FOCUSING SCHLIEREN VISUALIZATION OF TRANSONIC TURBINE TIP-LEAKAGE FLOWS

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ABSTRACT
This paper presents a focusing schlieren system designed for the investigation of transonic turbine tip-clearance flows. In the first part, the functional principle and the design of the system are presented. Major design considerations and necessary trade-offs are discussed. The key optical properties, e.g. depth of focus, are verified by means of a simple bench test. In the second part, results of an idealized tip gap model as well as linear cascade tests at engine representative Reynolds and Mach numbers are presented and discussed. The focusing schlieren system, designed for minimum depth of focus, has been found to be well suited for the investigation of three-dimensional transonic flow fields in turbomachinery applications. The schlieren images show the origin and growth of the tip-gap vortex on the blade suction side. A complex shock system was observed in the tip region and the tip-gap vortex was found to interact with the suction side part of the trailing edge shock system. The results indicate that transonic vortex shedding is suppressed in the tip region.

NOMENCLATURE

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<th>Symbol</th>
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<tr>
<td>a</td>
<td>unobstructed source image height</td>
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<tr>
<td>A</td>
<td>clear aperture of schlieren lens</td>
<td>mm</td>
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<tr>
<td>b</td>
<td>distance between cutoff grid lines</td>
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<td>c</td>
<td>chord length</td>
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<td>m</td>
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<tr>
<td>M</td>
<td>Mach number</td>
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<tr>
<td>n</td>
<td>number of grid lines per millimeter at cutoff grid</td>
<td>mm⁻¹</td>
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<tr>
<td>p</td>
<td>pressure</td>
<td>Pa</td>
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<tr>
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<td>angle change resulting in 10% brightness change</td>
<td>arcsec</td>
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<tr>
<td>φ</td>
<td>pairs of lines involved in forming each point in focusing schlieren image</td>
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<tr>
<td>τ</td>
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INTRODUCTION
Blade tip-leakage flows of unshrouded blade tips are known to reduce stage efficiency (Dixon and Hall, 2013). In incompressible flow, the loss associated with the tip-clearance flow typically accounts for one third of the overall loss of a turbine stage (Denton, 1993). Additionally, tip-clearance flows can lead to enhanced heat transfer in the tip-clearance, reducing the turbine blade life in high-temperature gas turbines (Wheeler et al., 2013; Moore and Elward, 1993; Jackson et al., 2015). Consequently, a comprehensive body of literature exists on low speed tip-gap flows. Far fewer studies, available in the open literature, have considered transonic and supersonic tip-leakage flows, as can be found in the final stages of low pressure steam turbines and ORC turbines. While some numerical studies on this topic exist (Wheeler et al., 2013) detailed experimental data are scarce.

Tip gap flows are known to be influenced by local flow details leading to highly three-dimensional and rather complex flow structures. In compressible flows, e.g. transonic flows, the tip region is expected to be dominated by effects associated with supersonic flow, such as shock waves and expansion fans (Moore and Elward, 1993; Wheeler and Saleh, 2013). Traditionally, schlieren photography has been used to investigate two-dimensional phenomena such as profile loss or the wake flow and trailing-edge shock system of transonic blade profiles (Kiock et al., 1986; Melzer and Pullan, 2019). Conventional schlieren systems, e.g. z-type setups with parabolic mirrors, a point light source, and parallel beam of light, possess a practically infinite depth of focus. The final image formed by such a system contains all density gradients that occur along the optical axis. In addition, some weaker density gradients that occur in some part of the flow field, such as in the blade tip region, might not be visible at all, as they can be obscured by stronger phenomena from other parts of the flow field. For the analysis of transonic tip-clearance flows it is therefore desirable to have a device available that allows to sharply focus on a specific plane, i.e. a focusing schlieren system.

This paper presents a focusing schlieren system designed for the investigation of transonic turbine tip-clearance flows. The paper is structured as follows: In the first part, the functional principle and the design of the focusing schlieren setup are presented. Major design considerations and necessary trade-offs are discussed. In the second part, some results of an idealized transonic tip-gap flow and of full scale linear cascade tests are presented and discussed briefly.

LITERATURE REVIEW
The principle of focusing schlieren systems has been known for quite some time. However, compared to conventional schlieren setups, that are a standard tool in compressible flow research, focusing schlieren are more uncommon. The idea of focusing schlieren was first described by Schardin (1942) more than 70 years ago. Based on Schardin’s work, two different versions of focusing schlieren systems emerged over the following years. Kantrowitz and Trimpi (1950) designed a system that consisted of two wide angle lenses but only allowed for a field of view smaller than the lens diameter. The other system was devised by Burton (1949, 1951). He only used a single lens and was the first to recognize, that the field of view is only limited by the source grid size and not by the schlieren lens diameter.

The most recent developments to the method were made by Weinstein (1993, 2010), who devised what has been termed in the literature as ”the modern focusing schlieren system” (Settles, 2012). Based on Schar din’s original system, he used a Fresnel lens to light the source grid and a high quality commercial camera lens as the schlieren lens. Thereby, he solved all problems that previous systems had suffered from, namely a small field of view, a large depth...
of focus and the difficulty of use (Settles, 2012). The use of a Fresnel lens also increased the image brightness by a factor of approximately 100 (Weinstein, 1993). Based on Weinstein’s focusing schlieren method a number of studies utilizing focusing schlieren was carried out over the past two decades. Alvi et al. (1993) added a fiberoptic sensor to the system that allowed for optical turbulence measurements in the plane of sharp focus. A similar system was used later on by Garg and Settles (1998) for measurements in a turbulent boundary layer. Gartenberg et al. (1994) used a focusing schlieren system for recording detailed pictures of high Reynolds number flows in a cryogenic wind tunnel. The system proved to be sensitive enough to detect flow features at Mach numbers as low as $M = 0.4$.

Recently, focusing schlieren systems were used for supersonic combustion research (Kouchi et al., 2015, 2017; Bühler et al., 2017). In steady-state combustion test facilities, large temperature gradients exist across the test section side windows causing a change of the refractive index of the glass. This change caused by the thermal gradients is larger than those caused by shock waves and expansion fans (Bühler et al., 2017). In such cases focusing schlieren systems present an opportunity to bypass and suppress the thermal distortions on the side windows.

FOCUSING SCHLIEREN SYSTEM

A focusing schlieren system consists of the same basic components as conventional schlieren in the sense, that there is a light source, an imaging lens, a cutoff, and an image screen. However, instead of using a single point or slit light source, a two-dimensional array of slit light sources is used (cf. Fig 1). These multiple light sources image through a lens onto a grid, that acts as a cutoff (Weinstein, 2010). Therefore, a focusing schlieren system can be seen as a number of conventional schlieren systems stacked horizontally above each other (Settles, 2012).

The optical axes of the individual schlieren systems are inclined at a small angle. The resulting individual schlieren images only form a sharp image, if the image plane is focused on a corresponding plane in the test area. This effect is shown schematically in Fig. 1 using the example of a single source point. All other density gradients that occur outside of this plane are to some extent offset from each other and will be blurry (Kantrowitz and Trimpi, 1950). This effect, which is similar to the focusing principle of a normal lens, lends the focusing schlieren

![Schematic illustration of the focusing effect of a focusing schlieren system using the example of a single source point (adapted from Weinstein (1993)).](image-url)
system its main characteristic i.e., its ability to sharply focus on a specific plane.

**Optical Layout**

Figure 2 shows the schematic layout of the focusing schlieren system with all major components. An LED array with a nominal electrical power of 70 W is used as an extended light source. A Fresnel lens with a diameter of \( d = 317 \text{ mm} \) and a focal length of \( F = 217 \text{ mm} \) redirects the light towards the schlieren lens.

Next to the Fresnel lens is the source grid that consists of alternating opaque and transparent lines, where every transparent slit represents an individual light source. Various methods for manufacturing the grids can be found in the literature. In the present case, the grids were made from acrylic sheets on which the black grid lines were printed by means of screen printing. This technique was found to be capable of producing opaque lines with sufficiently sharp edges. The cutoff grid is usually produced by exposing photographic film mounted at the sharp focus of the source grid (Settles, 2012). While this method is said to be time-consuming it has the advantage of producing an exact photographic negative of the source grid, that contains all its imperfections (Weinstein, 2010). However for the present work, the quality of the prints was high enough that both source and cutoff grid were printed. The screen printing technique was found to be precise enough to produce a pair of grids that could yield an adequate amount of cutoff and sensitivity.

The schlieren lens is a fast commercial camera lens with a focal length of \( F = 85 \text{ mm} \) and a maximum aperture of \( f/1.4 \). At the image plane a second Fresnel lens is positioned that redirects the light towards the camera. Theoretically, a camera can be placed directly in the image plane. However, depending on the properties of the schlieren system the image magnification \( m = l'/l \) can be considerable, resulting in a small field-of-view. This effect is especially pronounced for systems where the depth of focus is minimized as will be shown in the next section (cf. Eq 2). In the present case, a Fresnel lens with a diameter of \( d = 264 \text{ mm} \) and focal length of \( F = 317 \text{ mm} \) was necessary to focus the image on the camera.

The distances between the different components and the schlieren lens can be estimated by applying the thin lens approximation

\[
\frac{1}{F} = \frac{1}{L} + \frac{1}{L'} = \frac{1}{l} + \frac{1}{l'},
\]

(1)

![Figure 2: Schematic layout of the focusing schlieren system.](image)
where $F$ is the focal length of the schlieren lens, $L$ is the distance between source grid and schlieren lens, $L'$ is the distance between schlieren lens and cutoff grid, $l$ is the distance from the plane of focus to the schlieren lens, and $l'$ is the distance from the schlieren lens to the cutoff grid. It should be pointed out, that the values obtained from Eq. 1 only serve as a starting point in setting up the system. Adjustments will have to be made during the alignment of the system to account for optical aberrations and geometric imperfections.

### System Properties

The design of a focusing schlieren system involves a trade-off between the different system properties, such as the sensitivity of the system, depth-of-focus, maximum image resolution, and field-of-view. For this study, the minimization of the depth-of-focus was a priority while maintaining adequate sensitivity and field-of-view.

Two definitions for the depth of sharp focus of a focusing schlieren system exist in the literature. According to Weinstein (2010), the depth of sharp focus is the depth at which the loss of resolution due to being out of focus exceeds the resolution of the optical system:

$$DS = 2\frac{l}{A}w.$$  \hspace{1cm} (2)

Herein, $A = F/f_\#$ is the clear aperture of the schlieren lens. The parameter $w$ is the resolution limit due to grid refraction effects, which is written as (Weinstein, 2010)

$$w = \frac{2(l' - L')\lambda}{mb},$$  \hspace{1cm} (3)

where $\lambda$ is the wave length of light, $b$ is the distance between two lines at the cutoff grid, and $m = l'/l$ describes the image magnification.

The second definition, the depth of unsharp focus, is the depth at which the loss of resolution due to being out of focus exceeds the size of some flow detail (Weinstein, 2010):

$$DU = 2\frac{l}{A}w'.$$  \hspace{1cm} (4)

Following Weinstein (1993) the characteristic size of the flow detail $w'$ was chosen with 2 mm.

As mentioned in the previous section, the focusing effect results from the blending of many individual images. The number of blended images that form the final image on the image plane

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<th>$DS$</th>
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<td>Kouchi et al. (2015)</td>
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<tr>
<td>Bühler et al. (2017)</td>
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<td>128</td>
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<td>-</td>
<td>±4.2</td>
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The outer diameter of the hypodermic needles was 1.5 mm. The left needle was traversed along the optical axis.

is defined as (Weinstein, 2010):

$$\phi = \frac{An(l' - L')}{2l'}.$$ (5)

Herein, $n$ is the number of grid lines in the cutoff grid per unit dimension. Weinstein (2010) recommends a value of $\phi > 8$ for good results.

The sensitivity of a schlieren system describes the minimum detectable deflection angle caused by the density gradient, where the schlieren system converts the deflection angle into a change in image brightness. Assuming that the smallest change in brightness detectable by the system is 10% of the sensitivity of the system, the sensitivity can be written as (Weinstein, 1993)

$$\epsilon_{\text{min}} = 0.1\epsilon_{[\text{rad}]} = 20626.5 \frac{aL}{L'(L - l)'} [\text{arcsec}],$$ (6)

where $a$ is the unobstructed source image height on the cutoff plane. The term $L'(L - l)/L$ accounts for the focusing capabilities of the system (Fish and Parnham, 1950) and the constant 20626.5 results from converting $\epsilon_{\text{min}}$ from radian to arc-second. For a system with high sensitivity the value obtained from Eq. 6 has to be minimised.

Table 1 shows the computed system properties of the focusing schlieren system used for this study. Two slightly different versions are listed, one for the idealized model and one for the linear cascade tests. The distance between the plane of focus and the schlieren lens $l$ had to be increased slightly for the linear cascade tests due to geometric constraints i.e., width of the test section. Thereby, the depth-of-unsharp focus $DU$ increased slightly, while all other system parameters remained almost unaffected. A comparison with focusing schlieren systems from the literature (cf. Tab. 1) shows that all systems have similar properties. This can in parts be attributed to the choice of schlieren lens, which in all three cases has a focal length of 85 mm.

The calculated depth of focus was validated using a simple bench test. Some results of this test are shown in Fig 3. Two hypodermic needles were placed in the plane of focus. The needles were connected to the in-house compressed air supply, resulting in a pair of two crossed supersonic under-expanded jets. At first, both needles were placed in the plane of focus (cf. Fig 3, left image) and consequently, both supersonic jets appear equally sharp in the schlieren image. The left needle was traversed along the optical axis, while the right needle remained in the plane of sharp focus. At an increment of 5 mm (cf. Fig 3, centre) the jet is already unsharp and out of focus, which corresponds well to the computed values for $DU$ given in Tab 1. At 10 mm only a shadow is visible in the background and no details of the flow structure can be made out.
APPLICATION TO TRANSONIC TIP-CLEARANCE FLOWS

Once the design parameter of the focusing schlieren system were tested and validated, the setup was used to investigate transonic tip-clearance flows. This section presents selected results of an idealized tip gap model as well as results of full scale linear turbine cascade tests. The main purpose of this section it to demonstrate the capabilities of the focusing schlieren system for the investigation of tip leakage flows. The results presented in the following were recorded with an exposure time of $1 \mu s$ at a maximum frame rate of 10000 fps. Thereby, instantaneous flow structures could by captured in the individual images.

**Idealized Tip Gap Model**

As a first test case, an idealised blade tip-clearance model (hereafter referred to as idealised model) was used to study fundamental blade tip-clearance effects under transonic conditions. The test section geometry is shown in Fig 4. A single blade, two passage cascade was used with a simplified blade profile, that is representative of a steam turbine blade tip section. The test section side walls were contoured to obtain a realistic pressure distribution on the profile, similar to a that of a real turbine blade with a stagger angle of $60^\circ$. While this setup presents a simplification with respect to the situation in an actual turbine or even a linear cascade, it has been shown in a previous investigation that it is a useful setup for the investigation of fundamental physical mechanisms (Passmann et al., 2018). Also, a similar concept was used recently by Melzer and Pullan (2019) to study the role of vortex shedding in the trailing edge loss of transonic turbine blades.

The chord length of the blade profile in the idealised model was $c = 62$ mm and the trailing edge diameter was chosen as $d_{TE} = 2.4$ mm leading to a ratio between trailing edge diameter and geometrical throat of $d_{TE}/o = 16\%$. The overall flow conditions can be characterized as follows: The inlet Mach number was of order $M_1 = 0.4$ and the isentropic blade exit Mach number was $M_{2,\text{is}} = 1.6$. This results in a Reynolds number based on chord length and exit Mach number of $Re = 2 \cdot 10^6$. All results for the idealized model were obtained at a constant tip-clearance height of $\tau/H = 2.8\%$. A similar value has been used in a previous numerical study by Wheeler et al. (2013).

Figure 5 shows three images of the flow field for the idealised blade tip-clearance model, where the image section was chosen to show the rear two-thirds of the blade profile up to the trailing edge (TE) and the passage below and above the blade. For each image the schlieren system was focused on a different plane along the blade height. The position of the three different

![Figure 4: Sketch of the test section geometry for the idealised blade tip-clearance model.](image)
Figure 5: Focusing schlieren images of the flow field in three different planes of focus for the idealised tip-clearance model. The tip gap vortex and its development along the chord length is shown for a tip-clearance of $\frac{\tau}{H} = 2.8\%$ and $M_{2,is} = 1.6$.

Figure 6: Focusing schlieren images of the flow field in three different planes of focus for the idealised tip-clearance model. The rear third of the blade chord length and trailing edge region is shown for a tip-clearance of $\frac{\tau}{H} = 2.8\%$ and $M_{2,is} = 1.6$. 

planes is shown in Fig. 4 (right). Close to the blade hub at $z/H = 30\%$ a two dimensional flow field is observed (cf. Fig. 5a). The pressure side TE shock (p1) of the neighbouring blade profile (i.e. the profiled tunnel wall) impinges on the suction side of the blade profile and is reflected at point r1. At this point it should be pointed out, that the circular pattern visible close to the suction side surface is not a flow feature but an artefact of the Fresnel lenses used for the focusing schlieren system. Slightly above midspan at $z/H = 60\%$ (cf. Fig. 5b) the pressure side TE shock (p1) of the neighbouring blade profile is still clearly visible. Additionally, a large flow structure can be seen schematically off the suction side surface. The structure is out of focus, but it can be made out that it originates downstream of the geometrical throat (coincident with the left image border of Fig. 5b) and then grows in size as it moves further downstream along the blade suction side.

On closer examination of Fig. 5c, this structure can be identified as the tip leakage vortex. For Fig. 5c the focusing schlieren system was focused on the tip gap region at $z/H = 97\%$. The tip-leakage vortex (indicated by an arrow in Fig. 5c) is now in sharp focus and dominates the flow field in the tip-clearance region. Additionally, an interaction between the TE edge shock p1 and the tip leakage vortex can be observed, resulting in a reflection of p1 further upstream on the blade suction side at point r3.
The rear third of the blade chord length and the TE region are shown in Fig. 6. Qualitatively a similar behaviour as described in the previous section can be observed. At \( z/H = 30\% \) (Fig. 6a) the flow field is two-dimensional. The reflected TE shock from the neighbouring blade (p1) is still visible at the left image border. At the trailing edge the flow field is characterized by the trailing edge shocks on pressure and suction side (te1, te2) and the wake flow region further downstream. At \( z/H = 60\% \) and \( 97\% \) (Fig. 6b,c) the turbulent fluctuations of the tip-leakage vortex become visible. Bearing in mind that the depth of unsharp focus of the schlieren system amounts to \( 10\% \) of the test section height \( H \), the tip-leakage vortex is found to occupy approximately the upper third of the blade span. This observation is in agreement with oil-flow visualizations by Passmann et al. (2018).

**Transonic Turbine Cascade Tests**

In addition to the tests on the idealized model, an investigation on a linear cascade with a representative turbine blade profile was undertaken. The experimental work for this part was carried out on the transonic cascade wind tunnel at the Laboratory of Turbomachinery at the Helmut-Schmidt-University in Hamburg, Germany. A detailed description of the wind tunnel facility has been given by Ober (2013).

Figure 7 shows a sketch of the transonic cascade wind tunnel and the linear cascade test section. The blade profile used for this study was the well known Von-Karman-Institute test profile. The profile loss has been investigated independently by four institutions (Kiock et al., 1986) and Wheeler et al. (2013) conducted a numerical study on tip-leakage flow. The cascade consisted of seven blade profiles plus two boundary profiles to obtain periodic flow conditions around the central measurement blade, as shown in Fig. 7. The profiles had a chord length of 61.2 mm and were arranged at a stagger angle of \( 30^\circ \). The blade spacing to chord ratio was \( s/c = 0.71 \) resulting in a spacing of 43.3 mm. The cross-sectional area at the test section inlet was \( 300 \) mm \( \times \) \( 100 \) mm. The facility was operated under steady-state conditions and the total temperature at the cascade inlet was close to ambient. The turbulence intensity at the inlet was

![Sketch of the transonic cascade wind tunnel (right) with details of the linear cascade test section (left).](Image)
Figure 8: Focusing schlieren images of the linear cascade test section for two mean exit Mach numbers of $M_{2,is} = 0.78$ (top row, images a-d), $M_{2,is} = 0.97$ (centre row, images e-h) and $M_{2,is} = 1.1$ (bottom row, images i-l) at $0^\circ$ incidence and a tip-clearance of $\tau/H = 2\%$. The field-of-view corresponds to the labelled area in Fig. 7.

of order 1.5% and was not increased artificially.

Figure 8 shows a set of results from the linear cascade tests. Three exit Mach numbers of $M_{2,is} = 0.78$, 0.97 and 1.1 were considered. For each Mach number the schlieren system was focused on four different planes along the blade span, with the plane $z/H = 99\%$ corresponding to the tip-clearance. All results were obtained at zero incidence and a tip-clearance of $\tau/H = 2\%$. At a blade exit Mach number of $M_{2,is} = 0.78$ transonic vortex shedding is observed at midspan (Fig. 8a). Recently, Melzer and Pullan (2019) investigated this phenomenon in detail...
and found that, depending on TE shape and size, transonic vortex shedding can occur at blade exit Mach numbers as low as $M_{2,is} = 0.65$. Under such conditions, shockwaves can be shed with each shed vortex. This occurs alternating on pressure and suction side. The corresponding shocks are labelled with the letters p and s depending on their origin (cf. Fig. 8a-c). While transonic vortex shedding is clearly visible at midspan, the tip leakage flow seems to suppress this phenomenon. In the tip-clearance region (Fig. 8d) only the turbulent fluctuations from the tip-leakage vortex are visible.

As the exit Mach number is increased to $M_{2,is} = 0.97$ (Fig. 8e-h) shock waves form near the TE. Close to the blade tip (Fig. 8g,h) evidence of the tip-leakage vortex becomes visible as a fine dark line. At present it is not entirely clear what this line represents. However, based on the numerical results by Wheeler et al. (2013) and the oilflow pattern of Passmann et al. (2018) it is thought that this line represents the points where the tip gap flow separates from the cascade tip-wall and rolls up into the tip-leakage vortex. Finally, a pattern of oblique shock waves is formed at the trailing edge as the exit Mach number is increased to $M_{2,is} = 1.1$ (Fig. 8i-l). Close to midspan (Fig. 8i) the suction side separation shock is visible that merges with the suction side TE shock (s).

The results presented in Fig. 8 show, that the focusing schlieren system is an adequate instrument for the investigation of transonic tip-clearance flows. The images show that the TE shock/wake system is influenced by the tip-clearance flow and in case of $M_{2,is} = 0.78$ suppresses transonic vortex shedding in the tip region. The extent of the tip-leakage vortex will be studied by additional instrumentation (e.g. five-hole probe traverses) in future work.

**SUMMARY**

A focusing schlieren system for the investigation of transonic tip-clearance flows was designed and commissioned. The system has a sharp depth of focus of $±0.3\, \text{mm}$ and an unsharp depth of focus of $±3.9\, \text{mm}$. This was confirmed experimentally. Results of an experimental study on an idealized tip-clearance model and a transonic linear cascade were presented. These results represent the first focusing schlieren visualization of transonic tip gap flows and show, that focusing schlieren is well suited for the investigation of such phenomena. The results of the idealised model demonstrate the origin and spatial extent of the tip gap vortex and an interaction between tip gap vortex and oblique shock pattern was observed. The linear cascade results indicated that the shedding of shock waves caused by transonic vortex shedding at an exit Mach number of 0.78 was suppressed near the blade tip by the tip-clearance flow. At higher exit Mach numbers the tip-leakage vortex formed a characteristic pattern which was interpreted to represent the separation area where the tip-leakage flow rolls up into a vortex.

**References**


