Dissertation title:

Numerische und experimentelle Untersuchungen zu strömungsinduzierten Verformungen von gefalteten Luftfiltermedien

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Within the scope of advancement of today's air filter elements, the mechanical strength of the pleated filter media is becoming more important. Due to the interaction of the fluid flow with the porous filter structure, especially at high pressure forces, flow-induced pleat deformation may occur. Therefore, the optimization of the mechanical stability of the filter pleats is a complex task. Previous measures are usually based on empirical data and they are expensive and time-consuming.

Hence, the aim of this thesis is the development of a new method which enables a virtual modeling of Fluid-Structure Interaction (FSI) for air filter elements. By consulting respective literature, one identifies shortcomings in knowledge regarding the modeling and validation of flow-induced deformation for filter elements. This concerns the anisotropic and manufacturing-related material behavior, the change of permeability of the filter medium as well as the coupling of the fluid and the porous filter structure in particular. Furthermore, it turns out that there does not exist an experimental approach to quantify and validate the flow-induced deformation of the filter pleats by using an entire filter element.

Within the framework of this thesis, new approaches and models based on the filter media scale and the filter pleat scale are developed and validated. To characterize the material behavior at the media scale, an anisotropic material model is built. For this purpose, necessary material constants are identified by using experimental data and estimates based on literature. The manufacturing-related effects on the material behavior at the pleat tips are taken into account by a special sub-model. Experimental investigations regarding the material behavior by using a bending test confirm the virtual material model which is then implemented into a more complex structural-mechanical model of a single pleat.

In a further part of this thesis, the flow-induced deformation on the filter pleat scale is considered. Therefore, analytical and numerical models are developed to describe the flow and the structural behavior of filter pleats physically and mathematically. An initial analytical approach enables the prediction of the filter pressure drop as a function of the geometrical and physical properties of the pleated filter medium.

For a more detailed analysis regarding the flow and the pressure field inside the filter pleats it is necessary to model the problem based on numerical methods. For this purpose, a symmetric geometrical model of a V-shaped

single pleat is introduced. The numerical calculation of the flow field is hereby realized by using the incompressible Navier-Stokes- Equations based on a Finite-Volume-Method (FVM). To consider the dust loading inside the porous medium a simplified loading model is implemented.

Regarding the structural-mechanical approach for the filter pleats an analogous model based on the Euler-Bernoulli beam theory is derived. It becomes apparent that the analytical and numerical solution show a good agreement for simple loading conditions. However, for a more inhomogeneous distribution of the mechanical loads the analytical solution is useful to a limited extend only. For this reason, it is also necessary to further consider the structural-mechanical problem on basis of numerical models. The numerical approach for the structural-mechanical model of the single pleat can be described mathematically by using the fundamental equations of elastostatics and being based on the Finite-Element-Method (FEM).

Due to the requirements in regard to flexibility, the coupling of the numerical flow- and structural model is realized by a so called partitioned approach. The interface to transfer forces and displacements is represented by the surface of the filter medium.

For the validation of the coupled fluid-structural model experimental tests to quantify the flow-induced deformation of the filter pleats are carried out. For the investigation of the pleat deformation a novel test setup is developed using a contactless measuring device. The experimental results show a significant impact of the pleat height on the pleats’ deformation. Furthermore, increasing the flow rate leads to disproportional deformation of the pleats. Those can be ascribed to non-linear effects due to a contact of the inner sides of the pleat.

Based on those experimental results the entire coupled fluid-structural model is then validated, considering the interplay of all sub-models. It is apparent that the downstream area in-between the inner sides of the pleats can be used as a comparative value for simulation and experiment. In addition, a comparison of the pleat’s surface profile in an un-deformed as well as a deformed state shows a good agreement of simulation and experiment in qualitative and quantitative manner.

Subsequently, two examples of application are presented. The first example shows the change of velocity and pressure field inside the pleat channels in an unloaded filter element during a flow-induced pleat deformation. The second example illustrates the impact of dust loading on the deformation of the pleats. Comparing the previous simulation method, without FSI, with the new simulation approach clearly demonstrates the significant impact of the pleat deformation on the filter element’s pressure drop. This applies for loaded filter pleats in particular. Furthermore, the pressure distribution inside the pleat channels is visualized by simulation data. The results of this work also provide an advanced insight into the quantity and the quality of flow-induced deformation of filter pleats.