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On the applicability of background oriented optical tomography for large scale aerodynamic investigations

M. Raffel, H. Richard, G. E. A. Meier

Abstract Density fields of the blade tip vortices from a helicopter in hover flight were visualized by a technique which does not require any installation on the helicopter or close to it. The results illustrate an encouraging prospect for the applicability of the technique. It offers the capability of at least qualitative investigations of unsteady density fields even in full-scale flight tests. The underlying principle is briefly described in this article and an extension to a three-dimensional quantitative technique by using multiple cameras is outlined.

1
Introduction

With the increasing use of civil helicopters the problem of noise emission from helicopters has become increasingly important within the last decades. Blade vortex interactions (BVI) have been identified as a major source of noise. It occurs mainly during descent flight conditions especially during the landing approach of helicopters and tilt rotor aircraft. As BVI noise is caused by the induced velocities of tip vortices, it basically depends on vortex strength and the miss-distance, which in turn depends on vortex location, orientation, and convective speed relative to the path of the blades. Therefore, many aeronautical research organizations develop and run numerical codes in order to predict the rotor wake (see e.g., Beaumier et al. 1994). These aerodynamic results can then be used for further numerical investigations of the acoustic near and far field of BVI. (e.g., Burley et al. 1991; Ehrenfried et al. 1991). The advantage of having improved numerical codes is to help predict BVI occurrence and to improve the ability of controlling, changing, and reducing the vortices and their paths in order to possibly reducing BVI noise significantly (C.L. Burley, personal communication, 1999). However, those aeroacoustic predictions would benefit significantly from detailed information on the structure and strength of the experimentally characterized rotor tip vortices.

2
Measurement technique for BVI research

In-flight full-scale experimental studies on BVI far field noise were conducted using a quiet aircraft flying in formation with the subject helicopter in order to establish the operational envelope for BVI occurrence (Boxwell and Schmitz 1982). Aerodynamic investigations in flight were conducted in order to measure surface flow, absolute pressures, and pointwise velocity fluctuations on the rotating blades (Cox 1977). However, due to the complexity of the underlying phenomena, more specific information was required on the global wake vortex structure, the tip vortex evolution from emission to interaction, its downstream convection, and vortex aging, in order to better understand the BVI problem and tackle it properly.

Theoretical and experimental studies were conducted in order to validate principles for predicting BVI and to determine the model-to-full-scale acoustic scaling conditions (Schlinker and Amiet 1983; Splettstösser et al. 1984) and generally confirm the benefit of wind tunnel tests. It has been found that high-speed noise at the advancing blades can be quite well scaled whereas the scalability of BVI noise undergoes certain restrictions. It is assumed that Reynolds number effects do not allow scaling the vortex dimensions easily (W.R. Splettstösser, personal communication, 1999). Therefore, aerodynamic rotor model investigations have been undertaken at large scales e.g., in the large low, speed facility of the Dutch–German Wind tunnel DNW-LLF (Splettstösser et al. 1997).

LDV measurements on helicopter rotor models have been intensively performed in the 70s and 80 (see e.g., Biggers and Orloff 1974; Sullivan 1973; Elliot et al. 1987). The technique in general is well described in the literature (see e.g., Durst et al. 1981). Two-component PIV measurements on helicopter rotor models have been reported by Murashige et al. (1997) and three-component measurements more recently by Raffel et al. (1998). It has been shown that aperiodic flow phenomena, even of small amplitudes, can lead to an underestimation of the actual vortex strength, and an overestimation of the vortex core size (Raffel 1997). By reviewing the literature from the last decade, it can be seen that particle-based flow velocity

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M. Raffel, H. Richard, G. E. A. Meier
Institut für Strömungsmechanik
Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR)
Bunsenstrasse 10, D-37073 Göttingen, Germany

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measurements have been applied most frequently. The most likely reason for this is because they are assumed to deliver the most quantitative information needed for BVI prediction. Density measurements of the BVI phenomena on the other hand are also desirable, because the vortices under investigation are compressible and the physical quantity needed for the aeroacoustic codes – the temporal surface pressure gradient of the rotating blade – can be estimated from the spatial density distribution with sufficient accuracy. Therefore, density measurements have been performed quite frequently, but mostly in two-dimensional basic investigation (e.g., Meier et al. 1998; Chandrasekhara 1994). Density gradient visualization by the Schlieren method has been conducted for instance by Tangler (1977) in a model rotor test and with strobed shadowgraphy of helicopter rotor wakes more recently by Leishman and Bagai (1998). It has been shown by the same authors (Bagai and Leishman 1993), that the assumption of algebraic vortex models allows drawing conclusions about the velocity field, but quantitative density results cannot be obtained easily. The known quantitative density measurement techniques like Mach-Zehnder or point diffraction interferometry seem to be less feasible for large or full-scale investigations on rotating systems, since they require delicate optical systems. For the aforementioned reason of limited scalability and the well-known imperfections of particle-based optical techniques to resolve the vortex core and their costs, additional large or full-scale measurements of an easy-to-use optical technique seem desirable.

3
A 'background oriented' optical density gradient technique

The principle of the optical technique, which we used for our studies, can best be compared with the density speckle photography as described by Debrus et al. (1972), Köpf (1972), and in an improved version by Wernekinck and Merzkirch (1987). Therefore, a description of density speckle photography will serve as an introduction to our approach.

In contrast to laser speckle velocimetry, where speckle patterns are generated by a double exposure of highly seeded flows, in density speckle photography speckle patterns are generated by a ground glass in order to derive density gradient information. Like interferometry, density speckle photography uses an expanded parallel laser beam, which shines through a transonic flow field or – in more general terms – through an object containing changes in the refraction index. However, in contrast to interferometry, speckle patterns are generated instead of interference fringes. In a first step a reference image is generated by recording a speckle pattern through air at rest before the experiment. An additional exposure through the flow under investigation (i.e., during the wind tunnel run) leads to a second exposure. The resulting images of both exposures can then be evaluated by correlation methods. In other words, without further evaluation efforts, algorithms, which were developed and optimized, e.g., for particle image velocimetry (or other forms of speckle photography), can now be used to determine speckle displacements. It can easily be shown that the deflection of a single beam contains information about the spatial gradient of the refractive index integrated over the optical path. Assuming paraxial recording and small deflection angles a formula for the image displacement ΔY can be derived, which is valid both for density speckle photography as well as for the background oriented technique which we used:

$$\Delta Y = Z_D M \varepsilon$$

with:

$M = Z_i / Z_B \sim$ magnification factor

$Z_D \sim$ distance dot pattern – density gradient

$$\varepsilon = \frac{1}{n_0} \int_{Z_D - \Delta Z_D}^{Z'_D + \Delta Z_D} \frac{\delta n}{\delta Y} \mathrm{d}Z$$

The deflection of the beams causes a displacement of the speckle patterns with respect to the patterns of the reference recording, which can be interpreted as density gradients – integrated over the optical path – by using the Gladstone–Dale equation. It is obvious, that from the two-dimensional density gradient an estimate for the density can be derived by integration. After this, the result is comparable to X-ray images and, like them, could be recorded and evaluated in a tomographic manner. However, for the speckle method this would not only require multiple cameras, but also multiple sending optics to form and direct the beams shining through the object under investigation. The main difference of the optical technique proposed in this article is that, in contrast to the techniques mentioned above, our technique does not require any optical devices on the sending side. The only optical part needed is an objective lens mounted, for instance on a video camera, on the receiving side. The camera used is focused on a random dot pattern in the background, which generates an image quite similar to a particle image or speckle pattern. For this reason we refer to this approach as being "background oriented". The flow field under investigation is located on the viewing axis and the refractive index gradients displace the dot pattern on the recording with respect to the reference recording (see Fig. 1).

When looking at this approach, it really seems to be quite similar to density speckle photography. However, two major differences can be observed: first, instead of a laser and beam-expanding optics, only a printout of a random dot pattern and white light are used. This results in significantly reduced efforts during the application of the technique. Second, the optical paths over which the density effects are averaged are divergent with respect to each other. This can result in a clear disadvantage when large viewing angles have to be used, but is of little influence for the recording distances of more than 30 m used for the tests described in this article. For a later extension towards "Background Oriented Optical Tomography" (BOOT), which is proposed by the third author Meier (Hintergrund-Schlierenverfahren, patent pending, Deutsches patentamt, 1999), the divergence of the optical paths should be no problem since convolution methods

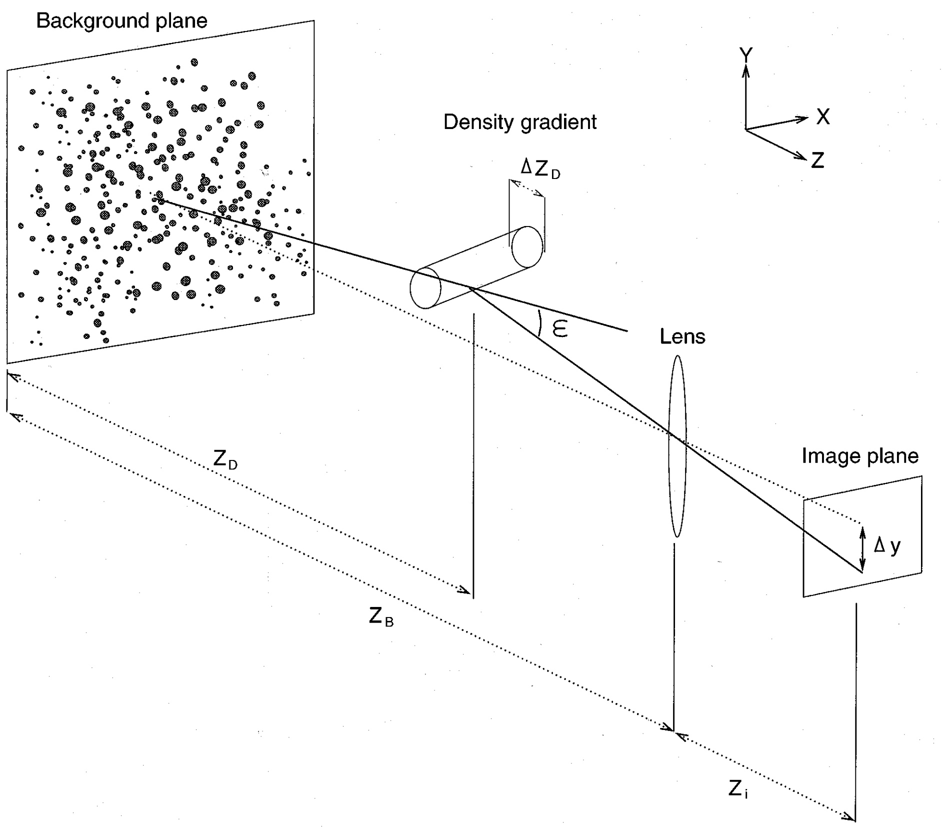

Fig. 1. Optical path for density gradient measurement by light deflection

for divergent beams are already known and described in the literature (see e.g., Herman 1980).

4 Application to a helicopter in flight

Initial flight tests were performed in order to verify the feasibility of BOOT for large scale aerodynamic investigations. The subject helicopter departed from the ground of DLR in Göttingen after aeroelasticty tests. Two progressive-scan CCD cameras were mounted in a window of a building at a horizontal distance of 32 m from the helicopter and 11.2 m above the ground. The two cameras used belong to our PIV equipment and have a 1024 × 1280 pixel resolution. They were mounted closely spaced together in order to try different magnifications of the same dot pattern simultaneously. A 100 mm lens and a 180 mm lens were mounted and directed to the same area on the ground. A random dot pattern was generated by splashing tiny droplets of white wall-paint with a brush onto the concrete ground. The pilot gave us time to record more than 50 digital images within a 20 s hover flight. The reference recordings were made directly after the departure

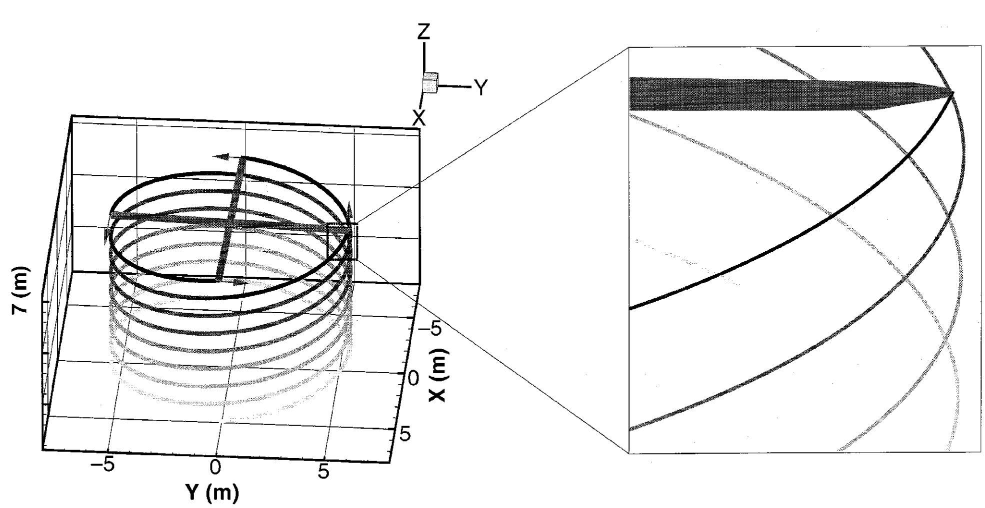

Fig. 2. Sketch of helicopter rotor, blade tip vortices and the observation area of the 100 mm lens

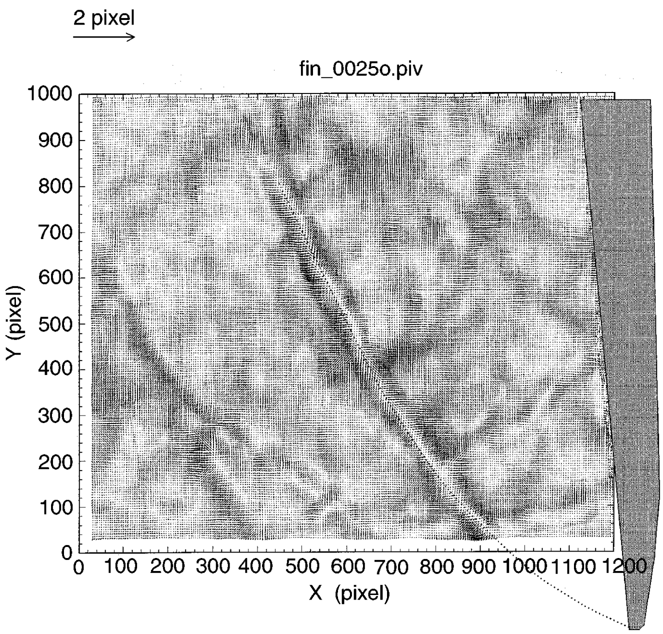

Fig. 3. Displacement data proportional to dρ/dx and dρ/dy (180 mm lens) rotated by 90° with respect to Fig. 2

of the helicopter. A sketch of the observation area on the ground, the rotor blades, and the vortices along the optical axis is shown in Fig. 2. Even if acceptable results could be obtained by using standard PIV software, more sophisticated programs helped to adapt the peak-fitting routine to the size of the dot images. We finally obtained the best result by using iterative Levenberg-Marquardt fitt to a 10×10 pixel area, where the values are weighted according to the Fisher transform (for details, see Ronneberger et al. 1998). The size of the interrogation window was 25×30 pixels searched in a window of 64×64 pixels. The evaluation leading to the vector plot shown in Fig. 3 was performed by massive oversampling using a 5 pixel stepwidth resulting in improved visibility of the flow structures under investigation. In Fig. 3 at least the young vortex shedding from the blade that just passed the observation area – trailing edge visible on the right hand side – can easily be detected. It lies directly on the blade tip path, which we were able to reconstruct from different recordings. Its elliptical shape is due to the underlying projection. Further elliptically-shaped structures can be seen, but are not as well organized as the theoretical vortex trajectories shown in Fig. 2. Grey value distributions proportional to the density have also been computed in different ways, but are not shown in this article for brevity. For future investigations the optical path should be chosen in such a way that vortical structures under investigation do not overlap.

5 Discussion

The measurements confirmed the feasibility of the BOOT technique for large-scale applications by the visualization of the blade tip vortices of a helicopter in flight. It has been shown that geometric parameters, such as location of the vortex relative to the rotor plane, orientation of the vortex axis in space, and some information about the vortex size, could be derived during future tests. In spite of the difficult experimental conditions, density gradient data were obtained, which allow the visualization of density fields with quite promising spatial resolution. Compared to previous measurements, the time needed for the setup and data acquisition can be considerably decreased. However, since one camera system allows the measurement of only two components of the spatial density gradient integrated over the optical path, data, like the orientation of the vortex axis in space, cannot be derived without changing the viewing direction. The use of a second camera in a stereoscopic arrangement would allow the measurement of the density distribution in space without averaging data from different cycles.

Future investigations have to be performed using multiple cameras in order to obtain more complete three-dimensional data. After having demonstrated the feasibility of the concept by the application to a technologically relevant but fluid mechanically quite complex problem, more detailed studies, e.g., of tip vortices from stationary blades, should be performed in order to better understand and possibly influence the complexity of the vortical structures under investigation.

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