Dynamic focusing for wide-field light-sheet scanning

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Abstract In scanning PIV the light sheet is shifted rapidly perpendicular to the planes of observation of a high speed camera thus obtaining a 2 component 3 dimensional measurement of the flow velocity. It is desirable to use high aperture optics to collect as much scattered light as possible from the tracer particles. However, high aperture optics also have a small depth of field, so that only a very small depth range can be scanned. One trade off is using telecentric lenses that produce a constant magnification and a large depth of field at the expense of aperture. Here the opposite trade off is presented. A lens system with a larger aperture thus smaller depth of field that is capable of focusing within the time needed for a volume scan using existing high speed cameras. The focusing lens is mounted on a ventilated loudspeaker, i.e. with a magnet system where the voice coil surrounds the magnet and the central pole piece is replaced by an external ring shaped pole. This allows the light to traverse the loudspeaker through the now open central opening. A test system using a small 144 mm woofer, an achromatic lens mounted on the speaker dust cap and an optical set-up similar to a telecentric lens allows scanning for a range of 90 mm with a field of view of 80 mm x 80 mm up to frequencies of 100 volume scans per second.

1. Introduction

Normally, PIV or PTV measurements are performed positioning the light sheet within the flow area and the camera with the lens system is adjusted to give a sharp image of the particles within the light sheet. The depth of field imaged by the lens onto the camera is relatively small due to the high aperture needed to collect the scattered light from the particles, Adrian (1991). PIV delivers two dimensional velocity vector data of the components within the illuminated plane, i.e. 2C-2D. The logical extension is to shift the light sheet in the third dimension rapidly and thus obtain also 3-d information of the flow field (2C-3D), Brücke r (1996). This technique called scanning PIV uses rotating mirrors or mirror drums to shift the light sheet. Figure 1 shows the set-up Kitzhofer, Kirmse and Brücker (2009) used for scanning PTV. Figure 2 shows the rotating drum with mirrors. Here the laser beam enters parallel to the axis of the drum. It then is reflected by each of the mirrors in turn. The mirrors are positioned on a helix on the periphery of the drum. Therefore, the reflection on each mirror is coupled with a shift of the beam along the axis of the drum. During the time it is reflected by each mirror the beam scans a certain angle due to the rotation thus producing the light sheet. The volume scanned by this system depends on the length of the drum and on the separation of the drum from the object. The number of light sheets in the volume scan equals the number of mirrors.

Fig. 1 Set-up for scanning PTV, a: continuous laser, b: optical system, c: rotating drum, d: high speed cameras with telecentric lenses, e: flow box, f: light sheets, (Kitzhofer et al. 2009)

As a consequence of the change of the position of the observed plane one should also shift the focus.
of the lens to maintain the tracer images sharp. Kitzhofer et al. (2009) solved this problem by using telecentric lenses that allow scanning within volumes of 10 cm\(^3\), without having to refocus the lens however at the expense of a low light level.

![Image](image1.png)

**Fig. 2** Rotating drum with mirrors mounted on a helix, (Kitzhofer et al. 2009)

Present high speed cameras allow frame rates of 3000 pictures per second. If one splits this number of images to resolve 10 to 20 shifted light sheets then 150 to 75 3d image scans (double for PIV) per second can be obtained. The scan of the different light sheets lasts therefore about 1/100 of a second. There exist no lenses to our knowledge that can refocus with such a speed. In the case of a wind tunnel the volumes of interest can be much larger, say 50 cm\(^3\). Telecentric lenses would then not only be economically prohibitive but also very large. Therefore, an optical system that allows focusing during wide field light-sheet scanning is needed.

### 2. Actuator

There is basically only one possible actuation mechanism that can shift a lens by the distance needed to refocus quickly enough: electrodynamically. Piezoelectric actuators are fast enough but have a limited displacement. Electrodynamical refocusing is widely spread as the technique used to keep the pits on a compact disc in focus. The lens used in these systems is very small, figure 3.

![Image](image2.png)

**Fig. 3** Focusing and tracking unit of the pick-up of a compact disc player

The larger size equivalent driver would be a electrodynamic actuator, e.g. a loudspeaker. However, standard loudspeakers (and actuators) are built with a magnetic pole piece centered in the ring magnet. The voice coil is located between the central pole piece and the upper pole plate within the ring magnet. Some loudspeaker manufactures produce ventilated systems where the voice coil is arranged outside of the ring magnet thus allowing a free opening in the centre of the magnet assembly, see figure 4.
A ventilated loudspeaker was modified by creating an opening at the centre of the dust cap onto which a lens mount made of plastic was glued, see Figure 5, left. The image on the right shows the back view through the magnet assembly.

As one can see even a larger lens could have been mounted on the system. However the moving mass of the loudspeaker is increased and this would deteriorate the dynamic behaviour of the system. Typically loudspeaker chassis have a free air resonance quality $Q_{ts}$ (Small 1972) that is lower than the value of 0.7 which would result when the chassis is mounted on an appropriate closed cabinet and that corresponds to a flat Butterworth response with a fast impulse response. Therefore, when the loudspeaker is now used as an actuator without a cabinet some mass loading is permissible without deteriorating the impulse response. The quality factor increases with added mass and should not exceed 0.7 to avoid overshoot. The chosen loudspeaker is a trade off between size of the central opening and the size of the loudspeaker as a whole. One could, of course use a large woofer that would allow a much higher payload but the basket of the speaker would be cumbersome. The cone of the speaker is actually not needed here but there is no specialized actuator to our knowledge that fulfils this task.
Not only the payload but also the maximum displacement of the actuator is limited. In the case of a loudspeaker the maximum displacement is half the difference of the length of the voice coil and the width of the pole plate, see figure 4. Figure 6 shows the calculated peak cone excursion vs. frequency for a drive with 2 watts for the chosen speaker using the theory of Small (1972). The maximum mechanical cone excursion of the chosen chassis is 3.5 mm. At low frequencies the peak displacement is therefore limited mechanically whilst at higher frequencies above a hundred Hertz the limit is the thermal power handling of the voice coil. Particularly this type of loudspeaker has a large voice coil (75 mm diameter) that can dissipate a large amount of heat. Therefore, using sufficient power (50 Watts) a peak displacement of 3.5 mm can be obtained also at 100 Hz. However, the same power at 10 Hz would destroy the loudspeaker mechanically.

One reason for the choice of a small woofer is that it has a frequency response that extends up to 3 kHz. This allows driving the speaker with saw-tooth signals which are more convenient than sinusoids for scanning. Saw-tooth signals contain many harmonics of the driving frequency that are necessary for the faithful mechanical reproduction of the electrical signal.

The chassis with the lens was used to build up exemplarily a quasi-telecentric lens system with a higher object numerical aperture as can be seen on the schematics of figure 7. The calculations of the lens system were performed using Winlens 4.4 a freeware program by Adams (1994-2007).

The resulting depth of field of this system is about 10 mm. The magnification varies depending on the position of the plane that is in focus (quasi-telecentric). The mean magnification of the optical system is 1/4.6 and varies by 6 %. This is now not truly a problem since the scaling of a digital image is easily done. However, this simple set-up has the drawback of distortion of the field of view. More effort is needed to design an optical system to cure this problem.
3. Results

Images were taken with a high speed Photron camera that was synchronized with the zero crossing of the signal driving the loudspeaker and shifted in phase to resolve the scan. The camera has 1024 x 1024 pixels and can operate up to 3000 fps. A ruler at 45° relative to the optical axis was used to determine at which position the image was imaged sharply at the peak of displacement of the lens.

![Graph showing focusing range vs. drive amplitude](image)

**Fig. 8** Focusing range of the system for saw-tooth drive vs. drive amplitude

Figure 8 shows the comparison of calculated focusing range with the measured range vs. driving voltage of a saw-tooth signal for various frequencies. The amplifier used to drive the speaker had a maximum output power of 5 Watts. There is an obvious difference between the calculated and experimental values, which is most likely due to non-linearities of the driver since at 100 Hz the difference is much smaller where the displacement is also small. However, this proves that it is possible to build up a lens system that can focus within a range of 90 mm depending on frequency and input power. The maximum displacement of 7 mm of the mounted lens could be used to focus a different type of optical set-up that can deliver a larger focusing range.

References


