An overview on Schlieren optics and its applications

Studies on mechatronics

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An Overview on Schlieren Optics and its Applications

Studies on Mechatronics

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Contents

Abstract

This work provides a short overview on the different schlieren visualisation methods. The introduction contains a brief explanation of the working principles followed by the historical development of the technique. After a sum-up of the physical theory behind schlieren image, the most important setups designs are compared and discussed. In context with the research of PhD Student Dirk Möller at the IMES institute of ETH Zürich, the focus was set on the possibilities for an eventual use of schlieren setups for ultrasonic wave imaging. Finally, an overview on the different applications of the schlieren method is given.

'Studies on Mechatronics' is a literature research paper that is required for the mechatronics focus in the mechanical engineering bachelor degree.

Chapter 1

Introduction

1.1 Overview

The main goal of this 'Studies on Mechatronics' report is to investigate the schlieren imaging technique and its uses for an application in the acoustic streaming research of Dirk Möller. Ultrasound waves are thereby used to manipulate suspended particles in a fluid which is inside small plastic chambers. So far, the shape of the resulting ultrasonic wave field can only be evaluated by calculation or by observing the impact of the pressure field on the particles suspended in the water. However, better information of the field is desirable. That information is what could be obtained by the help of schlieren imaging.

In this paper, the book 'Schlieren and Shadowgraph Techniques' of G.S.Settles ([1]) was mainly used as source for general schlieren systems. As Settles' main field of interest are fluid visualisations, in context with ultrasound setups different papers have been used as additional sources.

1.2 Basic principle of a schlieren system

In fluid dynamics, schlieren imaging is a common tool: With the technique, air flows and shock wave can be depicted very detailed for uses in aerodynamical studies. The ability of schlieren techniques to visualize air flows might appear quite surprising for someone who has never seen such an image before. The surprise certainly has to do with the fact that the physical properties of air is commonly neglected: In everyday life, air is experienced totally transparent and without any refractive effects. Similarly to the illusion that air has no friction, one does normally neglect all the refractive effects of air. Therefore, it can be hard to imagine how light and transparent gas flows

can be made visible with an optical apparatus. However, if one takes in account the way all transparent materials are seen by the eye, it may appear more plausible: When looking at glass, water, ice or other transparent media we only see the reflected image of the environment and, not to forget, the distortion of the background that comes from the *refraction* of the transparent media. Sometimes also *diffraction* happens. It is unclear, where the distinction lies exactly as usually, and unlike here, diffraction is used where the refractive index is constant. For further discussion see section 2.4). The materials that are studied with the schlieren technique now simply have very weak refractive indices and hence totally miss any *reflections*. This makes it hard to see the distortions by eye and thus even more surprising when one gets a first look at a schlieren image. Figure 1.1 shows a very nice example of a schlieren image that depicts waves and flows of surprising clearness. To make these inhomogeneities visible, amplification methods are needed. And that is exactly the point of a schlieren system.

As illustrated in Fig. 1.2, the trick to enhance the diffraction pattern is surprisingly simple. The image of a schlieren object has only to be focused by a lens (or eventually a parabolic mirror). Thus, all unrefracted light rays pass through the focal point, whereas the refracted rays will be deviated and hence pass only in the proximity of the focal point (as seen in Fig1.3). With the filter at that point, all light rays that are deviated into a distinct direction can be selectively filtered out so that on a projected image, the refracted ray which got filtered out appears as a dark spot on the image. Further explanation to the functioning of the different setup types will be given in the chapter 3.

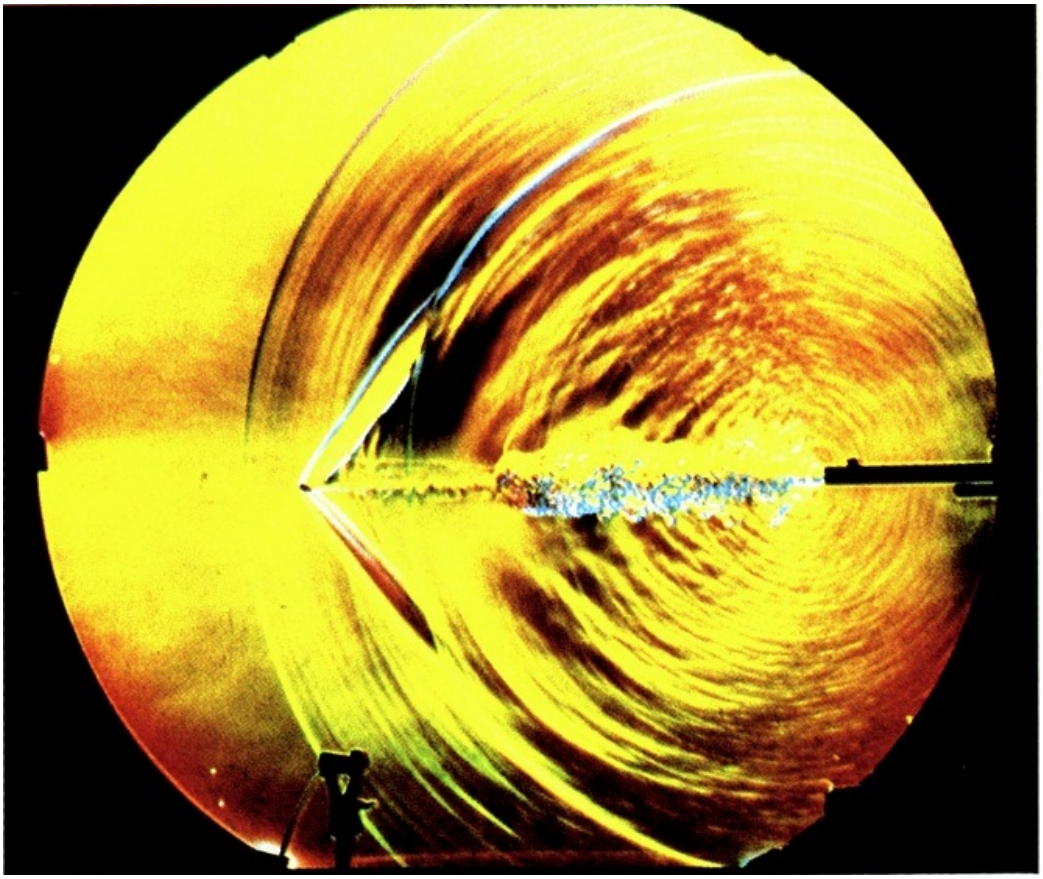

Figure 1.1: *This schlieren image of a bullet shot from a gun shows the variety of effects that a schlieren setup can visualise. The so-called colour filter gives the inhomogeneities a gradual illumination going from black over red and yellow to white. The shadowlike patterns resemble the reflection of waves on a water surface and represent the shock waves. The brightest spot is the turbulent nuzzle flow as the hot air carries a substantially larger refractivity. The illuminated circle correstponds to the background illumination from the parabolic mirror. One can see the shadows of the mirror suspension at the edge. [1]*

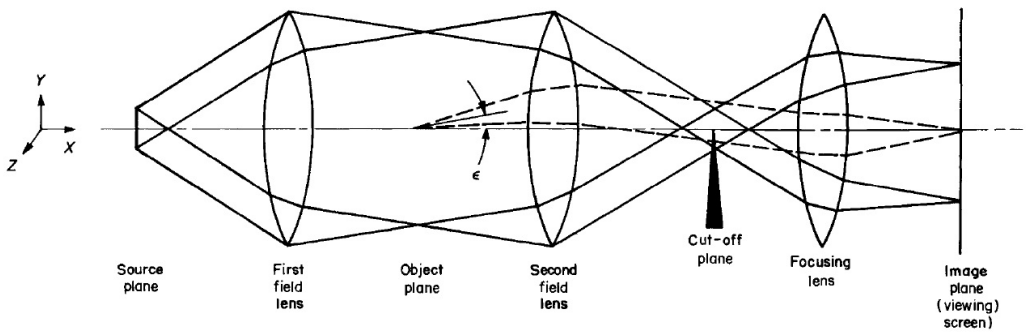

Figure 1.2: *Illustration of a standard schlieren imaging setup as it is also used for ultrasound imaging. It consists of a schlieren setup with basically two lenses and one knife edge filter. The dashed line represent diffracted light that is deviated in two possible directions, one of them being filtered out [1].*

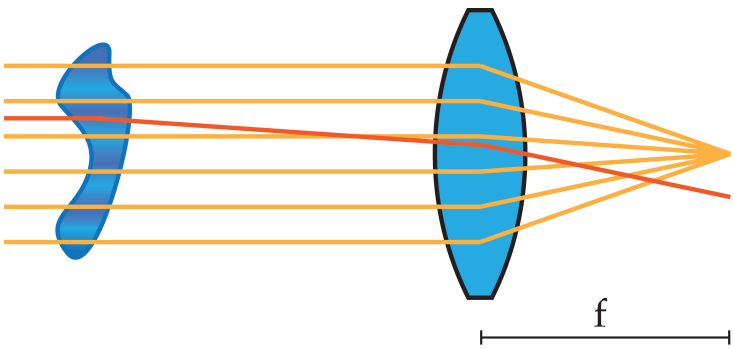

Figure 1.3: *In contrast to the unperturbed light rays, the refracted rays have a different angle toward any following lens. They therefore won't be focused onto the same spot as the collimated light.*

1.3 History of the schlieren method

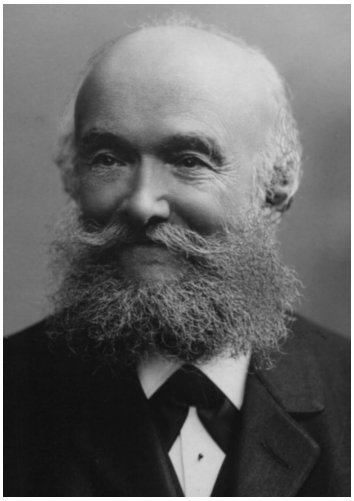

Figure 1.4: *August Toepler (1836-1912) [3]*

The famous experimental physicist Robert Hooke (1635-1703) was probably the first scientist to use a schlieren imaging setup. He used a simple system consisting of only one lens and the iris of the spectator's eye as filter (See section 3.1.2). Hooke was interested to see the flows of hot air in candle plumes. Unfortunately, his method was not clear enough for more detailed studies. Nonetheless, he described the observed convection phenomenae in his famous publication 'Micrographia' [1].

In context with the history of schlieren, a related technique is worth mentioning: For centuries, when testing a lens during fabrication, lens makers used a setup that goes back to dutch astronomer Christiaan Huygens (1629-1695). Its method has been very similar to the schlieren's: A distant light source is focused with the tested lens, resulting in a varying luminosity picture that indicates the tested irregularities in the lens shape (See Fig. 1.5, left side). These pictures build up the same way as the shadows of the fluid inhomogeneities in schlieren images: Small deviations of the background light rays result in a changing luminosity on a screen. French physicist Leon Foucault (1819-1868) improved the test, providing an outstandingly accurate method by blocking half the light with a knife edge at the focal point. Foucault's improvements of the optical shop test method showed to be the very foundation for the use of schlieren methods in physics.

In the sixties of the nineteenth century the German physicist August Toepler (1836-1912) invented the first advanced schlieren system for visualising

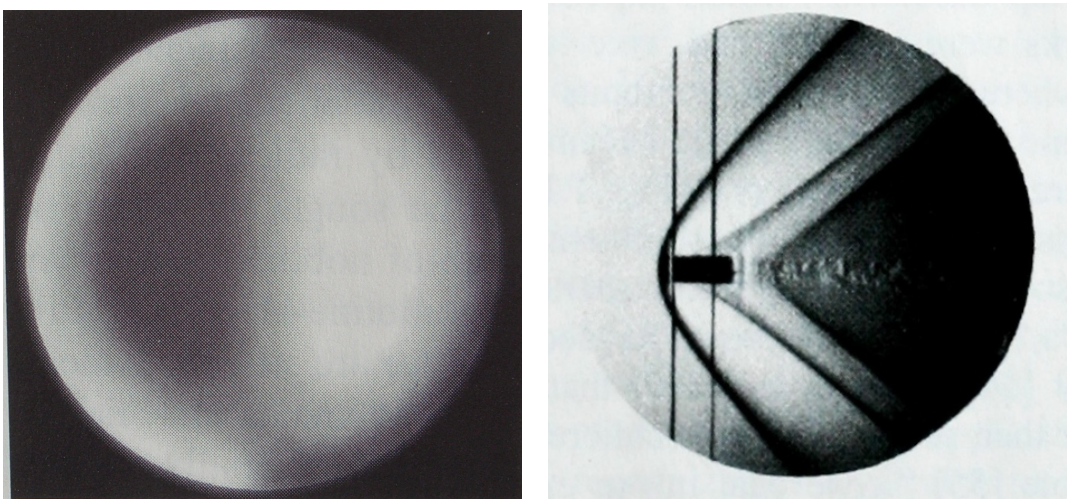

Figure 1.5: ***Left:*** *Image of a lens filtered with a knife edge as proposed by Foucault. The light passing the lens through the points corresponding to the darker parts are focused toward the filter, stopping their further propagation [1].* ***Right:*** *A schlieren photograph of a supersonic bullet's shock wave by Mach and his collaborators [1].*

flows. Developed from Foucault's lens test setup, it meant a big improvement in quality and sensitivity of the schlieren images. By using the filter Foucault introduced, his setup was able to enhance the contrast of schlieren images compared to shadowgraphs or Hooke's setup. As photographic cameras were not good enough at that time, the visualisation still went over the spectators eye. For his attempts to optimize the optics he is regarded as the father of scientific schlieren systems. He immediately saw the technique's possibility for the better study of flows and waves of fluids. Though he tried to depict sound waves in air without success, during his tests, he started to describe shock waves, which would later become the schlieren system's most important field of research. It was also him to name the effect after the German word for streak ('Schliere'). A name that has established itself even in the English language.

Giving such a great instrument for fluid visualisation, the technique saw a quick and great spread in the world of science, of course especially in aerodynamics. The famous fluid dynamicist like Ernst Mach (1838-1916) and Ludwig Prandtl (1874-1953) used schlieren as an important tool for their famous researches in fluid dynamics.

In the first half of 20th century schlieren became a crucial tool in the

upcoming field of aerodynamics. Germany, with researchers like Hubert Schardin (1902-1965), was the worldwide leader in aerodynamic schlieren research between the two world wars. After the end of the second world war in 1945, many of the German fluid dynamicists who were also schlieren specialists, were asked to emigrate to France or the U.S. to continue their aerodynamical researches. As many researcher followed the call, they brought with them their advanced schlieren systems. Before and during the war, Germany had been the worldwide leader in supersonic research, for which the main tool had been the schlieren imaging method. With the upcoming supersonic era in the states after the war, schlieren research found its new center in the U.S. where it has stayed over the years so far. Not changing in it's essence until today, schlieren systems kept its form over the past century up to today. However, schlieren's importance in fluid dynamics got slowly overtaken by computer simulations in the past few decades [1].

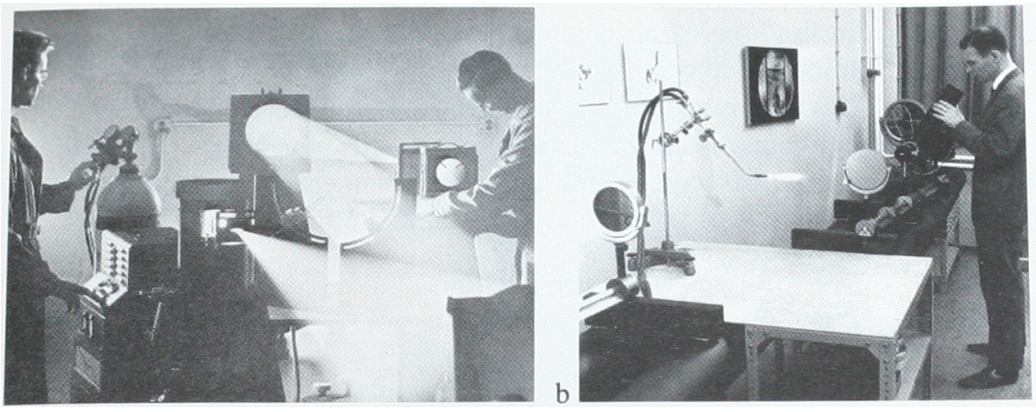

Figure 1.6: *Schlieren setups in the early 20th century. For the aerodynamical visualisation, parabolic mirrors of larger diameter were mainly used [1]. The developent of the fluid dynamics was pushed forward thanks to the imaging possibilities of the schlieren method.*

About the designation schlieren The hereby discussed optical setups are differently named throughout the literature: From *schlieren system*, *schlieren setup*, *schlieren method* to *schlieren technique*, many common designation exist. It is never the physical effect that is meant, having lost the meaning of the word *schlieren* from the original German 'Schliere' (the visualised inhomogeneities themselves), but rather the visualisation process as well as its setup.

Chapter 2

Theory

Figure 2.1: *Multiple shock wave of an F-111 supersonic jet. The image was taken without schlieren system or similar. [1]*

This chapter gives a brief overview of the physical effects that affect schlieren imagery. Basically, in a schlieren setup, a combination of refraction and sometimes diffraction deviates the light propagation. The deviations are caused by the spatial variation of the fluid's refractive index. For the analysis of the resulted images however, the physical reasons for these inhomogeneities need to be known. In the end, it is the refractive index variation

that is depicted on a schlieren image.

There are three main points that change a object's refractive index:

- Pressure gradients, e.g. in a ultrasound. In air, these are weak refractive index variation, only shock waves being strong enough to be seen by eye. An impressive example for this is the figure above.
- Temperature differences. These provoke the strongest refractivity variations and are thus most simple to visualise. A candle plume was among the first object to be studied by schlieren technique and can sometimes be seen by eye.
- Variations of the chemical composition of the material: A common example is sugar diluted in water where streaks can be seen by eye. Also, the flow of some gases can be seen in air, as the refractive index of those can vary importantly from the air's.

The exact distinction of refraction and diffraction is not exactly clear. In literature, the definitions are sometimes even contradictory. Often, diffraction is used for light deviation effects happening without a changing refractive index but discrete object patterns like in Bragg diffraction. The effect described in section 2.4 however is clearly a diffraction, although its origin is only the changing refractive index. For more distinctiveness, in this paper, effects that can be described using geometric optics will be referred to as refraction, deviations that can only be described with a wave equation as diffraction. Geometric ray optic theory is more or less sufficient for a first qualitative approach as well as for building up a schlieren setup. However, as for ultrasound fields in water the above mentioned special diffraction is fundamental, it will also be discussed.

2.1 A short overview of lens relations

As in the schlieren methods only convex lenses are used the equations for concave lenses will be left out. Also, the parabolic mirrors can be described analogously, with one side simply flipped over the lens plane due to the reflection. Certainly not correct enough for a complete description of mirror optics, this analogy is sufficient for this paper. Most of these relations should be well known, but as they are fundamental for working with schlieren will be recalled hereby.

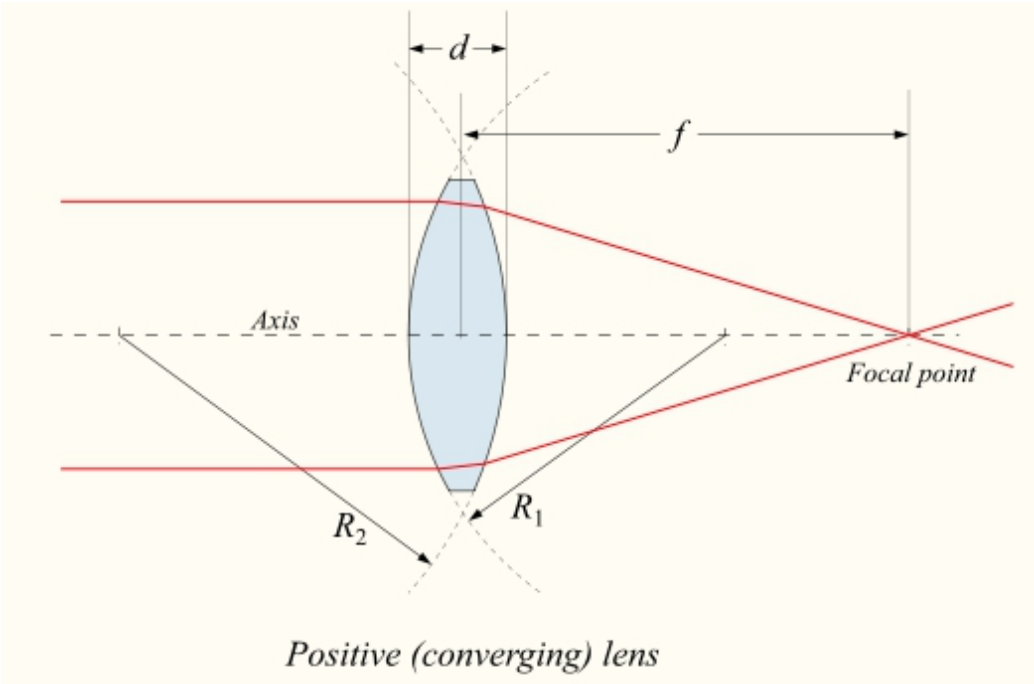

Figure 2.2: *Illustration of a Convex Lens. ([17])*

The convex lenses have an important property: they focus collimated light on one spot, the focal point. Each lens can be characterized by the distance of the focal point to the middle plane of the lens, which is the same on both sides of the lens. The so called focal length is defined by the curvature of both surfaces and the refractive index n of the material the lens is made[1]. The relation, which has the formula

$$\frac{1}{f} = (n-1)\left[\frac{1}{R_1} - \frac{1}{R_2} + \frac{(n-1)d}{nR_1R_2}\right] \tag{2.1}$$

[1] All following relations are only valid for optical systems in air or vacuum. This causes no problem so far.

is called Lensmaker's equation and defines the inverse of the focal length[2] of a convex lens.

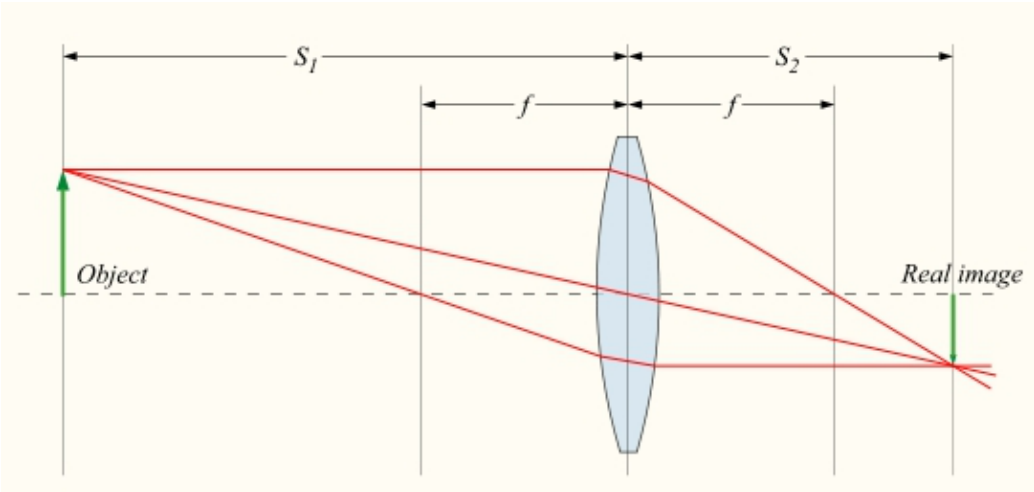

Figure 2.3: *Illustration of imaging properties of convex lens with a spheric curvature. ([17])*

Imaging Properties The following relation shows the imaging properties of a lens. If S_1 should be smaller than f, S_2 would need to be negative and result in a virtual image.

$$\frac{1}{S_1} + \frac{1}{S_2} = \frac{1}{f} \tag{2.2}$$

Spherical aberration However, most convex lenses cause one tenacious problem: For manufacturing reasons, many lenses are formed as a segment of a sphere. Being a good approximation, in most cases this causes no problem. Such lens have a diffuse focal point as it is not the same for the whole lens.

Chromatic aberration When using white light, another aberration effect occurs: As longer wavelength are refracted stronger, the focal length varies with the wavelength. Therefore, only one wavelength can be focused onto a plane of distinct distance. Simple solution to the issue is the use of a monochromatic light source or a wavelength filter.

[2]Focal length f, radii of curvature R_1 and R_2 and thickness on mid-axis d.

2.2 Refraction

Theory of refraction is necessary for the understanding of schlieren systems. It is the basic physical effect that makes schlieren visible. The equations presented here are a simplification of the complex wave propagation theory as they only describes the ray trace of refracted light. The derivation of the equations are left out mostly[3].

The ray curvature in a medium with varying refractive index n is given with the second derivative of the beam, which follows the equation

$$\frac{\partial^2 x}{\partial z^2} = \frac{1}{n}\frac{\partial n}{\partial x}. \tag{2.3}$$

The axis are chosen as seen in Fig. 2.4: The optical propagation direction of undisturbed light is the z-axis, the x-y-plane being perpendicular to it. The relation (2.3) is therefore also true for the y-axis and any direction perpendicular to the z-axis.

As we see, the curvature is proportional to the ratio of the refractive index' gradient over the index' value at the particular position itself. A light beam passing a refractive gradient parallel to the z-axis is hence not diffracted at all. The angle ϵ of deflection in the x-z-plane[4] is obtained by integration of (2.3). This results in

$$\epsilon_x = \frac{1}{n}\int \frac{\partial n}{\partial x}\partial z. \tag{2.4}$$

However, the relation is only an approximation for small deviations, as the ray is assumed to be parallel to z, which is not the case anymore after it is bent.

The relations are valid for continuous or abrupt changes of refractive indices, the latter being the border surface of two phases. This results in the standard scheme for refraction: the abrupt change of direction of light.[1, Pages 26/27]

2.3 The refractive index

Evidently, a quantitative analysis of a schlieren image can only bring information about the distribution of refractivity. To deduce the measures of interest, relations that describe temperature, pressure and density are needed. The

[3] An exact derivation can be found on page 338 of Settles [1]

[4] Again, this is true for any direction perpendicular to the z-axis.

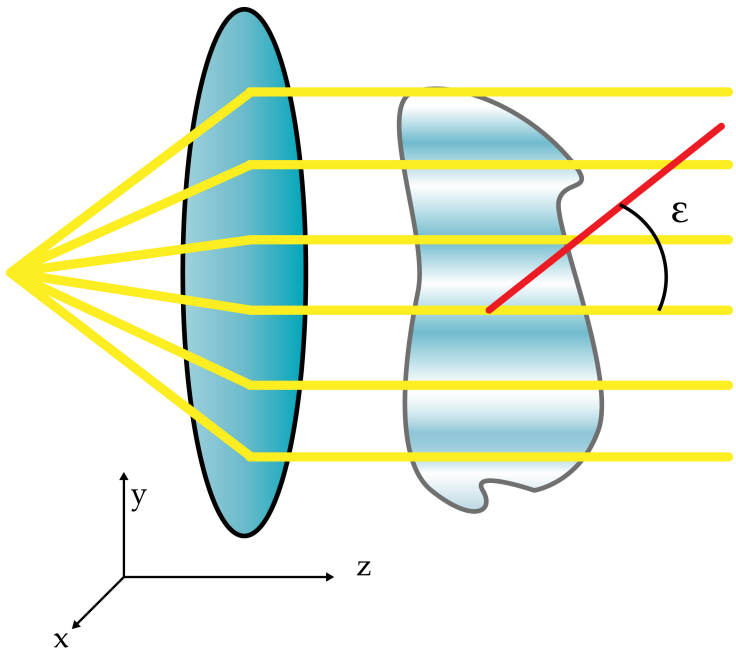

Figure 2.4: *ϵ defines the total angle of deflection.*

refractive index is known as the relation $n = \frac{c_0}{c}$ of light speed in vacuum c_0 over the light speed in the material.

In standard gases, the simple relation

$$n - 1 = k\rho \tag{2.5}$$

puts the density in relation to n and k, the Gladstone-Dale coefficient, which is specific for every gas and its conditions. However, the fluid of main interest for this study will be water, its refractive index is more complex to determine. As there is no simple arithmetical expression that sets the refractive index of water to either temperature or pressure, it has to be measured specifically. Examples of an experimental analysis can be found in different papers (e.g. [10, 11, 13]). Of course, every refractive index is only valid for one specific wavelength of light. The higher energy waves of shorter wavelength are less influenced by the material's influence on the electric field.

Further investigation on the exact relation between refractive index and the state of the fluid would be needed in regard to a quantitative evaluation of schlieren images. From the results of a measurement, the pressure distribution could be obtained. However, this exceeds the range of this report. In regard to the ultrasonic manipulation research it is nevertheless an interesting possibility for further research.

2.4 Raman-Nath-Scattering

In 1935 the two Indian physicists C.V. Raman and N.S. Nagendra Nath managed to describe a scattering effect that happens when a beam of collimated light passes a perpendicularly propagating beam of ultrasound in water. Under the circumstances of a homogeneous acoustic field, the deflection of a light beam cannot be described by the standard refraction theory. Their solution is very important for schlieren images of ultrasound and is therefore discussed here. [12]

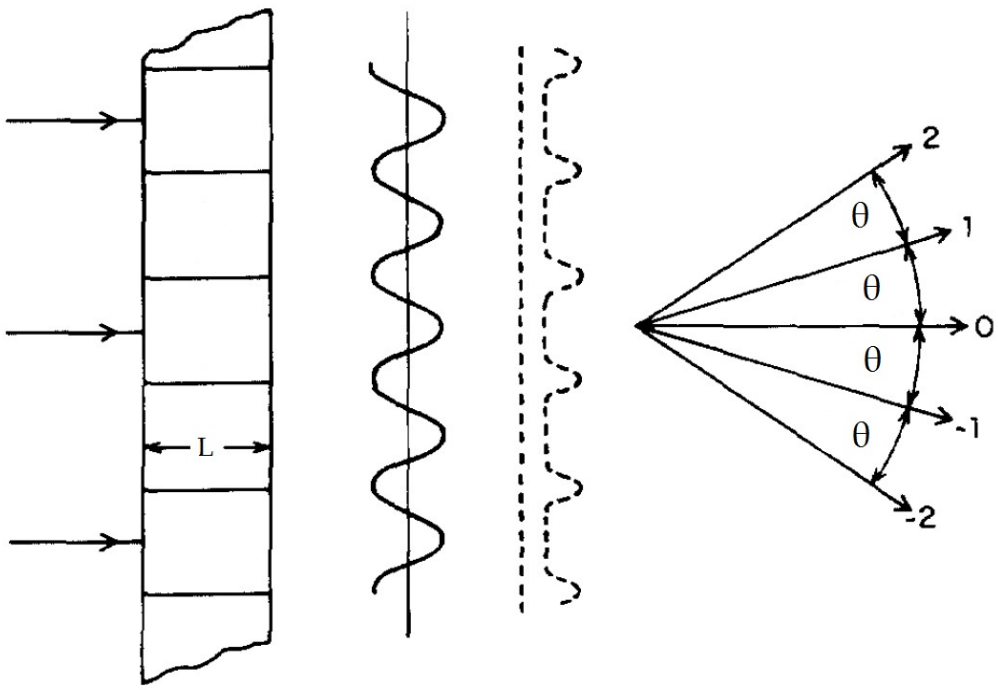

Figure 2.5: *Illustration of Raman and Nath's model. From each point on the surface, the light is emitted in the discrete directions shown. The dashed line represents the intensity of the emitted light depending on the vertical position. [14]*

Interestingly, light that passes a sufficiently thin band of ultrasound is scattered into discrete directions. As depicted in Fig. 2.5, the sinusoidal ultrasonic field diffracts light to n degrees on an angle of deviation θ that fulfills following equation:

$$\sin(\theta) = \pm\frac{n\lambda_l}{\lambda_s}. \tag{2.6}$$

The wavelengths are denoted with λ_l for light and λ_s for the ultrasound wave. The ultrasound wave which produces the periodic change of refractivity is modeled as

$$\mu(x) = \mu_0 - \Delta\mu sin(\frac{2\pi x}{\lambda_s}) \tag{2.7}$$

and is assumed as stationary in time. The relations stay the same for moving waves. Interestingly, the values of deviation do not depend on the total refractive index change in the wave. Only the intensity of the rays will be affected by the amplitude of the ultrasound.

The scope of Raman-Nath diffraction The Raman-Nath phenomena has evidently some limiting factors. For a Raman-Nath diffraction to happen, the Klein-Cook parameter $Q = \frac{2\pi\lambda_l L}{n\lambda_s^2}$ needs to be much smaller than 1 [2]. Solved for L, and with the undisturbed refractive index $n = 1$ this gives

$$L \ll \frac{\lambda_s^2}{2\pi\lambda_l}. \tag{2.8}$$

For any $L \gg \frac{\lambda_s}{2\pi\lambda_l}$, the undiffracted light overweights and the Raman-Nath effect is negligible.

Chapter 3

Examples and Applications

The possibilities of visualising the inhomogeneities of the refractive index are not limited to the standard schlieren system. Actually, there is not really a definite *schlieren setup* but rather endless variations that use quite different techniques to visualise refractive index variations. This chapter provides a short overview over some of these different methods with mirror and lens systems being the main two methods. The applications however are very similar for all different visualisation techniques and are presented at the end of this chapter.

Figure 3.1: *The usage of schlieren setups is wide: The downflows of a clean room worker are observed on this picture [4].*

3.1 Related examples

3.1.1 Shadowgraph

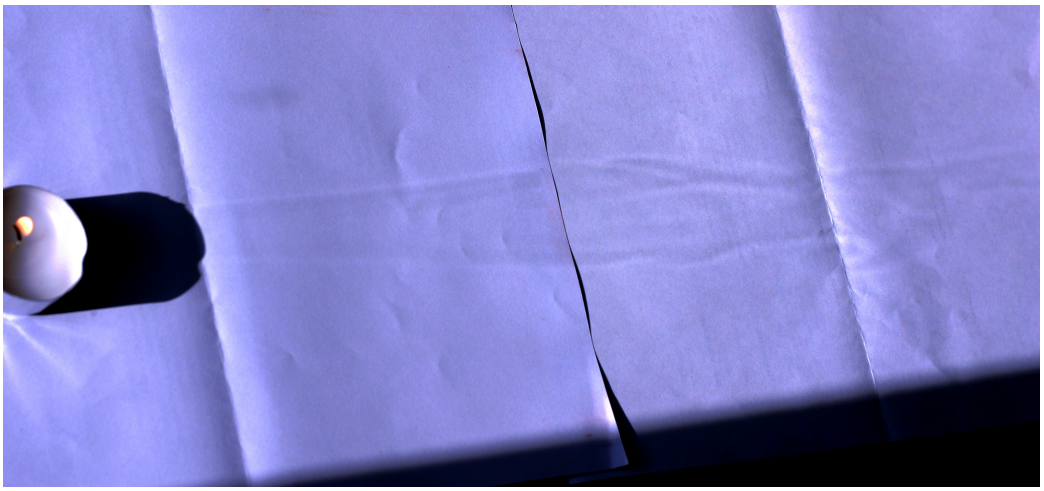

Figure 3.2: *Picture of a shadowgraph taken in sunlight. A similar result may be obtained by using one distant point light source instead of the sun. Both produce approximately collimated light. This is good enough as the shadowgraph is not an exact technique at all.*

The simplest way to visualize diffracted light is the shadowgraph method (Fig. 3.2). Using the approximately parallel sunlight and a projection plane, the diffracted light provides a visible shadow image of the fluid. The light rays that are deflected by going through the inhomogeneity lead to the brightening up and darkening of spots on the screen. From one's everyday experience the shadowgraph of hot air from a fire or a candle projected on the sunlit ground is certainly well known [1].

3.1.2 Hooke's schlieren system

In contrast to the shadowgraph systems a focused optical image is produced for a schlieren image. Therefore, a convex lens or parabolic mirror is required at least. Using only one lens, Robert Hooke's setup is the simplest method that can be regarded as real schlieren setup. As shown in Fig. 3.3 he used two candles: The first being set in the imaging plane corresponding to the spectator's position, providing the background illumination point of the lens, whereas the second candle simply produces visualised hot air [1]. It may be easily tried at home, a sufficiently large convex lens being the only requirement. A cosmetic parabolic mirror which is more often to find in a household

would be an alternative for the large lens. It would though be necessary to position the light source on the same side as the spectator.

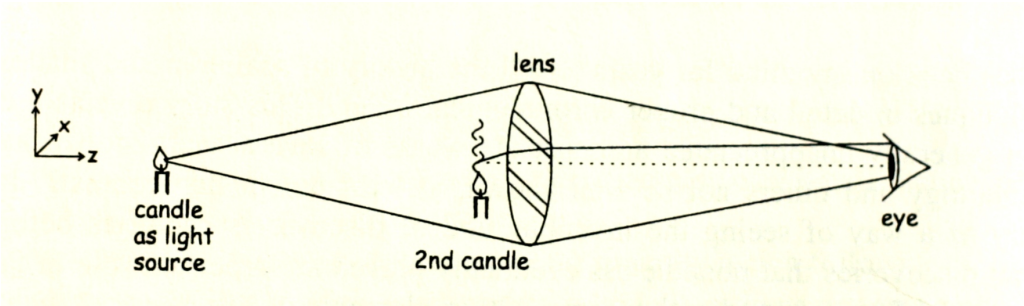

Figure 3.3: *Hooke's simple schlieren system consisting of one candle background illumination source and an other as source for the hot air that is examined.*

3.1.3 Flickering air

An example for the varying refractivity that most people have seen is the flickering of hot air from an engine or a fire. Even without schlieren system, the flow can be seen qualitatively. The distance to the background is the key to see the effect best. Similar to inhomogeneously transparent materials (like view-blocking windows), the further an object is behind the disturbance, the more distorted it gets. The same effect is visible on Figure 2.1. Background oriented schlieren systems use an approach that is closely related to this simple photographing: By comparing the undisturbed background to one with the distortion, the image of the disturbance can be computed (see subsection 3.3.1).

Figure 3.4: *Hot air convection in the Savannah. The image of the horizon is perturbed due to the inhomogeneous refractive index field [5].*

3.2 Mirror and lens systems

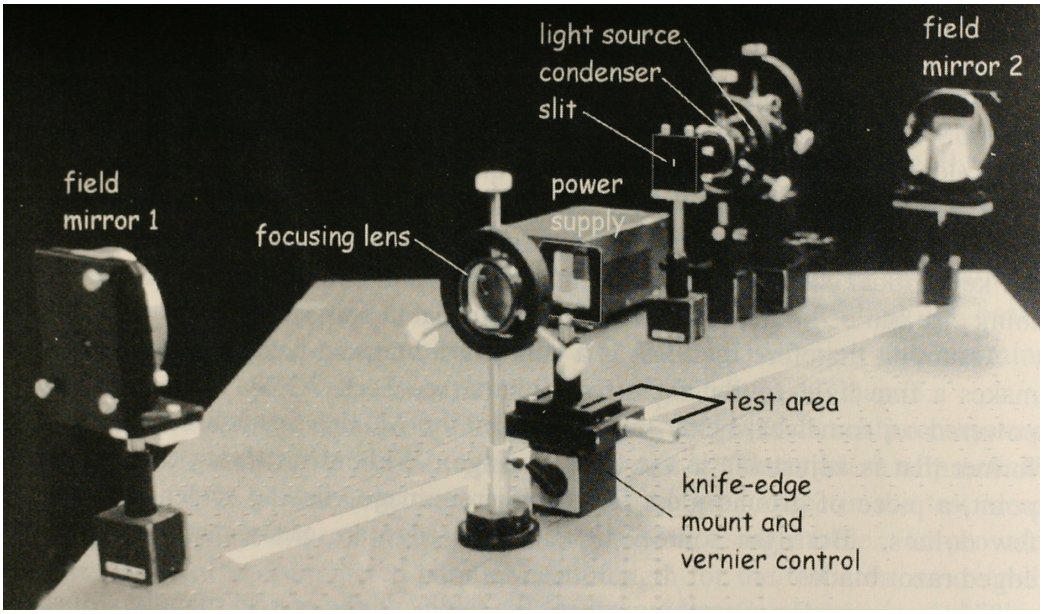

Figure 3.5: *An example of a modern z-shape mirror system. High precision mounting devices are used for the optical parts, as the alignment has to be as exact as possible [1].*

Of the systems that can be regarded as *standard schlieren setups* there are two major groups: First, the lens systems using convex lenses for the optics as described so far. Secondly, instead of using lenses also parabolic mirrors can be applied for collimating and focusing the light. Though the two setups are optically more or less equivalent, some characteristics diverge substantially. Therefore, one of the first questions that has to be answered before setting up a schlieren system is whether to use mirrors or lenses. Of course a combination is possible, though it has to be payed attention that the advantages of both are not canceled out by the others disadvantages.

Historically, lens setups represent the original schlieren systems. When exactly the first mirror setups emerged is not clear. However, in the height of the aerodynamical schlieren research in the first half of the 20th century, the mirror setups had become the most used setup type, probably because the quality of the parabolic mirrors had reached better standards. An example of a setup of that time can be seen on Fig. 1.6. Mirror setups have since been favorably used for larger flow visualisation. However, for ultrasound imagery, lens systems are still in use (see for example [6]).

3.2.1 Lens setups

The core of a lens setup consist of only two lenses: A first that collimates light and a second that refocuses it onto a point. The alignment has to be on one single axis. This is also the advantage of the setup, as all elements have just to be oriented in one single direction and aligned onto the same axis. As depicted in figure 3.6, additional optics are sometimes needed to produce a point light source and to project the final image onto a screen, usually being simply a camera.

One possible variation is by using only one optical lens, similar to Hooke's setup (section 3.1.2), but with the eye being replaced with a standard filter and a camera. As the object would not be illuminated by collimated light anymore, the schlieren image would not image the deviations equally for the whole test area though.

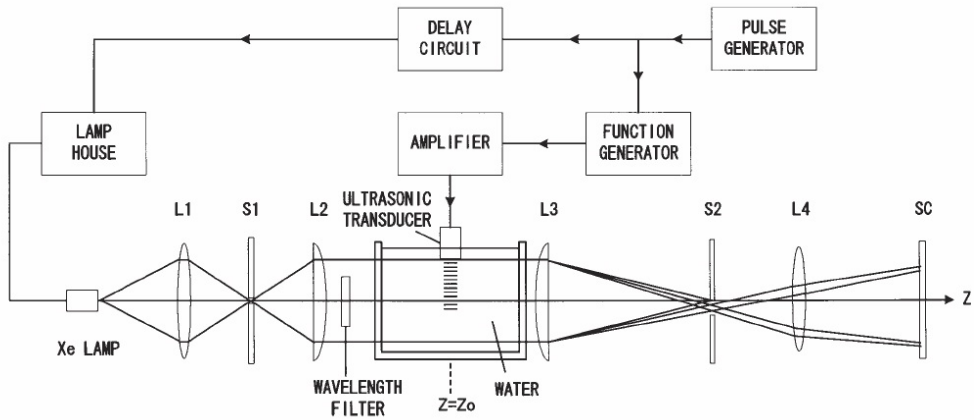

Figure 3.6: *This setup used for ultrasonic imagery is a standard lens setup. It essentially consist of two main lenses (L2 and L3), one for collimating light, the other for focusing it onto the filter plane. Some additional lenses are part of the illumination (L1) and the image projection system (L4). Additionally depicted is the combination of the illumination and the ultrasound transducer for coordination of the image illumination [7].*

3.2.2 Mirror setups

Mirror system, obviously, cannot be aligned on one axis as the light is reflected and needs a folded setup (for the typical z-shape see Fig. 3.7). This can be an advantage to save room. However, it implies an arrangement that is more difficult to set up. Nevertheless, the advantages are considerable:

Chromatic aberration is not a problem for mirrors. As only one polished surface and no internal quality is needed, the price is remarkably lower than for lenses. In larger setups the price of the optics becomes very important, therefore lenses are hardly used for more than 10 cm diameter [1, Chapter 3].

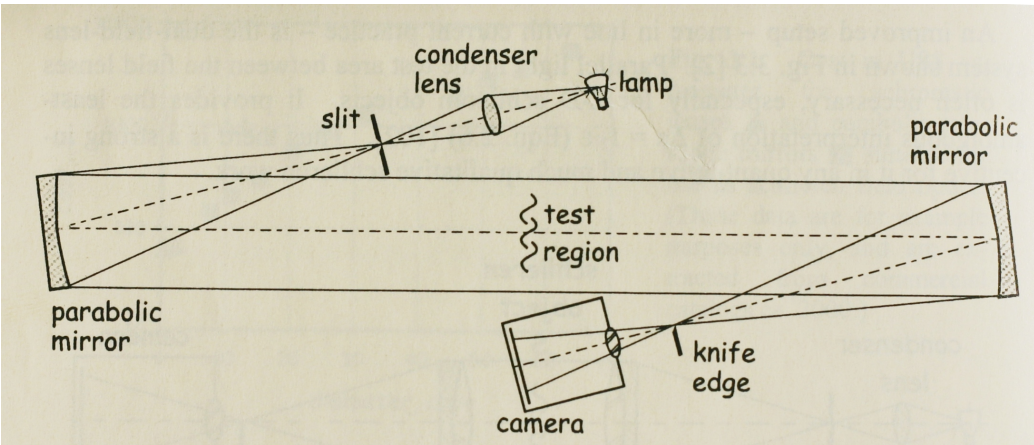

Figure 3.7: *The standard mirror alignment with mirrors is called z-type, after the shape of its alignment. It is the corresponding setup to the linear lens array [1].*

Aberration Unlike lenses, mirrors have the same geometrical properties for all wavelength, so no chromatic aberrations occur. But, similar to lenses, most mirrors are shaped in the form of a sphere section. Though cheaper in production, the shape consequently produces spherical aberration problems like spherical lenses. These can become visible when filtering the light for the schlieren visualisation. The ideal form would be a parabolic mirror where all parallel incoming light is focused on one spot. However, as mirrors have to be off axis for not projecting the light back from the origin, the parabolic mirrors are not optimally aligned. So called off-axis aberrations happen then. An elegant solution to that problem is shown in Fig. 3.8.

In analogy to the single lens setup a variety of one-mirror setups can be arranged. Besides the on-axis variant shown in Fig. 3.8, where the returning beam is deflected away from the source. An elegant solution is to combine the filter function with the mirror. Another possibility is to position the light source off axis so that the light is focused away from the source. For that, an elliptical mirror would be needed to suppress aberrations.

3.2.3 Different Filter Types

Apart from the differences, there is one thing that is exactly the same for both mirror and lens setup: As the optics are principally the same, filtering works equally on both systems.

The use of a simple razor blade as filter is widespread and in no point advised against. The sharpness is needed to prevent other diffraction effects on the edge. Usually oriented horizontally, the edge filters any perpendicularly diffracted light beams, as these are focused onto the blade. This filtering is the actual process that makes the 'schliere' visible, producing the shadows on the screen. However, changing the filter form and orientation is a useful alternation to the standard system. It allows to set the emphasis on specific grades or directions of deviation [1, Chapter 7.1.3]. A popular method is to use gradual color filter, so to give the light of certain regions colors according to their deflection. Examples of color filters and filters of different shape can be found in Fig. 1.1 and 3.9.

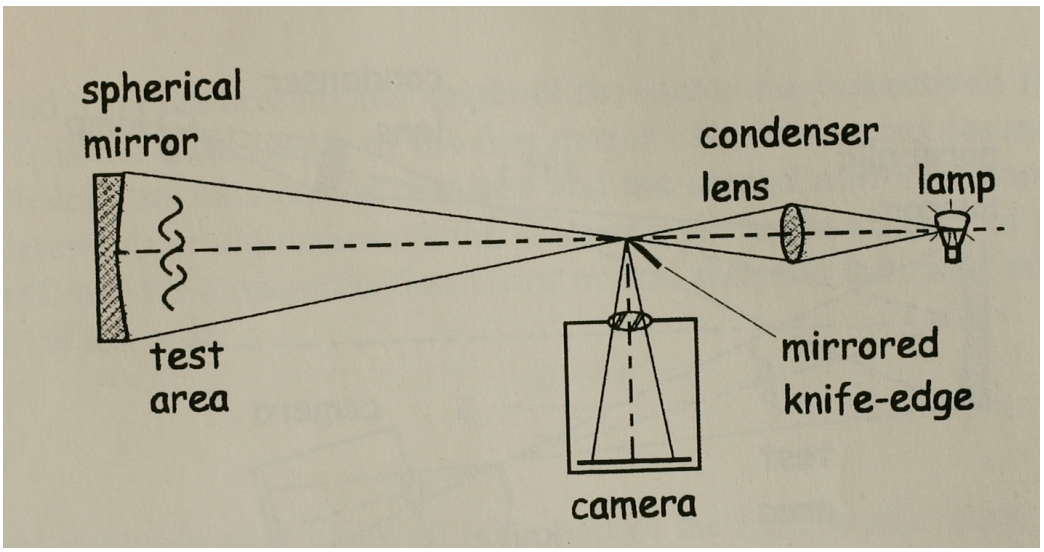

Figure 3.8: *Instead of blocking half the light the filter projects half the light to the camera. The off-axis aberration can be avoided that way. A similar approach uses a beam-splitter and filters afterwards. [1]*

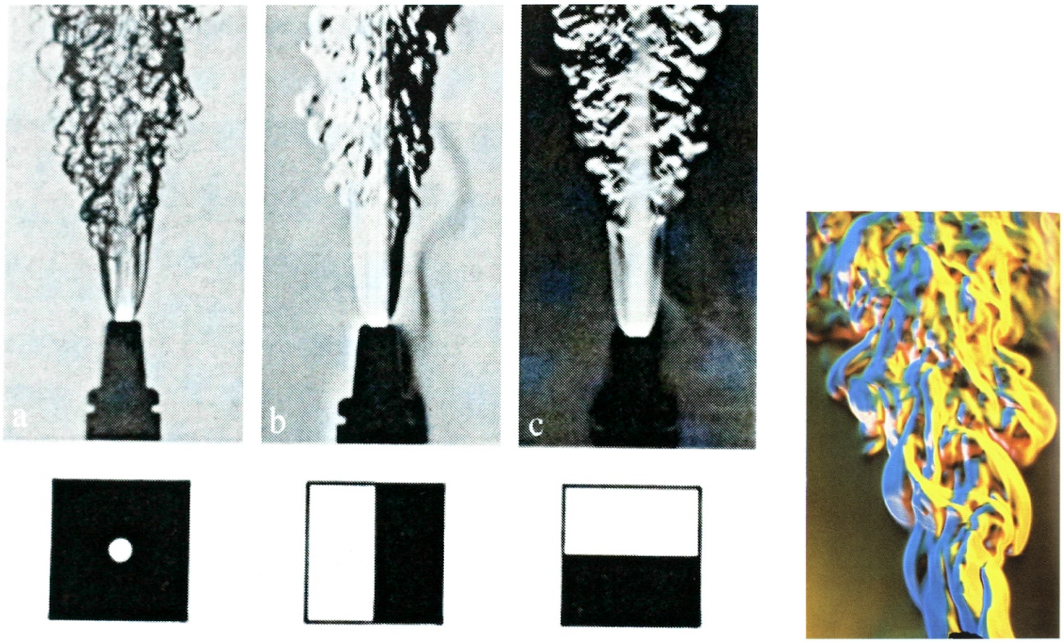

Figure 3.9: ***Left:*** *Array of horizontal and vertical knife blade filter and pinhole filter [1].* ***Right:*** *An image of a candle plume recorded with a colour filter [4].*

3.3 Further types of schlieren setups

3.3.1 Background Oriented Schlieren Imaging

The main problem of the standard schlieren method is their need of a special setup that mostly limits the application to labs or other indoor uses. This is exactly the point where background oriented schlieren imaging has its advantages. Instead of filtering deviations from the background light, standard photographs are being compared with the help of computers. From the differences of an image to the unperturbed background the deviation field can be computed. While working better with backgrounds with clear patterns, the technique has been tested in open air for measuring the flows of a helicopter rotor as seen in Fig. 3.10. However, as it depicts diffractions that happen in a three dimensional field of larger scale, the information of a 2-dimensional image is principally not very useful. The tests have therefore been made using a stereoscopic setup that was used for the computation of the three dimensional field [16]. It can be questioned if the technique should count as schlieren method as it is not using any filter that 'sorts' the deviated light beams in any way.

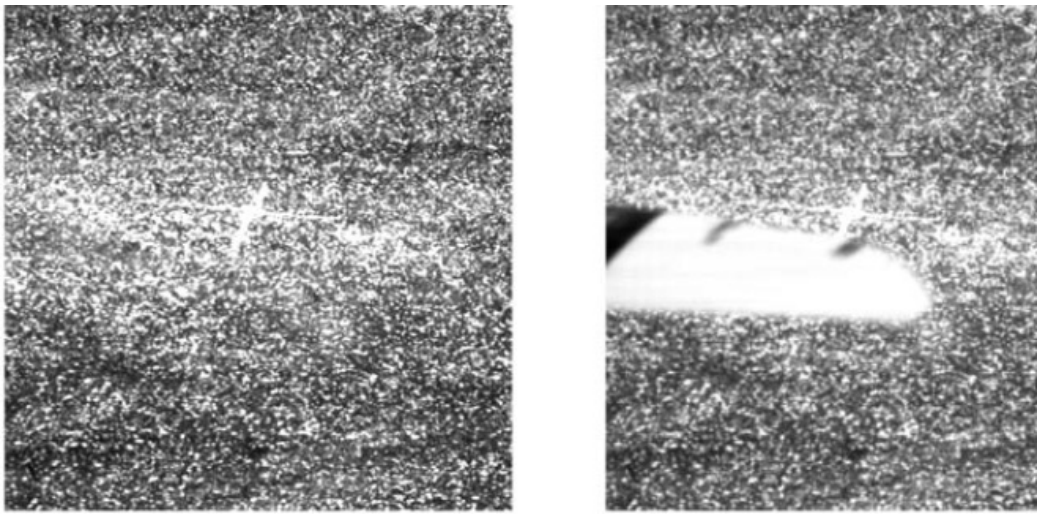

Figure 3.10: *Computer image of a reference field (left) and with a helicopter rotor passing (right). Invisible to the bare eye, the small deviation are easily calculated numerically [16].*

3.3.2 Filtering with Digital Micromirror Device

An interesting, rather modern filter method is proposed by Carsten Unverzagt *et al.* [8]. Instead of a static filter they use a so called DMD (digital micromirror device) to produce an arbitrary filter pattern. It consists of transparent rectangle with microscopic mirrors as pixels that can change their inclination. Similar devices are used in common projectors. The filter therefore works similar to the one in Fig. 3.8. It allows to change the filter shape during measurement. This is especially with regard to a more quantitative measurement very useful, as different filter patterns have different characteristics that can be combined. Additionally, from the same measurement, data of different filters is available at practically the same time.

Figure 3.11: *Image of a DMD screen. Its resolution is of 1024x768 pixels. Such device are used in high quality prjoctors [8].*

3.3.3 Grid Filter

Quite a different approach is made with the grid filter systems. The setup that can be used on a arbitrary scale works similar as the Moiré-effect does: An image of a periodic pattern is projected through a field of disturbances. After that, the image is projected through a filter that has the same pattern and produces a sort of interference with the original image that makes the flow visible. For an example of a produced image see Fig. 3.12.

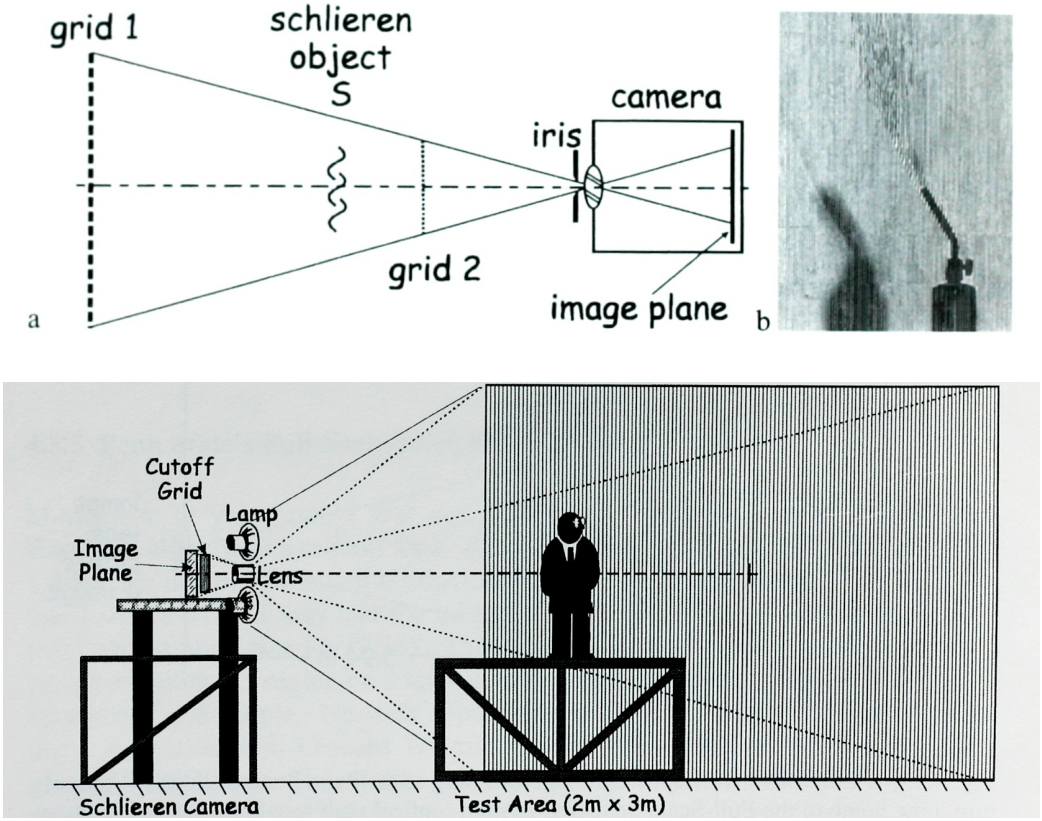

Figure 3.12: *Two examples of grid filters. The lower one is used for large scale images. For such sizes setups with mirrors are too expensive, grid filter are therefore good for that. [1]*

3.4 Application field

As commented before, schlieren visualisation has been the favorite tool of fluid dynamicists for a long time. Before computer simulations and visualisations were available, schlieren was the only way to visualise transparent fluid flows and shock waves without influencing the measurement. Shock waves for instance can't be visualised with smoke-tracking methods for streak lines. But this is by far not the only application field: Settles [1] mentions several other applications reaching from manufacturing, safety tests and energy optimisations where schlieren has been used.

Today, the use of computers for simulations is certainly the main reason why schlieren optics are not as common as it was in the large part of the 20th century. Nevertheless, the impressive results and the relatively low price and complexity of such setups still provide an important reason for the use schlieren setups in various scientific areas.

3.4.1 Fluid mechanics

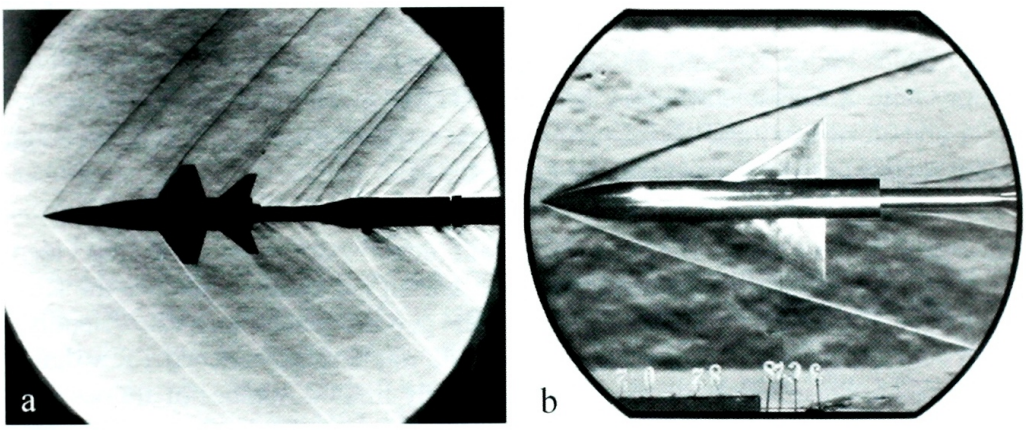

Figure 3.13: *Typical examples of supersonic wind tunnel images. The schlieren technique was essential to the development of the theory on shock waves of Mach and other fluid dynamicists. [1].*

In the research of supersonic flow the schlieren visualisation technique has been a crucial tool for providing wind tunnel measurements as it allows a very detailed image of an instant of the flow. As seen in Fig. 3.13, the shock waves of supersonic rockets can be visualised extraordinarily well.

Another important schlieren application is heat convection visualisation. Mainly energetic questions as the thermic flux in buildings are answered with

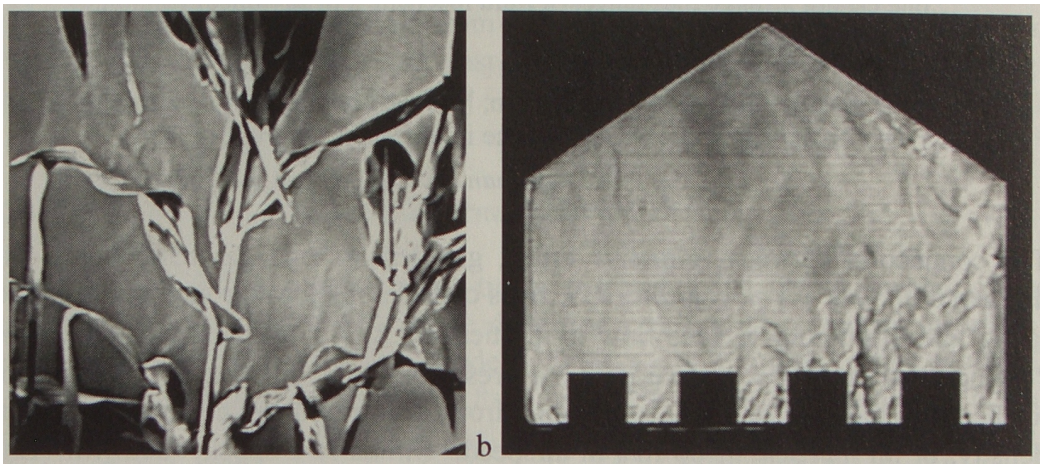

Figure 3.14: *Left side: Even the air flow around the leafs of a corn plant can be visualised. This was used for agronomical research. Right side: A model greenhouse section with the heat convection produced by the sunlight heat. [1].*

the schlieren method. An interesting example are the agricultural tests of thermal convection as seen in Fig. 3.14. Even small scale thermic convection on plants has been possible to visualise.

3.4.2 Material Testing

Of course, not only fluids and gases can be tested. Small scale unevenness and production allowances that are commonly measured with interferometers or similar high sensitivity methods can also be tested with schlieren setups: Like for the lens testing setup (see Chapter 1.3), any inhomogeneities of the surface in a transparent material can be visualised with a schlieren setup. The small bumps or irregularities in the structure cause the same deviation of the light as in fluids. In Fig. 3.15 one can see the shadow patterns produced by the deviation.

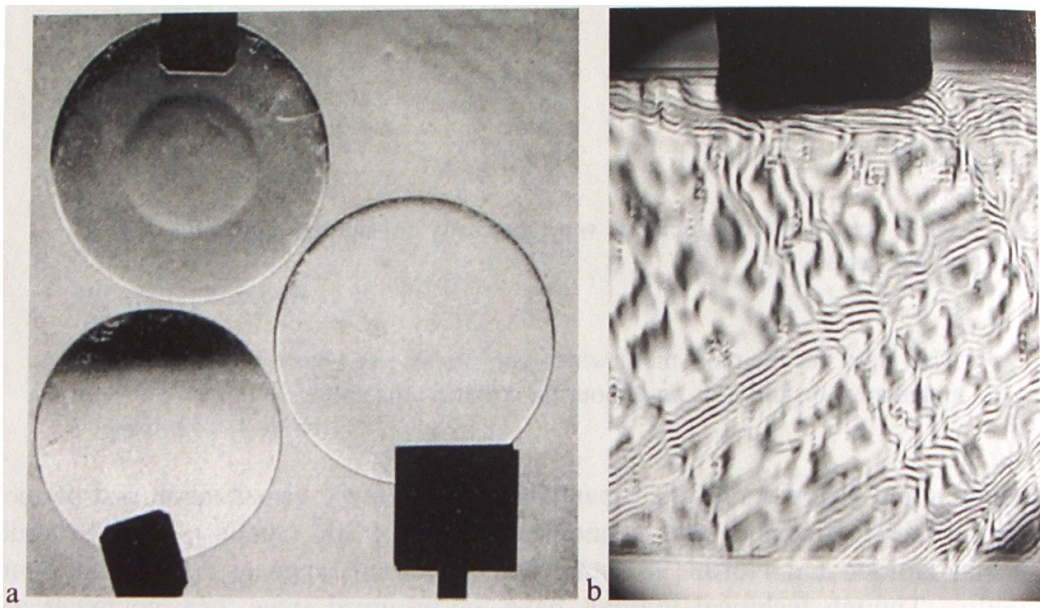

Figure 3.15: *Besides fluids, a schlieren setup can of course be used for transparent solids as well. The schlieren technique originates from a test used by lens maker to see irregularities produced during manufacture (see Fig. 1.5, left side)[1].*

Chapter 4

Conclusion

Is the schlieren technique an option to image ultrasound waves? A distinct 'yes' is the answer. The subject has been studied and prevalently applied in practice by different research groups as well as mentioned in several papers. Interestingly, most of these research groups working with ultrasound are connected to the medical technologies. Often, ultrasonic transducers needed to be analysed for their wave emission properties. For that, adapted systems with a lens setup have been used. Unfortunately, beside the axial dimensions and rough sketches of the used systems no detailed information has been found. A probable explanation is that the almost infinite variety of different realisations possible do not substantially influence the result. Nonetheless, in regard to the building of an own ultrasonic setup, the known specifications of the ultrasound setups represent good guidelines.

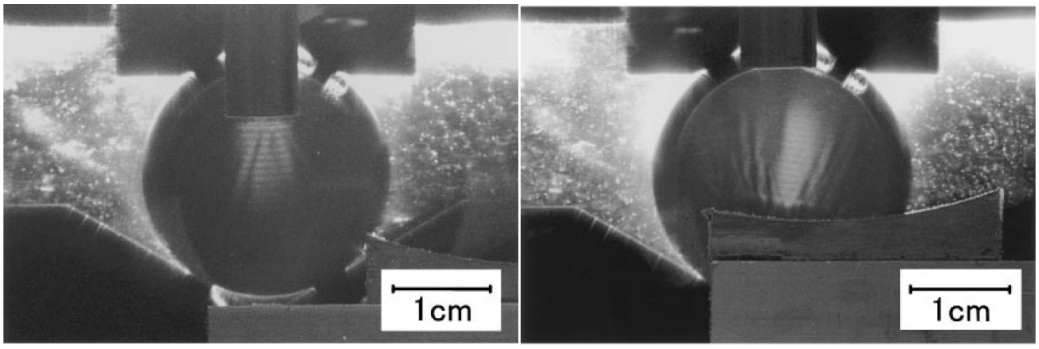

Figure 4.1: *A 2 MHz wave pulse right after emission (left) and after reflection on a curved metal piece. Again, interference is very well visible [7].*

4.1 Expected Results

A look on the previous ultrasound visualisation results is promising. Ultrasound waves of all ranges have been imaged with high resolution in time as well as in space. As shown in Fig. 4.1, each wavefront and the propagation direction can be seen easily. However, most measurements have been of a pure qualitative basis to measure form of propagation of ultrasonic pulses. Nevertheless, some approaches to a quantitative use of schlieren images to determine acoustic intensities or water pressures have been made and are technically possible [6].

List of Figures

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