Dynamic Pressure Reconstruction using the VFM

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Abstract Full-field pressure measurements are highly relevant in material testing, component design and investigations of flow-surface interactions. Current standard methods are based on point measurements using transducers or tappings. This study shows that full fields slope measurements obtained using deflectometry allow pressure reconstructions with the Virtual Fields Method (VFM). The investigated air jet impinging on a flat plate allowed an assessment of pressure reconstruction capabilities for mean as well as fluctuating quantities. The resolved amplitude of pressure fluctuations is well below 100 Pa, which is remarkable. The method is computationally inexpensive and allows full-field surface pressure measurements which cannot be achieved easily with current methods.

Introduction Slope measurements from deflectometry in combination with the Virtual Fields Method (VFM) allow reconstructions of pressure distributions on thin plates. The VFM approach is based on the Principle of Virtual Work (PVW) and thin plate theory. It requires knowledge of the plate material parameters, surface curvatures and accelerations as well as a set of virtual fields to be chosen. Curvatures and accelerations are calculated from the measured surface slopes. Slope information is required over the entire domain. Virtual fields were defined piecewise using Hermite 16 shape functions. The approach was recently used for known mechanical point loads [3]. Mean and fluctuating pressure distributions were investigated in this study. A sensitivity analysis allowed assessing the systematic error of reconstructions. Dynamic Mode Decomposition [5] was used to investigate pressure fluctuations. The results were validated using pressure transducers. The reconstruction of the low amplitude pressure fluctuations is particularly remarkable, as such low pressures are usually only measured point wise using arrays of pressure transducers.
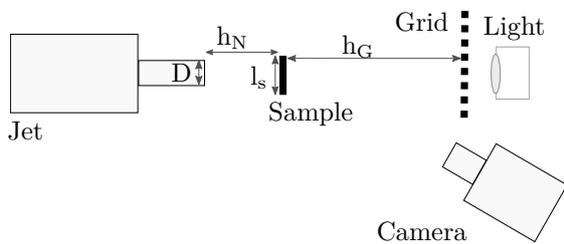

Figure 1: Experimental setup.

Setup Deflectometry is an optical technique for surface slope measurement [6]. The sample plate is deformed locally by and impinging air jet, resulting in variations of the surface slopes. The camera recording the grid reflection was directed at the reflective back side of the plate with the grid positioned next to it at distance h_G=.96 m from the sample (Fig. 1). A first-surface glass mirror of thickness t=1 mm and side length l_s=9 cm was used as sample. The jet-nozzle diameter was D=2 cm, the exit dynamic pressure p_{exit}=620 Pa, the distance between nozzle and sample h_N=4 cm and the Reynolds number ca. Re=$4 \cdot 10^4$. Deformations of the reflected grid image on the reflective surface allow calculating the slopes from the corresponding phase shift. Curvatures are then calculated using spatial differentiation of the slopes, deflections using spatial integration, and accelerations through temporal differentiation of the deflections.

Pressure Reconstruction The VFM was developed for material parameter identification and further used in force and pressure reconstructions [1]. It does not rely on iterative procedures to match numerical and experimental results like FEM updating and does not require knowledge of the boundary conditions. The equilibrium of an isotropic, homogeneous plate through the principle of virtual work, assuming pure bending and linear elasticity, is given by equation 1.

$$\int_S p(t_i) \cdot w^* dS = \rho h \int_S a(t_i) \cdot w^* dS + \int_S \kappa^* D \kappa(t_i) dS \qquad (1)$$

(a) Mean pressure reconstruction (PRW=22, Gaussian kernel σ=7).

(b) DMD mode for 857 Hz at time step t=0 ms (PRW=32).

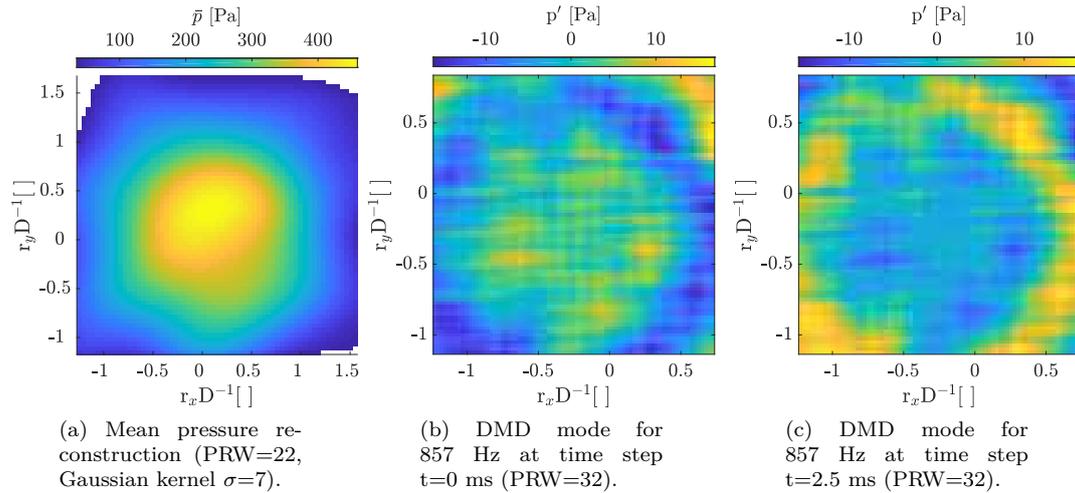(c) DMD mode for 857 Hz at time step t=2.5 ms (PRW=32).

Figure 2: Pressure reconstruction results.

Here, p is the investigated pressure, t_i a point in time, S the surface area, ρ the material density, h the plate thickness, a the acceleration, D the bending stiffness matrix and κ the curvature. w^* and κ^* are the virtual deflections and curvatures. Hermite 16 element shape functions are well suited to obtain virtual fields for the thin plate bending problem [4, chapter 14]. A window of four Hermite elements of a chosen size is used for local pressure reconstruction and shifted over the entire field of view.

Results Measurements were conducted using deflectometry and processed with the VFM. Mean and fluctuating pressure distributions on a reflective surface bending under an impinging jet were reconstructed from slope maps. Figure 2 shows example results for mean pressure and DMD modes, showing vortex rings impinging on the surface and propagating radially outwards. Pressure distributions and magnitudes were validated using pressure transducer measurements and agreed well with literature (e.g. [7], [2]). The small pressure amplitudes extracted using DMD open possibilities for future studies on aerodynamic load distributions and turbulent structures on surfaces.

References

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