INTEGRATIVE SIMULATION METHOD FOR THE PREDICTION OF ANISOTROPIC AND TIME-DEPENDENT MECHANICAL BEHAVIOR OF INJECTION MOLDED FIBER-REINFORCED FAN IMPELLERS – NUMERICAL AND EXPERIMENTAL APPROACH

Andre LASS[1], Sebastian HERTLE[2],
Dietmar DRUMMER[2], Frank-Hendrik WURM[1]

[1] *University of Rostock, Institute of Turbomachinery (ITU), Albert-Einstein-Str. 2, 18059 Rostock, Germany*

[2] *Friedrich-Alexander-University Erlangen-Nuremberg, Institute of Polymer Technology (LKT), Am Weichselgarten 9, 91058 Erlangen-Tennenlohe, Germany*

SUMMARY

The present paper deals with an integrative simulation method to predict time- and load-dependent mechanical behavior of a radial fan impeller considering the anisotropy caused by injection molding of fiber reinforced thermoplastics. Pressure-dependent viscosity of the melt is taken into account in the injection molding simulation, which improves the accuracy of numerical results. Aerodynamic loads have been mapped to the structural model of the radial fan, whereby their influence regarding the structural deformation have been found negligible. It is shown, that the influence of mechanical anisotropy on the eigenfrequencies and radial displacement cannot be approximated with an isotropic material model using a single scaled Young's modulus. Finally, two strain measurements systems, based on 3D digital image correlation and strain gauges, are presented, which will be applied to fan impellers in further research to validate numerical results.

INTRODUCTION

Currently installed fans are responsible for more than 10% of the total European energy consumption. Therefore, minimum efficiencies have been defined to ensure that future developments aim for the lowest energy consumption. Nowadays, fans are increasingly produced using fiber reinforced plastic materials as it contributes to energy and resource savings and reduces weight. Injection molding offers great flexibility in the design of innovative, noise reduced and energy efficient fans, as blade add-ons like winglets, gurney flaps or vortex generators as well as special shaped leading or trailing edges can be incorporated.

Besides the named benefits increased demands result for the structural analysis. The common isotropic material assumption is not valid if fiber reinforced materials are used in injection molding process, as the local elasticity relates to the process-induced direction and distribution of the fibers within the part. Since, the fan is a rotating turbomachinery, operational conditions like the rotational speed and fluid pressure distribution are acting on the impeller. In addition, time-dependent deflections of the structure can arise due to material creep, which can result in structural failure, as unexpected contact of rotating and stationary parts, like impeller and casing, may occur. The design process of the fan impeller needs to ensure the structural strength for all expected operating conditions including material creep. Therefore, to predict the mechanical behavior of fiber reinforced fan impellers an integrative simulation method is required. In the present paper an integrated method is outlined and applied to a radial fan impeller. Here, operational conditions and anisotropic material properties are investigated, while creep will be considered in the next research phase.

INTEGRATIVE SIMULATION METHOD

The integrative simulation method for fan application is based on the coupling of multiple numerical methods. Namely, it includes the numerical simulation of injection molding of fiber reinforced thermoplastics, the determination of aerodynamic loads and the structural analysis, which deals with strength prediction and modelling of creep behavior. In Figure 1 a schematic overview of the integrative simulation method for fan applications is depicted.

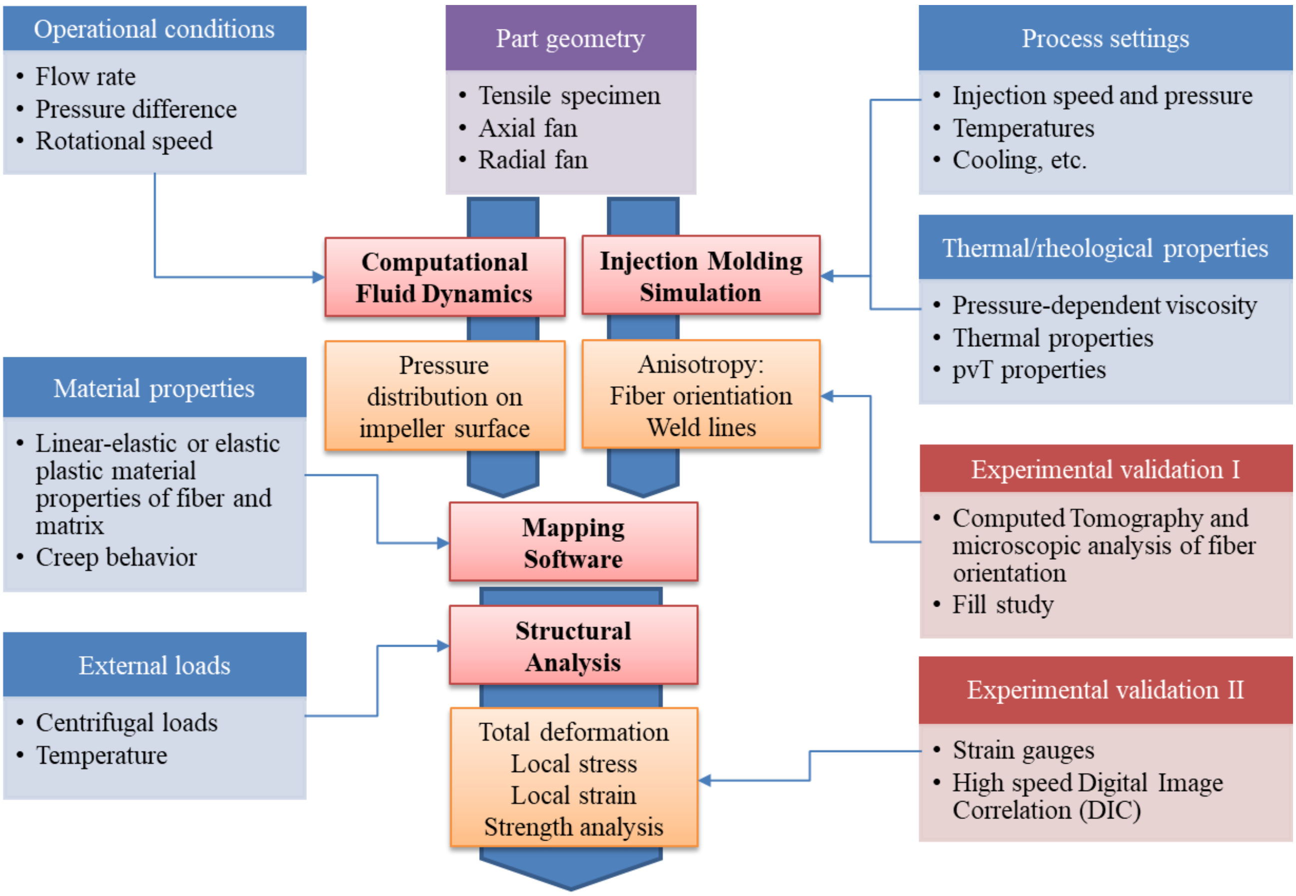

Figure 1 Schematic overview of integrative simulation method for fiber reinforced injection molded fans

Within the current effort the simulation environment is built by combining commercially available tools:

- Injection Molding Simulation (IMS): *Moldflow Insigth* (Autodesk, Inc.)
- Computational Fluid Dynamics (CFD): *Ansys CFX* (Ansys, Inc.)
- Structural Analysis (FEM): *Ansys Mechanical* (Ansys, Inc.)
- Mapping Software: *CONVERSE* (PartEngineering GmbH)

Usually material properties of fiber reinforced thermoplastics are limited by the manufactures to few information like isotropic Young's modulus and tensile strength of a tensile specimen with an idealized fiber/filler orientation distribution. To predict the time-dependent mechanical behavior of injection molded fiber reinforced fan impellers additional material properties are required. Therefore, the following investigations must be done for a tensile specimen of the chosen material:

1. thermal/rheological material characterization: derive thermal/rheological properties of the material for injection molding simulation
2. Biaxial tensile testing: measure stress-strain curves & calculate isotropic material properties
3. material calibration: approximate individual mechanical properties of matrix and fiber
4. creep tests: determine load- and temperature-dependent creep curves and derive parameters/coefficients for numerical creep modelling

After determining the thermal and rheological properties of the melt and defining the process settings the IMS can be conducted. To derive an accurate fiber orientation in IMS an orientation model like *Folgar-Tucker* (FT), *Reduced Strain Closure* (RSC) or *Anisotropic Rotary Diffusion - Reduced Strain Closure* (ARD-RSC) or others needs to be chosen based on the materials fiber length and/or experimental results (see Figure 1 – Experimental validation I). For short fiber-reinforced thermoplastics (SFT) the RSC-model usually yields good agreements with experimental results, while for long fiber-reinforced thermoplastics (LFT) the ARD-RSC-model is recommended [1].

If an appropriate orientation model has been selected, the fiber orientation can be mapped onto a structural model using a suitable mapping software. In the present software environment, the influence of the fiber orientation on the mechanical and thermal properties of the injection molded part is considered by the application of micro-mechanical models in CONVERSE. As describe in [2], CONVERSE is based on the transversal isotropic stiffness of a composite according to the approach of Tandon and Weng [3]. To account for the fiber orientation distribution across the injection molded part thickness the mapping tool conducts a weighted averaging of the transversal isotropic properties as presented by Advani and Tucker [4]. To determine the transversal isotropic stiffness of the composite the estimation individual material properties for matrix and fiber are required. Namely, these are the Youngs's modulus (E), Poisson's ratio (ν), Density (ρ) and the thermal expansion rate (α). Additionally, the fiber weight fraction (Ψ) and information regarding the fiber geometry (L/D) must be measured or approximate. On the one hand, the mechanical properties of the fibers usually can be estimated using literature values (e.g. glass, carbon). On the other hand, the matrix properties need to be calibrated as its mechanical properties may significantly differ from the unreinforced grade due to additional coatings added by the manufactures to improve fiber-matrix adhesion. Finally, experimentally determined creep curves for various loads and temperature can be used to determine a creep master curve, which will be implemented in a numerical creep model.

In the design process the aerodynamic loads as well as centrifugal loads shall be considered with respect to the environmental boundaries. For example, material properties must be determined as a function of the expected temperature.

RESULTS

The integrative simulation method has been applied to a six bladed, injection molded radial fan manufactured using Albis ALTECH PP-H A 2040/159 GF40 CP. This polypropylene homopolymer contains about 40 weight-% short glass fibers.

Injection Molding Simulation

For IMS the geometry of impeller and feed system has been meshed with 10 three-dimensional tetrahedral element layers across the wall thickness. The Hot runners between feed system an injection location have been modelled using multiple one-dimensional beam elements. The Process Settings have been set based on the ram speed and geometry, as well as the packing pressure measured at the injection molding machine. The molding material properties provided by *Moldflow Insight 2017* are enhanced by editing the standard Cross-WLF parameters to account for pressure-dependent viscosity η:

$$\eta = \frac{\eta_0}{1 + \left(\frac{\eta_0 \dot{\gamma}}{\tau^*}\right)^{1-n}} \tag{1}$$

$\eta_0, \dot{\gamma}, \tau^*$ and n refer to the zero-shear velocity, the shear rate, the critical stress level and the power law index in high shear rate regime, respectively. The zero-shear velocity is defined via modelling parameters in:

$$\eta_0 = D_1 \exp\left[-\frac{A_1(T - D_2 + D_3\,p)}{A_{\tilde{2}} + T - D_2 + 2\,D_3\,p}\right] \tag{2}$$

The corresponding parameters for the Cross-WLF approach have been determined experimentally by [5] and are summarized below:

$n = 0.295$; $\tau^* = 8901.21$ Pa ; $A_1 = 4.9045$; $A_{\tilde{2}} = 261.79$ K

$D_1 = 40762$ Pa s ; $D_2 = 513.15$ K ; $D_3 = 2 \cdot 10^{-6}$ K/Pa

In Figure 2 the injection pressures for the case of the pressure-independent and pressure-dependent viscosity parameters are compared to measured results. All results have been normalized using the maximum measured injection pressure. Clearly, the numerically calculated injection pressure considering pressure-dependent viscosity yields a better match with measured results.

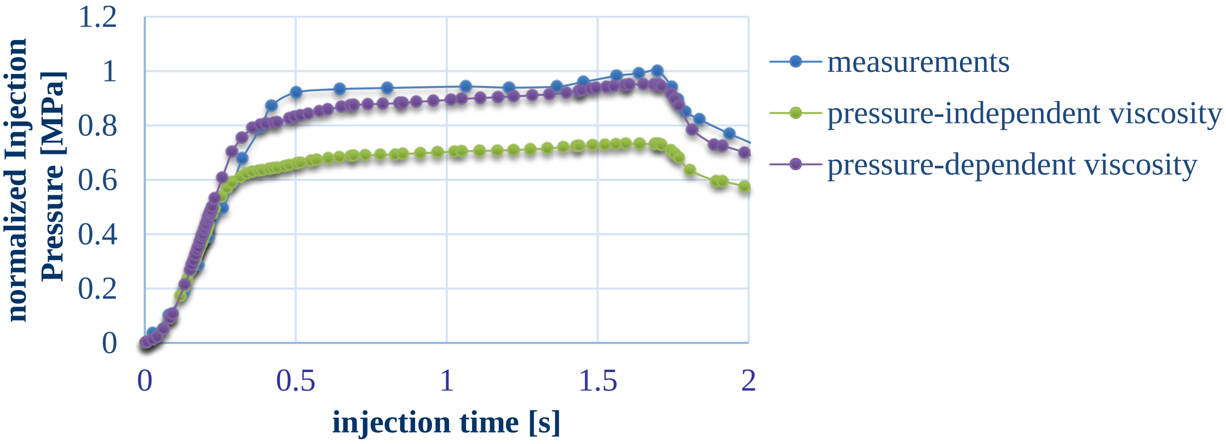

Figure 2 Time-dependent injection pressure for radial fan impeller

Fiber orientations have been modelled using the Moldflow Rotational Diffusion (MRD) model. The standard MRD modelling parameters have been retained. In Figure 3 a qualitative comparison of the fiber orientations is shown in the transition from blade to shroud, where the melt observes a divergent flow as it flows through the blade passages and distributes in opposite direction. Due to shear flow the fibers are more likely orientated in flow direction near to the walls and transverse in the mold center. This behavior can be seen in the microscopic cut as well as in the injection molding simulation, where the first principal value of the fiber orientation tensor refers to the degree of orientation in flow direction.

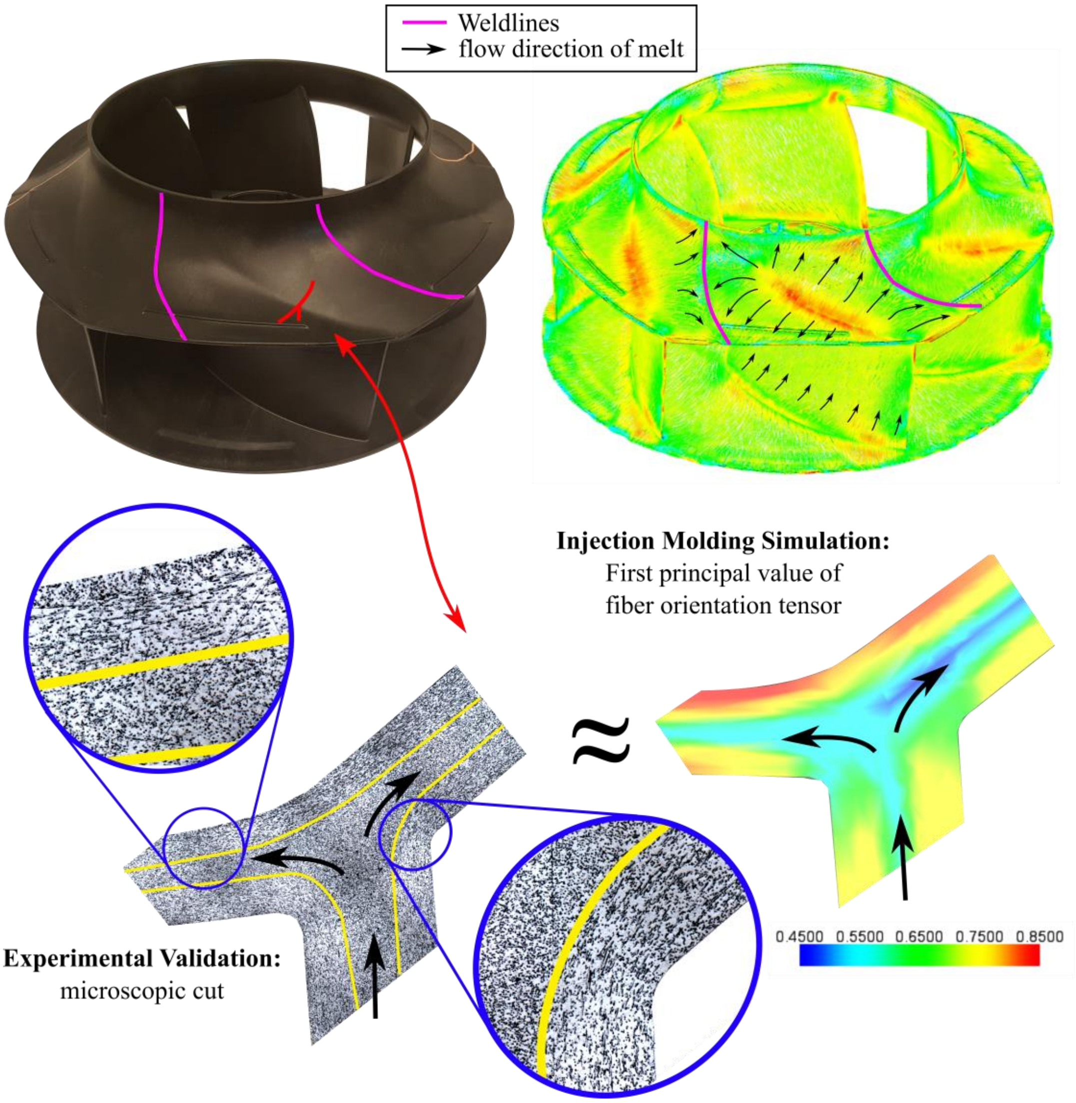

Figure 3 Distribution of fiber orientations in radial fan impeller

Computational Fluid Dynamics

To determine the pressure distribution at the impeller surfaces a numerical Simulation using Reynolds-averaged Navier-Stokes (RANS) equations in Ansys CFX has been conducted. To account for turbulence the k-ω-SST along with a streamline curvature-based turbulence production correction is applied.

The impeller is placed behind at a wall with an inlet funnel, which separates the vacuum chamber from the atmospheric environment. Based on the fan diameter D, the vacuum chamber and atmospheric environment are modelled as cylindric fluid domains with a diameter and total axial extensions of 5D. In Accordance with the number of blades, $1/6^{th}$ of the domains have been meshed as rotational symmetry can be assumed.

Numerically and experimentally derived characteristic curves of the radial impeller reveal a good agreement in a broad band of operational conditions as seen in Figure 4, which validates the determined pressure distribution at the impeller surfaces.

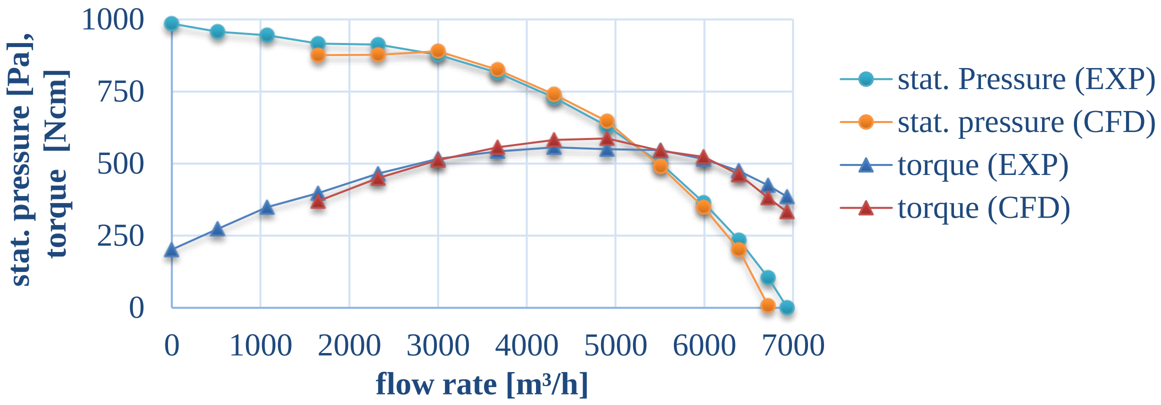

Figure 4 Characteristic curves for radial fan impeller

Structural Analysis

Fiber orientations are mapped to a structural model of the impeller in terms of the local element coordinate system and linear-elastic or elastic-plastic or 45 different material properties are defined to account for various degrees of fiber orientation ranging from isotropic to pure unidirectional local composite behavior. The mesh has been defined using hexahedral elements with five elements across the wall thickness to consider the layered distribution of the fiber orientations (cf. Figure 3).

All Simulation have been conducted for best efficiency operating conditions (BEP – best efficiency point) at 2100 rpm. Two modelling approaches for the material behavior have been compared. First, the standard approach assuming isotropic, linear-elastic material properties is investigated. The isotropic Youngs's modulus is estimated by $E_{iso} = k_{iso}E_t$ where $k_{iso} = [0.6 \dots 0.65]$ scales the tensile modulus provided by the manufacturer $E_t = 7800$ MPa as proposed by [6]. Second, anisotropic, elastic-plastic material is defined. For this simulation the material properties of matrix and fiber have been calibrated using a specimen with 2mm wall thickness. In Figure 5 the results of numerical and experimental determined stress-strain curves for the calibrated materials are shown. A good agreement of curves is found for strains up to 0.6 % for the fiber, matrix and composite material properties given in Table 1. Both modelling approaches result in an overall composite density of $\rho = 1220.5$ kg/m³.

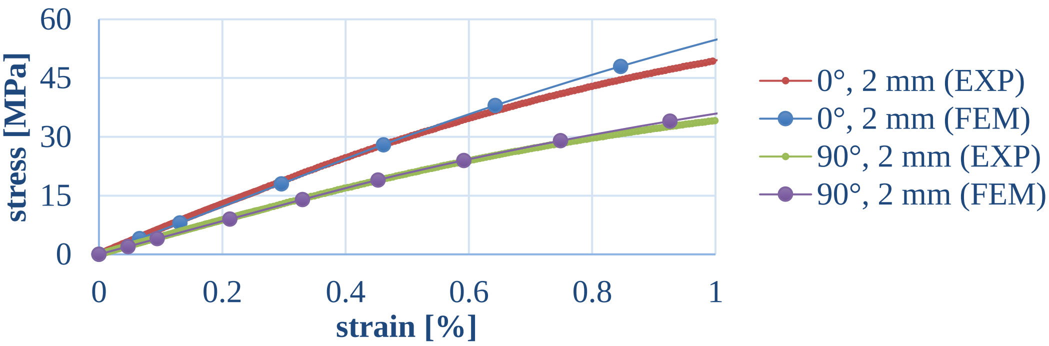

Figure 5 comparison of stress-strain curves for tensile specimen

Table 1 Elastic-plastic Material properties

Matrix	Fiber	Composite
$E_m = 2150$ MPa	$E_f = 73000$ MPa	$L/D = 14$
$\rho_m = 0.9$ g/cm³	$\rho_f = 2.62$ g/cm³	$\Psi = 40$ %
$\nu_m = 0.34$	$\nu_f = 0.22$	

The eigenfrequencies and the maximum radial displacements (with and without aerodynamic loads) have been investigated. In Table 2 the determined 1st to 5th eigenfrequencies of the radial fan impeller are given. In case of anisotropic, elastic-plastic material properties all eigenfrequencies are less compared to the isotropic, linear elastic approach. The Brackets indicate the range of results for the determined values of the isotropic Youngs' Modulus E_{iso} given by [6].

Table 2 Comparison of eigenfrequencies

Mode	**#1: Isotropic, linear-elastic**	**#2: Anisotropic, elastic-plastic**	$\left(\frac{\#2}{\#1} - 1\right) \cdot 100\ \%$
1st and 2nd (lateral)	[138.3 … 144] Hz	131.5 Hz	[-4.9 … -8.7] %
3rd (torsional)	[215.1 … 223.9] Hz	207.6 Hz	[-3.5 … -7.3] %
4th and 5th (axial, mixed)	[245.4 … 255.4] Hz	243.5 Hz	[-0.8 … -4.7] %

The blade passing frequency of the radial fan impeller is given by $f_{bp,BEP} = b\, f_{BEP} = 210$ Hz, where $b = 6$ and $f_{BEP} = n/60$ are the number of blades and the operating frequency at a rotational speed of $n = 2100$ rpm, respectively. Considering anisotropic and elastic plastic material properties the resulting eigenfrequencies are reduced up to 8.7 % ($k_{iso} = 0.65$), independent from the mass properties. Thereby, the distance of the 3rd mode (torsional) to the exciting blade passing frequency reduces from 6.2 % to 1.2 %. Fiber orientations and material properties should be taken into consideration if critical speeds are assessed.

Beside the eigenfrequencies the radial displacements have been determined for various loading conditions: (a) centrifugal load, (b) aerodynamic load and their combination: (a) + (b). A reference node is utilized to compare the radial displacements resulting from the material modelling modeling approaches. The reference node has been selected based on the maximum radial displacement observed at the blade trailing edge in case of isotropic, linear-elastic material properties for the combined load condition (a) + (b). In Table 3 the radial displacements of the reference node are given. Least deviation of isotropic and anisotropic natural frequencies has been found for $k_{iso} = 0.6$, therefore it is used as basis for comparison.

Table 3 radial displacement of reference node at the blade trailing edge under various loading conditions

Load condition	**#1: Isotropic, linear-elastic**	**#2: Anisotropic, elastic-plastic**	$\left(\frac{\#2}{\#1} - 1\right) \cdot 100\ \%$
(a) centrifugal load	$[7.68...7.09] \cdot 10^{-4}$ m	$7.56 \cdot 10^{-4}$ m	[-1.56 ... 6.63] %
(b) aerodynamic load	$[-7.59...-7.01] \cdot 10^{-6}$ m	$-7.37 \cdot 10^{-6}$ m	[-2.90 ... 5.14] %
(a) + (b)	$[7.61...7.02] \cdot 10^{-4}$ m	$7.48 \cdot 10^{-4}$ m	[-1.71 ... 6.55] %

It can be stated that:

- radial displacements are less if anisotropic, elastic plastic material properties are considered
- aerodynamic loads are reducing the maximum radial displacement of the trailing edge due to pressure distribution in radial fan impeller
- aerodynamic loads result in radial displacements about two orders of magnitude smaller than centrifugal loads → aerodynamic loads are neglectable
- The influence of anisotropy on the mechanical behavior cannot be approximated with an isotropic material model using a single scaled Young's modulus:
    - reducing k_{iso} improves the prediction of Eigenfrequencies, whereas the magnitude of radial displacement deviations increases
    - anisotropy has a higher influence on lower than the higher natural frequencies

STRAIN MEASUREMENT SYSTEMS

The distribution of stress and strain strongly depends on the local fiber orientation of the glass fiber reinforced injection molded material. To validate the numerically determined strain results two different types of strain measurement systems have been conceived. First, an optical system based on digital image correlation will be discussed for strain distribution measurements on selected regions. Second, a strain gauge measurement system, which is used for local strain measurement.

Optical Strain Measurement System

A 3D digital image correlation (DIC) is developed to investigate the strain distribution on the surface of an impeller. In 3D DIC a stereo camera system (two cameras) is used to take digital images at different times of the test object. On the surface of the test object, a speckle pattern is applied, which is tracked by the camera system. A software correlates the speckle patterns of the different time steps, transforms the movement of the pattern to a vector field and calculates the strain field thereby (Figure 6).

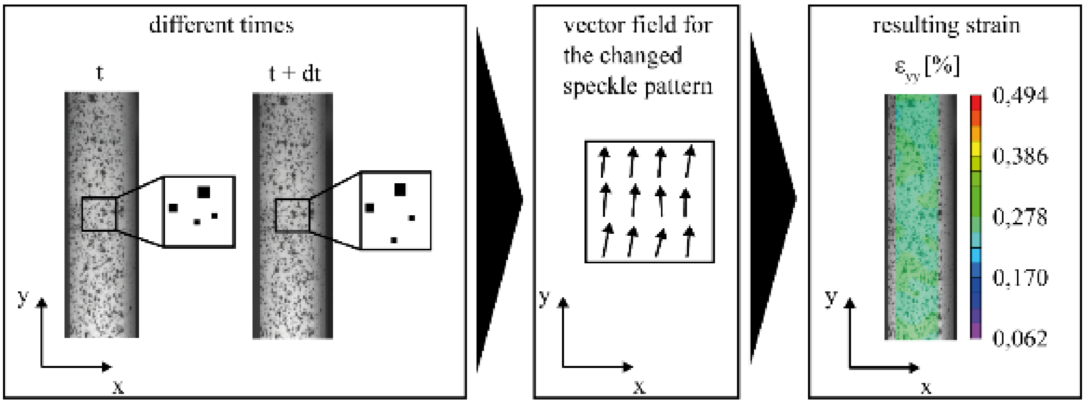

Figure 6: basic steps of the digital image correlation procedure

For the investigation of the strain distribution on the surface of a rotating impeller, the used high-speed cameras CamRecord CR3000x2, Optronis have to measure very small strains of about 0.2 % to 0.3 %. A comparison between a 2D-DIC strain determination and an extensometer showed a maximum discrepancy < 5 % for a strain of 0.26 % and an application of this method could help to localize the maximum strains of an impeller in use. Figure 7 shows the planned test setup.

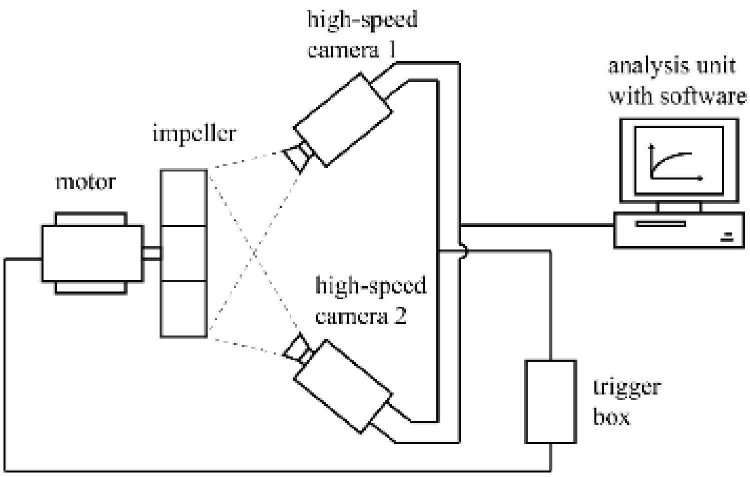

Figure 7: test setup for 3D DIC – schematically

An electric motor drives the impeller and sends the information about the rotation angle to a trigger box. At a defined position, the box triggers the cameras and the high-speed cameras capture a short sequence of images of the rotating impeller. The impeller has a speckle pattern on the surface, which the 3D-DIC software analyses and calculates the strain fields by. This procedure is carried out for different time steps over a longer period of time, so the creep behavior of the impeller in use can be detected and a local strain distribution results.

Strain Gauge Measurement System

To validate numerical results and optical strain distribution measurements local strains are investigated using the stain gauges technique. As the fan impeller is rotating a telemetry system has been developed to transfer strain gauge measurement results and electrical power between the rotating and the stationary frame. In the rotating frame, strain gauges with 350 Ω will be applied to specific locations at the impeller surface. On a rotating send unit, the strain gauges are connected to appropriate 1/4th Wheatstone bridges, which operate with a constant voltage of 5 V delivered by an AC/DC transformed inductive power supply. Within the send unit the strain signals are processed and transferred to the stationary frame, where the strain signal is reconstructed and forwarded to an analysis unit with software (cf. Figure 8).

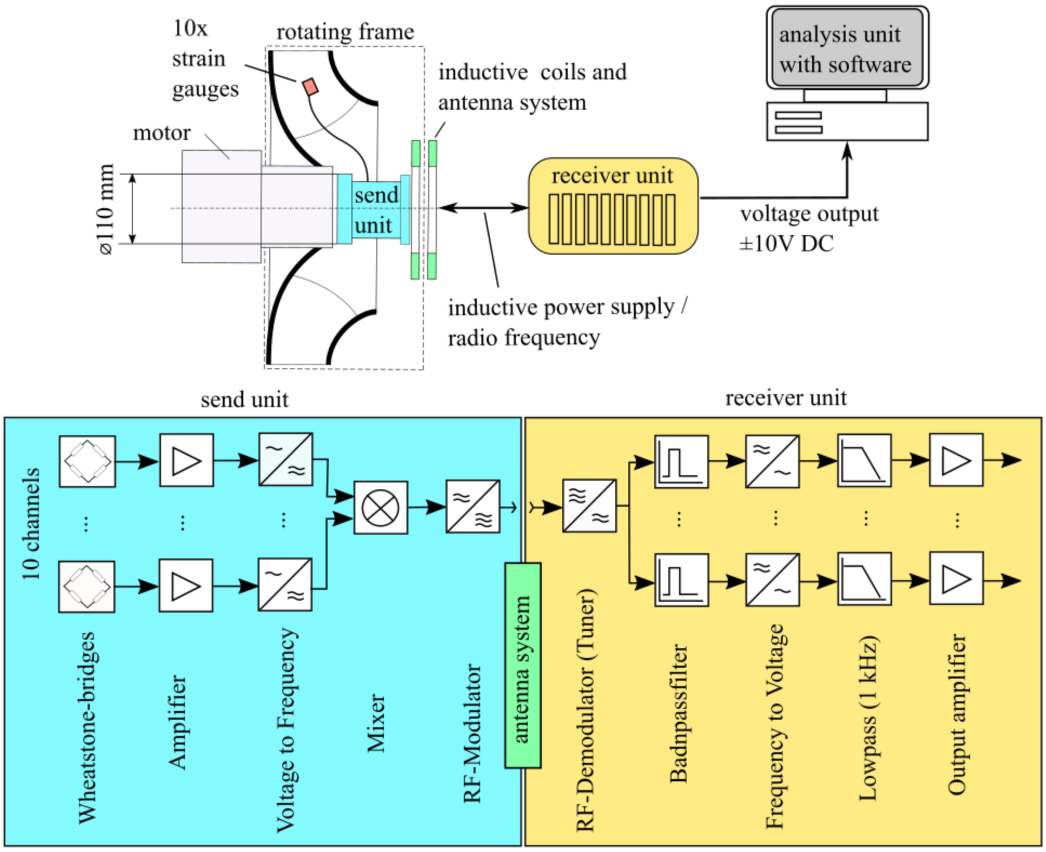

Figure 8 schematic test rig system (top) and signal processing in strain gauge telemetry (bottom)

The send unit has an outer diameter of 110 mm and can be applied to any impeller with a maximum speed of 2500 rpm and sufficient space aligned to the rotation axis. In the current approach the system allows to measure up to ten strains gauge signals with a maximum sampling frequency of 1kHz. The measuring range of presented telemetry system is related to the K-Factor of the used strain gauges, with an accuracy of 0.5 % from its maximum value. For instance, a standard strain gauge with a K-Factor of 2 allows to measure a maximum strain of 5000 ± 25 µm/m.

Due to water-proof design of the system it can be applied to impellers in humid air conditions and even submersed rotors. The System has already been applied at a two-bladed submersed rotor, measuring the time- and load-dependent blade deformations under operating conditions.

CONCLUSION AND OUTLOOK

Based on the integrative simulation method a radial fan impeller has been investigated regarding the influence of process induced anisotropic material behavior and aerodynamic loads. The following conclusions can be drawn:

- Considering pressure-dependent viscosity improves the accuracy of the simulated injection pressure in the filling phase compared to experimental results.
- Fiber orientations effect the eigenfrequencies and radial displacements of the investigated fan impeller as the local structural stiffness varies throughout the part. Consistent isotropic modelling of mechanical behavior with single scaled Young's modulus is not possible.
- Near to the best efficiency point of the radial fan impeller the deformation caused by aerodynamic loads are about two orders of magnitude smaller than deformation caused by centrifugal load.

Time-dependent displacements of the fan impeller will be investigated by extending the presented integrative simulation method to consider the creep behavior of the fiber reinforced polypropylene. Creep curves have been experimentally determined and will be used to calibrate an appropriate creep model in the further research.

Two strain measurement have been conceived and will be applied to an axial and radial fan impeller to validate the numerical strain results.

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