Combined Planar PIV and LDV Profile-Sensor Measurements in a Rotor-Stator Disk Configuration

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ABSTRACT

Many technical applications are characterized by or at least comprise flow scenarios with two parallel surfaces that spin around the same axis with relative angular velocity Ω and are separated by a small gap *s* in axial direction. In case of very small gap heights *s* < 1 mm the application of commonly used measurement techniques does not lead to reasonable velocity information. The presence of structured surfaces renders such experiments even more difficult. In order to meet the combined requirements of a large field of view in the plate-parallel *r* – ϕ plane combined with extremely accurate axial resolution of the velocity profiles perpendicular to the surfaces in *z*-direction, the combination of a standard planar PIV system and the novel LDV profile sensor (LDV-PS) [Czarske et al. (2002), Meas. Sci. Technol. 13(12):1979] is tested in the present study. Particularly, a comparison of smooth and grooved disk geometries is performed in rotor-stator configuration for gap ratios *G* < 10⁻² and corresponding gap Reynolds numbers $Re_s < 20$.

1. Background

Many technical applications are characterized by or at least comprise flow scenarios with two parallel surfaces that spin around the same axis with relative angular velocity Ω and are separated by a small gap *s* in axial direction. The resulting flow in the gap commonly serves either to improve the solid-fluid heat transfer or to manipulate the inter-plate momentum transfer.

In turbo machinery, for instance, significant amounts of cooling flow cross the axial gap between rotor and stator in the region of the hub. This rotor-stator configuration was and still is subject to optimization, where detailed information on the developing velocity profiles is desired in order to fully uncover the heat fluxes between either surface and the passing flow; see e.g. Owen (1988), Owen and Rogers (1989), Gan and MacGregor (1995), and Poncet et al. (2005). The typical circumferential velocity u_{ϕ} along the gap *s* is shown in Figure 1(a), where the velocity profile and

the disk-normal coordinate *z* are normalized with the local disk speed Ωr and the gap height *s*, respectively. Generally, this combination of characteristic quantities is used in tribology to define the Reynolds number of the problem according to $Re_t = \Omega r s/\nu$, where ν is the kinematic viscosity (Please refer to e.g. Tauviqirrahman et al. (2013) or Gropper et al. (2016) for more details on tribology and (mixed) lubrication). Note that Figure 1(a) also introduces the so-called gap Reynolds numbers $Re_s = \Omega s^2/\nu$, which appears as a family parameter in the diagram. Finally, the rotational number $Re_{\phi} = \Omega R^2/\nu$ is typically defined as a third characteristic measure for problem, where only the outer radius *R* of the rotor/disk is considered as length scale (Lance and Rogers, 1962).



(a) Normalized gap profile of circumferential velocity $u_{\phi}(z)$ for various gap Reynolds numbers Re_s (adapted from Lance and Rogers, 1962).



 (b) Various lamella geometries as used in wet clutches: Grouped parallel grooves and waffle grooves (Source: www.ortlinghaus.com, copyright © 2016 Ortlinghaus-Werke GmbH, reprinted with permission)

Fig. 1 Rotor-stator characteristics: (a) Disk-normal profiles of circumferential velocity $u_{\phi}(z)$ for smooth surfaces and (b) examples for grooved rotor surfaces.

Complementary to the flow in rotor-stator configurations, a field of applications with co-rotating disks centers around the investigations into cooling efficiency of data storage devices (i.e. hard drives disks), where particularly the disk-disk and shroud-disk interplay on the resulting flow and heat distributions motivates numerous research efforts. Examples are provided in the reports by Tzeng and Humphrey (1991), Shirai *et al.* (2011), and Tsai *et al.* (2007), for instance.

The inter-disk momentum transfer is the key feature for lubrication gaps like open clutches, for instance. In comparison to turbo machinery, such rotor-stator configurations are characterized by an extremely small gap ratio G = s/R in the order of $10^{-3} - 10^{-2}$, where *R* denotes the outer disk

radius. Once the clutch opens, it is desired to achieve the lowest possible drag momentum from the tumbling clutch disk. Consequently, numerous research efforts aim at optimizing the lubrication flow between clutch plate and rotating clutch disk, where various complex (and partly arbitrary) groove geometries (see Fig 1(b)) have proven to lead to significant drag torque reduction; see e.g. Razzaque and Kato (1999), Missimer and Johnson (1982), or Takagi *et al.* (2011).

However, the scaling laws of thin-slit rotor-stator systems $G \ll 1$ with non-smooth surfaces still remain to be fully understood. Furthermore, today's capabilities for numerical simulations of such rotor-stator systems with arbitrary groove geometries are rather limited, such that experimental reference data for a robust verification/validation process appears to be extremely beneficial. In case of large gap heights in the range of centimeters and moderate gap ratios G > 1, numerous experimental efforts successfully achieved considerable results by both intrusive and nonintrusive means (see e.g. Poncet *et al.* (2005), Tsai *et al.* (2007), Wu (2009), and Tzeng and Humphrey (1991)). In contrast, there is a lack of experimental results for gap sizes in the sub-millimeter range at moderate and small gap ratios. A few exceptions have been published by e.g. Lee and Nishino (2011) or Tang et al. (2015), who made use of micro PIV setups to investigate the flow filed in the gap. However, these studies were limited in such that all dimensions of the considered measurement volume necessarily remained in the sub-millimeter range.

2. Objective of the Present Study

In order to meet the combined requirements of a large field of view in the plate-parallel $r - \phi$ plane combined with extremely accurate axial resolution of the velocity profile in the perpendicular to the surfaces in *z*-direction, the combination of a standard planar PIV system and the novel LDV profile sensor (LDV-PS) as introduced by Czarske *et al.* (2002) is tested in the present study. Particularly, a comparison of smooth and grooved disk geometries is performed in rotor-stator configuration for gap ratios $G < 10^{-2}$ and corresponding gap Reynolds numbers $Re_s < 20$. All experiments are conducted in a specially designed test facility as shown in Figure 2, where disks of an R = 75 mm radius can spin in the range of 0.5 Hz < $\Omega < 10$ Hz.

The gap height can be precisely adjusted in the range of 0.2 mm < s < 5 mm by means of a micrometer screw leveler. A cartoon of the experimental setup is provided in Figure 3, which indicates both the physical dimensions of the considered problem and the orientation of the applied









Fig. 2 Test facility and experimental setup: (a) LDV-Profile Sensor, optical access through the bottom window (λ /10 glass pate); (b) PIV, optical access of laser and camera through sidewall (plexiglass) and bottom window (λ /10 glass pate), respectively.



(b) considered disk geometries: (1) smooth, (2) grooved

Fig. 3 Sketch of test facility; (a) Cartoon of the rotor-stator configuration, the physical dimensions of the setup and the optical access of the applied measurement techniques; (b) two different disks with optional grooves are considered.

measurement techniques (Figure 3(a)) and the investigated plate geometries (Figure 3(b)). In order to mimic structured surfaces as present in clutch flows and through flow as occurs in both clutches and turbo machinery, two different disks with a centered hole have been designed, where one disk is comprised of six additional grooves; see Figure 3(b). Generally, it is hypothesized that the footprint of the groove geometry can be identified in the PIV results of the $r - \phi$ plane; despite the fact that the velocity distribution is inevitably averaged across the gap height *s*. This $\vec{u}(r, \phi)$ -velocity map then guides the subsequent LDV-PS measurements in the $\phi - z$ plane, which provide additional information on axial profiles of circumferential velocity.

3. Measurements and Data Processing

3.1. Considered Parameter Space

Four different parameter combinations of angular velocity Ω and gap height *s* were chosen to provide four pairs of similar Reynolds numbers; see Table 1. In addition to the primary question, whether such flow scenarios can be characterized with combined PIV/LDV-PS measurements, this kind of comparison directly addresses the following two questions: (i) Which Reynolds number describes the problem at hand, and (ii) how does the presence of fixed and moving wall disturbs the results?

Tab.	1	Conducted	experiments	Exps.	#1-#4:	Chosen	parameter	combinations	and	resulting		
Reynolds numbers; four pairs of identical Reynolds numbers appear in bold font.												

	Exp. #1	Exp. #2	Exp. #3	Exp. #4
applied technique(s)	LDV	LDV/PIV	LDV	LDV
s [mm]	0.4	0.7	0.4	0.7
G = s/R	$5.3 \cdot 10^{-3}$	$9.3 \cdot 10^{-3}$	$5.3 \cdot 10^{-3}$	$9.3 \cdot 10^{-3}$
<i>f</i> [1/s]	4.05	4.05	7.10	2.32
$\Omega = 2\pi f \ [1/s]$	25.45	25.45	44.61	14.58
$\mathbf{u}_{\Phi}^{\mathrm{LDV}} = \Omega r _{r=45mm} [\mathrm{m/s}]$	1.14	1.14	2.01	0.65
$Re_t = \Omega rs/v$	458	802	803	459
$Re_s = \Omega s^2 / v$	4.07	12.47	7.14	7.14
$Re_{\phi} = \Omega R^2 / v$	$14.3 \cdot 10^{5}$	$14.3 \cdot 10^{5}$	$25.1 \cdot 10^{5}$	$8.2 \cdot 10^{5}$

3.1. PIV

A commercial PIV system comprising a Quantel EverGreen Nd:YAG ($\lambda = 532$ nm) dual-cavity laser and a PCO Pixelfly camera (14 bit, maximum resolution1392 × 1040 pixels) was utilized, which was operated at a repetition rate of 4 frames per second (fps), triggered by the angular position of the disk. A 50 mm f/1.4D Nikon Nikkor lens was fitted to span approximately 120° of the disk, which resulted in a spatial resolution of 18 px/mm. Polyamide powder (5 µm) was used as tracers. The beam waist was carefully adjusted right before the gap entrance, such that a divergent light sheet with appropriate thickness crossed the gap. As such, it was ensured that the entire gap height was illuminated. The pulse distance was adjusted to achieve a median displacement of ≈ 5 px for the outer part of the flow component u_{ϕ} .

A total number of N = 20,000 image pairs was recorded to ensure statistical significance of the obtained data. The raw images were processed with a multi-grid/multi-pass correlation scheme with initial/final IA size of 128/32 px and a final overlap of 50%. Outliers ($\approx 1.2\%$) were identified by a normalized median test of threshold 4 (Westerweel and Scarano, 2005) and were replaced by the second highest peak determined in the respective correlation fields.

3.2. LDV-PS

The ILA LDV-Profile Sensor was used for the LDV measurements, which was developed in cooperation with ILA GmbH, OPTOLUTION and the Technical University of Dresden. The sensor is comprised of two Nd:YAG lasers ($\lambda = 532$ nm and $\lambda = 561$ nm), which build two overlapped measuring volumes with divergent and convergent interference patterns, respectively. Please refer to the original publications of Czarske et al. (2002) or Shirai et al. (2006) for details of the working principle, and consider the data sheet for details of the utilized profile sensor (ILA GmbH, 2015). Silver-coated hollow glass spheres (5 µm) were used as tracers. Two/three consecutive measurements were conducted at the center of the grooves (r = 45 mm) in so as to measure the full gap height of 0.4 mm / 0.7 mm with a maximal sensor extent < 0.8 mm.

A total number of *N* > 100,000 valid particles were registered per measurement to ensure statistical significance of the obtained data. This information was further post-processed this respect to phase in order to achieve full access to the spatial information in the ϕ – *z* plane. Note that first tests of a phase-resolved analysis of the LDV-PS data were reported by Neumann et al.

(2012,2013), where the spatio-temporal body force distribution was determined from the recorded information of a LDV-PS.

4. Results

4.1. PIV Results

The PIV results for the considered geometry are shown in Figure 4. Note that the velocity fields



(b) Radial component of the flow $u_r(r, \phi)$

Fig. 4 PIV results: Circumferential $u_{\phi}(r, \phi)$ (a) and radial $u_r(r, \phi)$ (b) components of the flow in the $r - \phi$ plane. The red dashed line (r = 45 mm) indicates the perimeter, where the centers of the six circular grooves are located (black circles). This line together with the gap height *s* span the measurement area for the LDV-PS experiments. Furthermore, the disk dimensions are indicated with black lines.

are normalized with the local disk velocity Ωr . Even though these results are averaged across the gap height, there still remains a distinct footprint of the grooves in the flow field. Figure 4(a) demonstrates that flow behind the grooves is comprised of a slow-speed wake at the inner part and a jet-like flow at the outer part of each perturbation. This perturbation can be also recognized in the radial component of the velocity field, where obviously the jet-like part is fed from either side, thus leading to the opposite-signed radial component; see Figure 4(b). Accordingly, the counter-event happens at the inner part, where the wake-like circumferential flow behavior leads to deviation of the flow to either side of this wake. The red dashed line at r = 45 mm in Figure 4 indicates the perimeter, where the centers of the six circular grooves are located (black circles). This line also indicates the $\phi - z$ plane, where the LDV-PS experiments were conducted.

4.2. LDV-PS Results

The LDV-PS experiments were performed at the perimeter, where the centers of the six circular grooves are located, i.e. at r = 45 mm (see red lines in Figure 4). This particular $\phi - z$ plane was chosen from the PIV results to compare the velocity profiles $u_{\phi}(\phi, z)$ of smooth and grooved disks, thus to characterize the disk-normal impact of the grooves on the gap flow. The results for both grooved and smooth disk geometries are show in Figures 5 and 6, respectively. Generally, both diagrams indicate that the LDV-PS is capable to measure such high velocity gradients even in internal configurations. Furthermore, it is demonstrated in Figure 6 that this information can be evaluated in a phased-locked manner to uncover the impact of structured surfaces on the resulting velocity fluctuations. As expected, all four experiments with the smooth disk lead to identical Couette-like flow profiles within the uncertainty margin of the measurements (cp. also Figure 1(a) for small gap Reynolds numbers). However, the boundaries of both the spinning disk and the fixed glass bottom introduce bias errors to the velocity pdfs in proximity of either wall.

The un-shifted character of the LDV-PS renders the detection near-zero velocities impossible. The cut-off velocity of the chosen sensor is 0.1 m/s, which in turn leads to overestimated velocities in case of a such chopped pdf of registered particles near the wall. Due to the slow disk velocity, the resulting velocity fields of Exp. 4 include a wide extent of elevated relative noise into the gap. Additionally, reflections of the spinning disk significantly contributed to the data as spuriously registered particles, which was especially sensible at the edges of the grooves (see Figure 6). Consequently, a quantitative comparison of the four results from the grooved cases appears rather meaningless at the present stage. Nonetheless, it can still be concluded from the LDV-PS measurements that the disk-normal extent of the groove patterns affects the flow of the entire gap.



Fig. 5 LDV-PS results for Exps. 1–4 (smooth disk surface): Circumferential velocity $u_{\phi}(r, \phi)$ in the $\phi - z$ plane at a radius of r = 45 mm (cp. red line in Figure 4).



Fig. 6 LDV-PS results for Exps. 1–4 (grooved disk surface): Circumferential velocity $u_{\phi}(r, \phi)$ in the $\phi - z$ plane at a radius of r = 45 mm (cp. red line in Figure 4). The six grooves along the perimeter are sketched as well to indicate the phase relation the resulting velocity fluctuations.

5. Concluding Remarks

A combination of planar PIV and LDV-PS measurement systems has been tested in the present study in order to identify/outline the general applicability of this combined approach to gap flows with wide aspect ratios. The experiments have been conducted in rotor-stator configuration with optionally groove disks to mimic the flow scenarios of open clutches and the obtained data demonstrate the capability of the chosen combination of techniques to investigate the flow in thin gaps s < 1 mm with structured (grooved) surfaces.

The PIV results reveal a mean inter-disk velocity distribution u_{ϕ} , $u_r(r, \phi)$, which is averaged across the gap height *s* as per the applied approach. This PIV information, however, reasonably uncovers the footprint of groove geometries, i.e. indicates the locations of groove-related flow patterns. In the present case these patterns are comprised of an inner slow-speed wake and an outer high-speed jet in the wake of each circular groove.

The LDV-PS measurements indicate that the disk-normal extent of these patterns spans the entire gap and is inclined according to the disk speed, which is an important insight adverse effect like drag and corresponding drag torque are to be manipulated. However, two issues were encountered during the LDV campaign, which render a quantitative interpretation of the obtained data difficult. First, reflections of the spinning disk – particularly at the edges of the grooves – significantly contributed to the data as spuriously registered particles. Therefore, it is foreseen to run a comparable set of experiments with refractive index matched oil to eliminate this issue.

Second, due to the un-shifted character of the LDV-PS, near-zero velocities cannot be recorded. The present sensor cuts off at 0.1 m/s, which turned out to be a fairly high lower boundary for the pdf of registered particles in proximity of the fixed wall. In case of rotor-stator gap flows, the spatial extent if this bias obviously scales with the angular velocity of the spinning surface. Since the parameters for real clutches typically range in gap heights of s < 0.5 mm and frequencies f in the range of $10^1 - 10^2$ Hz, this adverse bias is presumed to be limited to the immediate vicinity above the fixed surface. Nonetheless, efforts are presently undertaken at ILA GmbH to overcome this velocity-threshold issue. Particularly, a new shifted version of the sensor is currently developed, where a bragg cell will be incorporated into the profile sensor to create an appropriate frequency shift. Presumingly, this modification will then allow to resolve both (near-)zero velocities in the range of mm/s and flow recirculations within the measured velocity profiles.

Finally, in spite of the present issues with wall reflections and hardware filters/un-shifted lasers, the present feasibility study demonstrates that the combination of standard planar PIV together with the novel LDV-PS indeed opens avenues for a branch of flow applications, when extremely thin gaps are to be investigated over a wide surface parallel domain.

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