Light-in-flight holographic particle image velocimetry for wind-tunnel applications: off-site reconstruction of deep-volume real particle images

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Abstract
Holographic particle imaging techniques for air-flow investigations are mainly limited to small-scale laboratory experiments. The two main reasons are the limited light power available in conjunction with small tracer-particle sizes, which must be in the order of 1 \( \mu \)m to properly probe air flows, and the increased background noise from out-of-focus particles in deep volumes preventing investigations with higher particle densities. To ensure a good accuracy of the velocity measurements by faithful reconstruction geometry, the evaluation of particle images is often conducted in the original recording set-up. The time-consuming scanning process, however, blocks the flow facility during evaluation—a disadvantage for measurements in costly industrial wind tunnels. For an alternative, we have introduced off-site reconstruction and evaluation. In recent papers (Hinrichs et al 1997 Opt. Lett. 22 828–30, Herrmann and Hinsch 2001 DLR-Mitteilung 2001–03: 4th Int. Symp. on Particle Image Velocimetry (Göttingen)) we have furthermore demonstrated principles to cope with little object light and to suppress background noise. Here we present a successful implementation of these principles for wind-tunnel measurements.

Keywords: HPIV, particle holography, light-in-flight holography (LiFH), Nd:YAG laser (pulsed/cw), noise limit, wind tunnel, 3D flow measurement

(Some figures in this article are in colour only in the electronic version)

1. Introduction
Particle holography is the most promising technique to map the three-dimensional velocity distribution of complex non-stationary flows (Hinsch 2002). Such measurements are truly instantaneous and non-invasive. But air flows, and especially those of high complexity, are still difficult to investigate with holographic particle image velocimetry (HPIV)—the extension of particle image velocimetry (PIV) to the third dimension. For this technique two holograms are recorded from a flow seeded with tracer particles. During reconstruction their respective particle images are compared to determine a three-dimensional displacement and the local velocity is calculated. Researchers are concerned with a few problems, of which those most essential for wind-tunnel measurements are reviewed in this section. The basics of solutions to cope with weak object light and noise are recalled, and an application to wind-tunnel measurements is described.

1.1. Weak object light
The holographic recording of particles within air flows has been demonstrated many times in laboratory-scale experiments. But since micrometre-size particles have to be
introduced to faithfully follow the flow, the available light, even
from state-of-the-art laser systems, sets limits to the maximum
cross section of the illuminating beam and thus limits the size
of the volume which can be investigated.

The established and still unsurpassed recording materials
for the holograms are silver halide emulsions (Bjelkhagen
1995). Though these are of low photographic speed, they
offer a solution to the problem of weak object light. Due to
their large dynamic range even weak objects, which do not
show up in a reconstructed image under typical conditions, are
registered as small transmittance modulations on the film. In
the reconstruction these low-intensity particle images can thus
be detected by integrating light over time on an appropriate
sensor (Herrmann and Hinsch 2001). This method has been
used in the present study to allow for the proper small seeding
particles to investigate a wind-tunnel flow and yet allow an
extended volume.

1.2. Noise in particle images

The relevant flow structures are often in the sub-millimetre
range, while they have to be recorded simultaneously over
a volume of typically several centimetres in size in all
dimensions. This requires dense seeding to sample the
field with sufficient accuracy and leads to higher background
noise from out-of-focus images in the image plane under
consideration. The signal-to-noise ratio (SNR) as defined by
Goodman (1967) is given by the ratio of the deterministic
‘particle’-image intensity $I_0$ to the variance $\sigma_N$ of the
background intensities, where $\langle I_N \rangle$ is the average background intensity:

$$\text{SNR} = \frac{I_0}{\sigma_N} = \sqrt{I_0/2\langle I_N \rangle}. \quad (1)$$

To guarantee a given SNR the number density $n_s$ of the
seeding particles must not exceed a maximum value which
 grows with the limiting imaging aperture $\Omega$ and decreases with the depth $L$ of the recorded volume (Pu et al 2002):

$$n_s \leq \frac{\pi \gamma \tan^2 \Omega}{LM^2(I_0/\langle I_N \rangle)_{\min}}, \quad (2)$$

where $\lambda$ is the wavelength, $\gamma$ the so-called signal integrity
factor with values between unity and zero (describing the
deviation from an ideal spherical wave) and $M$ is approximated
as the ratio of the pixel size of the sensor to the mean speckle
size (Goodman 1984). From this formula it is clear that the
configuration of the recording and reconstructing set-up is of
great influence and it is not possible to assign $n_s$ a general
value.

Following this discussion, there are two possibilities to
properly record flows from deep volumes, i.e. to achieve
sufficient SNR even at large values of $L$:

(a) The aperture $\Omega$ may be increased. This, however,
usually goes with an increasing complexity of the set-up
(Zhang et al 1997) or encounters a variety of unwanted
effects related to the recording materials (e.g. emulsion
shrinkage and mechanical stability of the substrate) and
the optics involved (Barnhart et al 1994). Such set-ups are thus unsuitable for wind-tunnel measurements, where
industrial requirements are for practically manageable
equipment.

(b) The effective depth $L$ may be reduced. This can be
achieved even without decreasing the overall physical
depth of the measurement volume by utilizing coherence
requirements of holography, resulting in a set-up which
has been called light-in-flight holography (LiFH) in
other contexts (Abramson 1996). This technique was
introduced recently for flow investigations (Hinrichs et al
1997). An increase in effective SNR or, accordingly,
a higher maximum number density of particles are thus
possible.

The aim of the present paper is to demonstrate the
applicability of the light-in-flight technique. Since it is based
on a reduction in the reconstructing aperture the counteracting
influence of aperture and depth has to be investigated in detail.
This is the topic of another study (Hinsch and Herrmann 2003).
As shown later in this paper, the present experiments operate
in a range of particle densities in the vicinity of the limits set
by the above formula.

As long as weak objects are recorded and reconstructed
with the integrating method, another source of noise plays an
important role. Scattered light from the emulsion grains of
the developed holographic plate adds coherently to the out-
of-focus noise and can even hide particle images. It can
be found that the SNR of particle images also depends on
the ratio between object and reference intensity during the
recording of the hologram (Goodman 1967, Kozma 1968).
Yet it is possible to record particle ensembles with object
intensities of approximately three orders of magnitude less
than necessary to obtain the best diffraction efficiency from
a hologram (Herrmann and Hinsch 2001).

1.3. Light-in-flight holography for flow analysis

Let us briefly recall the use of light sources with a
coherence length of only a few millimetres for applications in
flow investigations (light-in-flight holographic particle image
velocimetry (LiFH-PIV)). The idea is the following: object
wave and reference wave can interfere only when the difference
in the path these waves have travelled is less than the coherence
length of the light. As shown in the example of figure 1,
reference light incident from the left has to travel a longer
path to the right side of the holographic plate than to the left.
Object light scattered from particles is recorded only if this
path length differs by no more than the coherence length $l_c$
from that of the corresponding reference light. Thus, with
proper alignment, particles from a shell in the middle of the
observed field are recorded in a small region in the middle
of the plate, particles from a front shell on the left and from a
rear shell on the right. For the reconstruction of a real image
a conjugate reference wave (i.e. an inversely travelling wave)
is used to illuminate the hologram. This can be achieved
with a single planar wave for recording and reconstruction,
when the hologram is turned by 180° after development. Upon
reconstruction from a single point only a shell with a depth of
roughly half a coherence length shows up—in the case of an
extended aperture this grows by about half its diameter $D$ and
is referred to as the coherence depth $D_0$. The background
of holographic particle images is therefore reduced considerably.
This method has been applied successfully to the investigation
of flows in a small wind tunnel (Hinrichs et al 1998) and
in the transition region of a free air jet (Geiger et al 2000). These experiments have been performed with a double-pulsed ruby laser—a light source of high energy but which has many disadvantages. For the removal of directional ambiguity and for cross-correlation analysis, for example, an electro-optical switch had to be introduced to split the double pulse by a polarizing beam splitter. This paper focuses on improvements to overcome these and other constraints previously reported in the application of LiFH-PIV.

1.4. Real particle images and their evaluation

For the reconstruction of a high-fidelity real image a properly conjugated reference wave is needed in order to avoid distortions. Preferably light of the same wavelength is used to avoid cumbersome angular corrections. To serve as the conjugate wave in many set-ups a highly planar reference wave is used. It is essential that the propagation axis of this wave inclines at the same angle with the holographic plate after it has been exposed, developed and replaced—flipped, however, over its vertical axis. Alignment of such a set-up can be critical, especially when more than one reference beam is used for a double-exposure recording (angular multiplexing for separable holograms and cross-correlation analysis) to determine the displacement of small particles with high accuracy (Sholes and Farrell 2000). Furthermore, even small deviations from a planar wave (e.g. spherical aberrations from lenses) have an impact on the shape of particle images and their relative positions (Chan et al 2000), which results in an artificial non-uniform displacement field superimposed on the original flow field.

The evaluation of holographic particle images is conducted by scanning the entire volume with a CCD sensor, either bare or in conjunction with a lens or microscope objective. This process is usually time-consuming and strongly depends on the technical equipment used to translate the CCD and to acquire, pre-process and store the huge amount of image data from each single hologram. After or even during the acquisition these images are evaluated to extract the displacement data. Different set-ups to accomplish an effective but accurate evaluation have been presented in the past, based either on stereoscopic reconstruction for a larger aperture (Barnhart et al 1994), particle centroid extraction and correlation of their positions to reduce computing time and storage needs (Pu and Meng 2000) or combination of two perpendicular views (2D correlation as in ordinary PIV) to optimize the accuracy along the depth coordinate (Zhang et al 1997, Sheng et al 2003). A straightforward solution is the three-dimensional correlation of sub-image sets obtained by the scanning procedure. This has become feasible thanks to recent developments in computing, and has been used in this study in a preliminary and simple implementation.

A separated reconstruction set-up can be favourable in HPIV for several reasons, the most important being the possibility to operate it while a simple set-up for recording can be used during the scanning and evaluation process of the previous recording. For measurements in costly wind-tunnel facilities this helps to reduce their operating times significantly. Moreover, reconstruction with pulsed laser sources, which are still expensive to operate and maintain, can be avoided. Most of the flow recordings nowadays (either planar or three-dimensional) are obtained with Nd:YAG lasers, which are also available as continuous-wave lasers, yet in a compact design with reasonable output power and stable operation over some days. Stable operation of the reconstruction laser is one of the key issues for high-accuracy measurements and is difficult to guarantee in high-energy pulsed lasers. Slight deviations in the propagation direction of the reference beam caused by pulse-to-pulse variations are difficult to avoid when the laser has to be fired continuously during the scanning process. Whereas deviations during the recording can be corrected for by an appropriate system which records fixed calibration points in space in each hologram, a fact which has not yet been considered, probably due to an increasing complexity of both the recording and reconstruction set-up. Finally, in a separate set-up with complex delivery of two reference beams the reconstructing and recording beams can be aligned independently. This, however, should be done under critical visual inspection (e.g. with calibration objects or markers) to meet the alignment requirements mentioned at the beginning of the section.

2. Nd:YAG based measurement system for wind-tunnel flows

In the present study the LiFH technique was applied for the first time using a double-cavity pulsed Nd:YAG laser ($\lambda = 532$ nm), especially designed for holographic flow measurements. A continuous-wave Nd:YAG laser was then used to build a separate set-up allowing for intensity-integrated reconstruction of weak particle images from two superimposed light-in-flight holograms of a globally seeded wind-tunnel flow.

2.1. Double-cavity laser system for holographic flow analysis

For the study of wind-tunnel flows a newly developed Nd:YAG laser system consisting of two laser heads and an external beam combination was used. The beams, produced from two Spectra Physics Quanta Ray Pro lasers are overlapped by a
dichroic mirror to ensure maximum output power of each laser. Therefore, both beams pass an external crystal for frequency doubling, which only affects the 1064 nm radiation. The beams are cross-polarized and have a nearly top-hat profile for a more homogeneous illumination of the particle field. The maximum pulse energy is about 1.5 J at a 10 Hz repetition rate for each laser. A nice feature of this system is a common laser seeder which allows one to choose between multimode operation for LiFH with a coherence length of some 7 mm and single-mode operation for ordinary holography, where the coherence length is limited by the pulse width (typically some 7 ns). Thus a direct comparison was possible to show the advantages of this technique (Hinsch and Herrmann 2003).

2.2. Recording set-up at the wind tunnel

In figure 2 the optical set-up at the wind tunnel is shown true to scale. The open test section is about 2 m wide and 1 m deep. In the flow a generic airfoil produced two counter-rotating tip vortices. A reference signal is produced by the first reflection from a glass wedge plate that is split into two polarization-dependent reference beams by a polarizing beam splitter (thin-film polarizer (TFP)). A detailed side view showing both arms of the unseeded laser is some 7 mm, the path lengths above and underneath the tunnel outlet is given in figure 3. A prism was mounted on a mechanical translation stage to control the path length of each reference beam. Since the coherence length \( l_c \) of the unseeded laser is some 7 mm, the path lengths need to be identical within 1 mm compared to the path length of the object beam. This travels over three bending mirrors (HEM) before it is expanded by a set of two coated lenses to illuminate a small part of the wake flow behind the profile. The position of the centre of the measurement volume is located at a distance of some 35 cm from the holographic plate, which was placed exactly at the flow boundary—far enough to avoid vibrations affecting the stability of the measurement system, but close enough to ensure high signals from the scattering particles. The delivery of the reference beams was realized in a vertical arrangement in order to maintain the same azimuthal angle \( \alpha \) of incidence onto the holographic plate, while the two recordings are distinguished by their elevation angles \( \pm \beta \).

Such an arrangement allows the same region to be reconstructed in depth from both the superimposed holograms through the same aperture on the hologram. To scan the depth the reconstructing aperture has to be moved along the line bisecting the projections of the planes of incidence of both the reference waves onto the hologram—in the present case this results in a horizontal scan through the centre of the hologram. For a successful three-dimensional correlation of the reconstructed particle image fields the particle images in space have to be as identical as possible, which is only

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**Figure 2.** Set-up for recording LiFH-PIV holograms at the 1 m wind tunnel at the German aerospace agency (DLR) in Göttingen, showing the beam paths from the laser heads through the combining optics and shutter, two mirrors (HEM) for adaptation of the beam height to fit the measurement area and the optics for holography, as explained in the text. For the out-of-plane propagation, as indicated by the dashed line, and details of the reference beams see figure 3.

**Figure 3.** Side view of the reference beams with spatial filters (pinhole) for a more uniform illumination of the holographic plate. Given in grey are the outlet of the wind tunnel and the cover box of the combining optics. The TFP directs each pulse according to its polarization into one of the optical arms, guided by specially coated broad-band mirrors (BBM). The beam is then directed out of the projected plane towards the holographic plate.
guaranteed when the reconstruction is done from the same aperture.

Perfect collimation of the reference beams was controlled by a shearing interferometer. The beam profiles of the two laser heads showed intensity variations typical of a multimode laser, and change with increasing distance from the laser-head aperture. Since a low pulse energy in the reference beams is already sufficient for a proper plate exposure, pinholes could be introduced without damage to improve the beam profile. A couple of holograms have been recorded under different conditions regarding type and size of particles as well as density—all having in common a very low amount of object light. They are elliptical because of the oblique incidence of the circular beams and they do not coincide with their different elevation angles $\pm \beta$. Exact alignment of both beams is made by adjusting the mirrors with micro-screws under visual inspection of a calibration hologram recorded under the same conditions.

2.3. Separated reconstruction set-up

To reconstruct particle image fields from the wind-tunnel-flow holograms—recorded under LiFH conditions—and extract image data throughout the whole volume an automatic read-out set-up was developed. It comprises of the optical set-up, two shutters, two mechanical translation stages and a controlling and image acquisition unit based on a single PC with large storage capacities, a frame-grabber and a CCD camera module. In the following some details of this set-up are described.

For this off-site reconstruction a continuous-wave laser (Nd:YAG at $\lambda = 532 \text{ nm}$ with $150 \text{ mW}$ in single longitudinal mode) with Gaussian beam profile is used. A top view of the beam handling unit (lower part of the set-up) is shown in figure 4. Both the reference beams are expanded, collimated and directed out of the plane by two highly planar ($\leq \lambda/20$) mirrors to illuminate the holograms. The collimation is checked by a shearing plate interferometer. The relative positions of hologram and mirrors are precisely scaled down from the arrangement at the wind tunnel to produce the same angles of incidence as before. Above this beam-handling unit, the scanning unit is placed next to the holographic plate (figure 5, left, showing a vertical cut as indicated in figure 4). For the sake of convenience, the complete arrangement has been turned by 90° with respect to the original recording orientation and the illumination of the plate (figure 5, right) is from below. Thus, angle $\beta$ is now the originally vertical component of the angle of incidence while the originally azimuthal component $\alpha$ determines the out-of-plane propagation direction in figure 4. Both the mechanical shutters, controlled by the computer, are used to block either reference beam.

Figure 5 also indicates the areas exposed by the two recording reference waves (grey shaded area), i.e. the contours of the holograms. They are elliptical because of the oblique incidence of the circular beams and they do not coincide because of their different elevation angles $\pm \beta$. Exact alignment of both beams is made by adjusting the mirrors with micro-screws under visual inspection of a calibration hologram recorded under the same conditions.

Ideally, during reconstruction, a circular aperture should be moved along the bisector of the propagation axes introduced earlier to select the region of depth currently under investigation. For this task a translation stage capable of movements in the x- and y-direction was used. Another translation stage—in this case three-dimensional—controls the camera position as shown in the left part of figure 5. Both translation stages as well as the image acquisition and the exposure times of the CCD sensor are controlled by the PC.

At each position of the sensor the reference beams are used alternately (switched by the mechanical shutters) to acquire both successive images without moving the sensor. This any repositioning error entering into the displacement measurement. A typical scanning process is started for a given xy-coordinate of the CCD sensor. The sensor is then scanned along the z-direction while the position of the
The digital images are stored on a hard-disk drive, each identified by its position in space and the corresponding reference beam. For their evaluation a three-dimensional grey-value correlation is performed. A first version of a data-handling routine has been implemented in Matlab® assembling sub-volumes from the image data and carrying out the correlation using three-dimensional FFTs. The demand on memory and computing power is still enormous and should be relaxed by further refinements. The present procedure represents a straightforward solution to provide input data for extended common PIV algorithms. It should be mentioned that the current version is still a very simple implementation examining the correlation results by means of their maximum values and applying sub-pixel algorithms to extract more accurate displacement data. It is still necessary to refine this approach using evaluation techniques well known from PIV, like window-shifting, iterative steps and validation criteria, as well as filter and interpolation methods (Raffel et al 1998).

3. Results

All holograms recorded at the wind tunnel have been examined in a first step for their particle image quality and density. In an intermediate check during the measurement campaign it turned out that appropriate particle image densities are only obtained by very long operating times of the seeding generator (four Laskin nozzles in a common base). To obtain a sufficient number of larger particles the generator was operated with lower pressure settings—that achieve a broader particle size distribution than commonly used in wind-tunnel measurements—for up to 1 h. According to previous measurements of size distributions using a similar pressure and also DEHS as the liquid, about 50% of the particles were smaller than 1 µm and only 7.5% reached sizes larger than 3 µm.

With a cross-sectional dimension of the object light beam of about 4 cm the scattered light intensities have thus been rather low. Judging from the type of reconstructed image we assume that only larger particles (i.e. $d_p > 1 \mu m$) contribute to the signals obtained from long-exposure reconstructions. Unfortunately, in most cases the particle image densities have still been too low to allow for a proper correlation analysis on the images obtained. For the best hologram, however, the particle density is high enough to evaluate the complete set of images by three-dimensional cross-correlations on 128³ pixel sub-volumes. A volume of $24.0 \times 18.8 \times 29.1 \, \text{mm}^3$ was scanned within 35 h of operation time of the read-out-unit, the bottleneck still being the slow translation stage moving the circular aperture over the hologram between exposures. The result are 5409 image pairs, each 2.5 MB in size—in total more than 13 GB of image data.

A sample plane from the reconstructed image is shown in figure 6 as an artificially assembled double exposure from the superposition of the images reconstructed by both the reference beams. The double structure in the particle image distribution is quite obvious. The noise level is still very low, allowing for a much higher number density of particle images within each single plane, yet their number was sufficient for a correlation analysis. Assuming a focal region of about 1 mm in depth the analysis of these images yields a particle density of about $12 \, \text{mm}^{-3}$. This allows a comparison with the situation described by equation (2). Taking for $L$ the coherence depth of about 14 mm and introducing the proper experimental data (angular aperture $\Omega = 1/35$, $\text{SNR} = 5$, $\lambda = 532 \, \text{nm}$ and best

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**Figure 6.** Artificially assembled double exposure from the superposition of two inverted digital images (1280 pixel $\times$ 1024 pixel). These are obtained from two successively reconstructed corresponding holographic real images of a wind-tunnel flow using either reference beam and an exposure time of 0.5 s. The field of view corresponds to $8.6 \times 6.9 \, \text{mm}^2$ and the $xy$-plane shown is located at $z = 14.1 \, \text{mm}$ in the measurement volume.
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Figure 7. Example profiles through the maximum value of a three-dimensional matrix of the correlation coefficient, the voxel size is $128 \times 128 \times 128 \text{pixel}^3$ and corresponds to a size of the interrogation volume of $857 \times 857 \times 6272 \mu\text{m}^3$, since the pixel pitch in the $z$-direction is $49 \mu\text{m}$ and in the $x$- and $y$-directions it is given by the pixel size of the CCD array (6.7 $\mu\text{m}$).

Figure 8. Evaluated wind-tunnel flow, 16 640 vectors have been obtained by three-dimensional grey-value correlation. The plane-like distribution of the vectors is a result of a relatively large separation between adjacent image slices, from which 128 enter in each correlation.

As mentioned before, the moving vortices behind the generic air foil provided an unfavourable flow configuration. A single snap-shot hologram of a small region is unlikely to reveal characteristic parts of a single vortex. Therefore, it is not surprising that the hologram yields mainly the mean velocity of the wind-tunnel flow. Figure 8 shows the complete...
correlation result; a total of 16 640 vectors have been obtained from an evaluation with 50% overlap of the interrogation cells (IC) in each direction. The plane-like distribution is a result of the densely spaced grid points along the x- and y-directions and the much wider spacing (approximately $\times 7.3$) along the z-direction. Besides some spurious vectors due to poor image quality in the lower part a net flow perpendicular to the mean flow is observed in some regions producing the arrows that project out of the planes (e.g. upper part). The mean velocity over all 16 640 vectors has been calculated as $\bar{u}, \bar{v}, \bar{w} = [0.01, 1.30, -0.28]$ m s$^{-1}$, which is a reasonable result compared to 1.5 m s$^{-1}$ for the pure wind-tunnel flow as determined from the rotation rate of the driving rotor. The quality of the correlation is still compromised because of the non-ideal path of the aperture that produced dissimilar particle images. However, future improvements in the properties of the reference beams should help overcome this problem.

Since the mean flow is not clearly visible in this representation a detailed view of the velocities in the interior of the flow field is shown in figure 9, the corresponding correlation coefficients are given as a contour plot in one plane. Here, an overlap of 75% was used, increasing the total number of vectors to 124 800 within the same volume. Even if these results do not furnish important flow data, it was shown that particle images could be extracted, of a quality sufficient for further processing—yet with still too low a particle density. A maximum depth of 47 mm has been covered from other holograms, the useable cross section of the measurement volume extended to $30 \times 30$ mm$^2$ providing particles of sufficient brightness even at its border.

4. Conclusion and outlook

It has been demonstrated that a special version of HPIV—so-called LiFH-PIV which facilitates effective background noise reduction by use of a short coherence light source for the recording—is capable of mapping the three-dimensional flow field from a globally seeded large wind-tunnel flow. The utilization of a separate reconstruction set-up using a continuous-wave laser effectively reduces the operating time of the wind tunnel and allows for simultaneous evaluation procedures. Furthermore, low-intensity particle images have been analysed by an integrating reconstruction method, thus reducing the effective energy density of the pulsed illumination light needed for the recording and allowing for considerably larger cross sections of the measurement volume. For the first time use of a three-dimensional grey value correlation of sub-volumes to analyse an extended volume mapped by particle holography has been reported. This approach, although very time-consuming and with high demands on computer power, is favourable when advanced evaluation algorithms are envisaged, most of which can be extended without loss of generality from the two-dimensional case. The restricted depth resolution, one of the drawbacks of LiFH-PIV, however, needs to be addressed in further refinements of this technique. Reconstructions with larger effective apertures are feasible without impairing the principle of limited depth reconstruction. For further wind-tunnel measurements the production of seeding particles needs to be optimized in terms of size distribution and density. For this purpose, investigations have been made to understand the physical processes of particle generation (Kähler et al 2002) and the influence of particle parameters on the holographic imaging process (Pu et al 2002). Increasing seeding densities could allow for smaller ICs, with a 64 pixel or even 32 pixel side length; non-cubic ICs in the pixel domain are also feasible.

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