / Contours / Contour Colors**.

- To display scan points during animation, click .
- To change from 3D- to 2D-view double-click the animation window. Double-click any of the 2D-views to show only that and double-click again to return. The “Z View” (top view) is often particularly illustrative, in showing more easily identifiable nodal lines and points.
- To pause/continue or animate stepwise, use the controls.
- To change viewing direction for the 3D animation: With the courser in the 3D animation window, click and hold down a mouse button while moving the mouse.
- To save still pictures of animated shapes: **File / Save Graphics in a File...**.

2) To copy spreadsheet cells to the keyboard: Select, press <Ctrl+C>, and paste them into other Windows applications. Or select / right-click and choose among options.

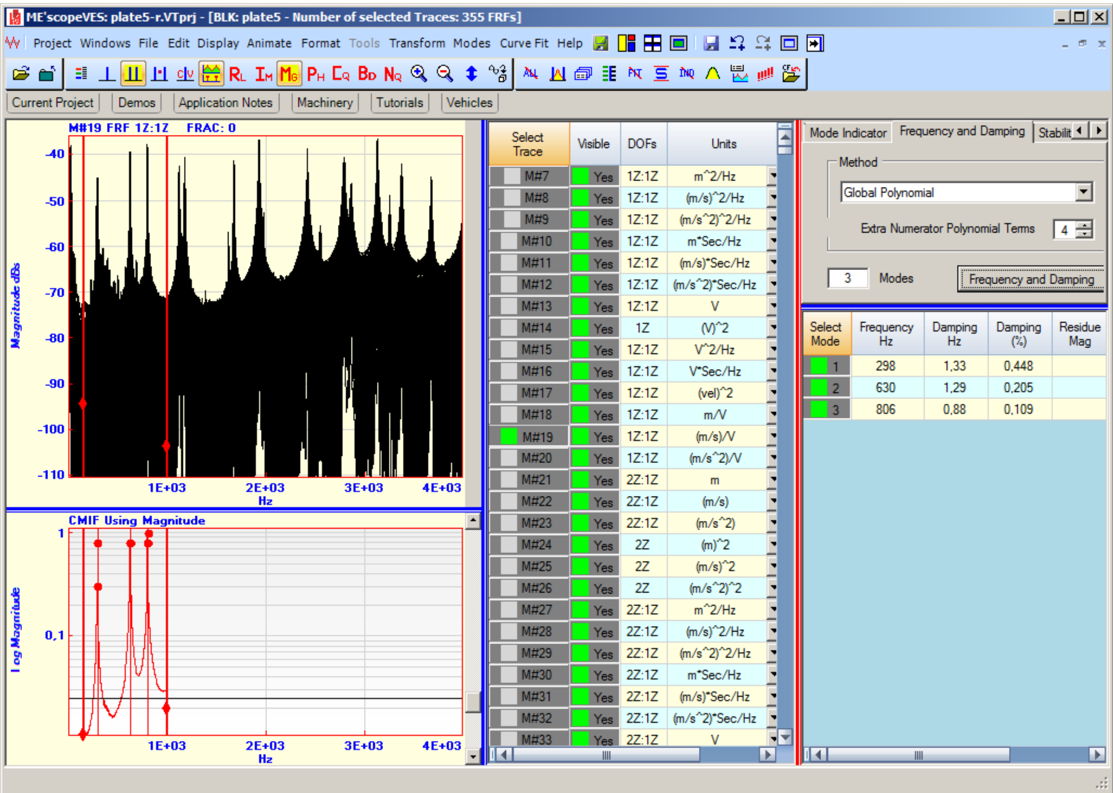

Figure 3 ME’scope during modal parameter fitting. The frequency band of the three lowest modes has just been defined (red vertical lines) on the overlaid plot (upper left) of all FRF measurements. In the Mode Indicator window (lower left) identified peaks appear as red dots. The resulting estimates of natural frequency and damping ratio appear as rows in the Modal Parameters spreadsheet (lower right).

Technical Specifications of the SLDV

Main physical principle	Laser Doppler velocimetry (frequency shift of backscattered light)
Main / typical application	**Non-contact full-field stationary and transient 0-100 kHz vibration analysis for structures of size ≈1 cm to 1 m**
Measured quantity	**Velocity / 1D out-of-plane** (optionally 3D)
Geometry input	a) Automatic 3D-scan by integrated laser distance sensor, *or* b) imported from CAE/FEM model
Output quantities	Out-of-plane field patterns for stationary vibrations / operational deflection shapes, or transient motion; Frequency output spectra, frequency response functions & coherence; Natural frequencies & damping ratios
Digital resolution	24 bit
Measurement ranges:	
Velocity	**0.001-10 m/s** (full scale ranges)
Frequency	**0-100 kHz**
Scan angle	±20° × 20°
Scan resolution	0.002°
Measurement time	≈n^2/50 s for an n×n spatial measurement grid
Measurement distance	0.125-100 m (or 0.250-30 m if the geometry scan unit is used)
Measurement object:	
Size	Typical: ≈1 cm to 1 m; Max.: Depends on distance (object as large as will fit inside scan angle); Min.: Down to 1×1mm with optional closeup unit
Geometry	Generally curved / 3D
Surface	**Diffusively reflecting** (i.e. *not* like a mirror or window glass)
Preparation	Connect to mechanical input source (e.g. shaker or hammer); Mount reference sensors if needed
Excitation	Integrated 4-channel signal generator (0-250 kHz) for driving external exciters (e.g. shakers): random, pseudo random, sweep, burst chirp, burst random,…
Ref. sensor channels	4 (optionally 8)
Software includes	Data acq. & analysis; Remote control; Spectral & coherence analysis (12,800 lines, optionally 204,800); Measurement grid layout; High res. geometry scan; Geometry data import (UFM, ME'scope, ASCII); ME'scope modal analysis (vibration modes, natural frequencies, damping ratios); Structural modification analysis; Data export in standard formats
Weight [kg]	20-30
Max. Power requirement	<600 W
Operation temperature	+5 to +40 °C
Safety issues	Class 2 laser (< 1 mw)