

BACKGROUND ORIENTED SCHLIEN TECHNIQUES FOR HELICOPTER RELATED LARGE SCALE AND FLIGHT TESTING

Markus Raffel, markus.raffel@dlr.de, DLR (Germany)
James T. Heineck, james.t.heineck@nasa.gov, NASA (USA)
Edward Schairer, edward.t.schairer@nasa.gov, NASA (USA)
Friedrich Leopold, friedrich.leopold@isl.eu ISL (France)
Kolja Kindler, kolja.kindler@dlr.de, DLR (Germany)

Abstract

Background Oriented Schlieren (BOS) methods suited for large-scale, in-flight testing are presented with special emphasis on the detection and tracing of blade tip vortices *in situ*. Feasibility and fidelity of reference-free BOS in conjunction with natural formation backgrounds and related evaluation methods are discussed, illustrating their simplicity and robustness. With image acquisition from a chaser aircraft the vortex field can be visualized for a wide range of flight attitudes, including complex maneuvers.

1. INTRODUCTION

Visualization techniques such as Schlieren photography, shadowgraphy or interferometry have been used in flow field diagnostics and analysis for many decades [11]. These techniques probe changes of the refractive index of a fluid caused by localized variations in thermodynamic properties, e.g. fluid density. In helicopter aerodynamics, Schlieren methods are widely used to probe concentrated blade tip vortices, the most dominant structure of rotary wing flows, and related phenomena such as blade-vortex-interaction, etc. [1,7,12].

There have been several attempts to take Schlieren photography and shadowgraphy out of the laboratory into the great outdoors [1,7,12,23,20]. Especially, when Mach and Reynolds number scaling effects are only insufficiently well understood, as is the case for blade tip vortices, full-scale, *in situ* experiments are desirable to address vortex-structure-interaction, far-field interference effects and complex wake flows. For this purpose, the background oriented Schlieren technique (BOS) [12,18] (also known as synthetic Schlieren [dalziel2000]) has been systematically refined for out-of-laboratory use in recent years.

The fundamental idea of the BOS technique is to visualize phase objects (i.e. density variations within the flow) by imaging an arbitrary, high-resolution speckle pattern with and without phase object in the optical path. Simple cross-correlation analysis of signal-reference image pairs then enables detection

of distorted regions of the pattern, i.e. localization and visualization of e.g. concentrated vortices. For the purpose of in-flight measurements, image acquisition needs to be reference-free and artificial patterns need to be substituted by natural formations of sufficient "arbitrariness", contrast, and extend. The former can be achieved by stereoscopic imaging, where the signal is segregated in the two images acquired simultaneously [7] while for the latter skirts of wood or grass lands can be used [6,7,12].

Here we introduce a simple BOS method to detect and trace density gradients in the field, on large geometrical scales without recourse to sophisticated optical equipment. Using two standard single-lens reflex cameras in a paraxial configuration, we developed a handheld sensor system which can be operated from the ground as well as from aboard an airplane or helicopter for in-flight visualizations.

In the following, the relevant variants of BOS are presented and major aspects of large-scale imaging using natural backgrounds are reviewed in relation to full-scale helicopter testing. Feasibility and fidelity of in-flight BOS applications are demonstrated by reference to subscale and large-scale wind tunnel experiments.

2. REFERENCE-FREE BOS

Background oriented Schlieren has many common features with laser speckle density photography [3, 8,21]. Laser speckle density photography is based on an expanded, parallel laser beam, which crosses through a phase object of varying refractive index.

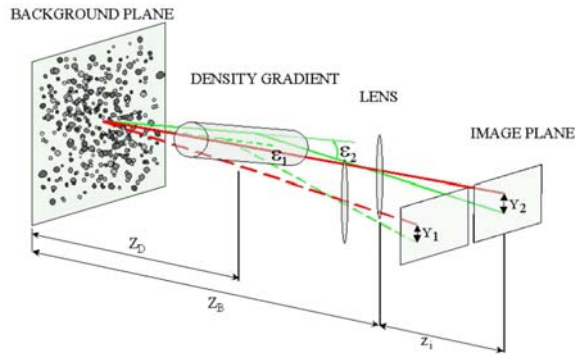


Figure 1 Measurement principle of reference-free background oriented Schlieren. Using two camera sensors at large object distances Z_B , background distortion by phase objects can be segregated either by finite inter-framing time steps between paraxial images of nearly identical views or by stereoscopic imaging of the background without time offset.

Phase objects are then detected by the distortion they exert on the speckle field. Compared to laser speckle photography or interferometry using incoherent light robustness and ease of use of BOS are improved by simplified recording. The speckle pattern, usually generated by the expanded laser beam and ground glass, is replaced by a random dot pattern on a surface in the background of the test volume, where spatial frequencies and image contrast are maximized.

Traditional BOS recording is as follows: first, a reference image is generated by recording the background pattern without flow; second, the signal image is acquired during e.g. the wind tunnel run and the resulting image pair is evaluated by cross-correlation methods as used for Particle Image Velocimetry (PIV). Available evaluation algorithms, developed and optimized for PIV are typically used to determine the pattern displacements. However we note that the deflection measured originates from about the refractive index gradient integrated along the whole line of sight, i.e. measurement fidelity is the best for clearly defined, concentrated, small structures within an undisturbed ambient (for details on ray tracing through gradient-index media cf. [4,17]). With the Gladstone-Dale equation relating the refractive index of gases to their density, the deflection along the line of sight can be written as [5,14]:

$$\tan(\epsilon_y) = \int_0^{\infty} \frac{1}{n} \frac{\partial n}{\partial y} dz$$

assuming the phase object to small in spatial extent (Fig.1). For paraxial recording and small deflection angles, the image displacement Δy reads

$$\Delta y = Z_D M \epsilon_y$$

with the magnification factor of the background $M=Z_i/Z_B$ and the distance of the background and the phase object Z_D .

According to the above equation, large image displacement is obtained for large Z_D . On the other hand Z_D is constrained by image blur. To maximize contrast at high spatial frequencies maximizing spatial resolution during evaluation, the optical system is focused on the background. Since correlation-based techniques implicate averaging over finite interrogation window areas, image blur does imply significant loss of information (provided d_i is considerably smaller than the interrogation window size), however, the larger the image displacement Z_D , the larger the blur of the phase structure itself due to the finite depth of field of the optical system.

To achieve reference-free data acquisition, two cameras are deployed in a paraxial or stereoscopic configuration (Fig.1). In both cases, the cameras record the same background. With the stereoscopic configuration, due to the different viewing angles, the image deflection at different positions in the different recordings, so that the two resulting images can be evaluated by cross-correlation. However, depending on the viewing angles, images may need to be de-warped prior to evaluation which might decrease the signal-to-noise ratio considerably depending on the quality of the background. With regard to reliability and robustness, we found paraxial imaging with finite inter-framing time steps to be favorable. Provided all optical length scales are large enough for the viewing angles to be negligibly small, the same section of the background is imaged successively by both cameras, where the signal segregation traces back to the movement of the phase structure, i.e. the vortex, itself. Furthermore, paraxial configurations are more compact which is beneficial for hand-operated units. This concept will be referred to as reference-free background oriented Schlieren.

Feasibility of reference-free BOS applications for in-flight helicopter measurements, with a stereo-system installed aboard the helicopter using both artificial and natural backgrounds, was shown a few years ago [7]. Recording through the rotor disk, focusing on sufficiently contrasty backgrounds ($Z_B=6R$, $Z_D=5R$) blade tip vortices can be visualized and even core density estimates can be inferred by tomographic reconstruction of presumably cylindrical vortex cores. However, the measurement noise level was reported to be elevated when compared to laboratory applications. In favorable conditions, i.e. in the laboratory, state-of-the-art reference-free BOS methods are sensitive enough to gain high-resolution visualizations of tip vortices but also of

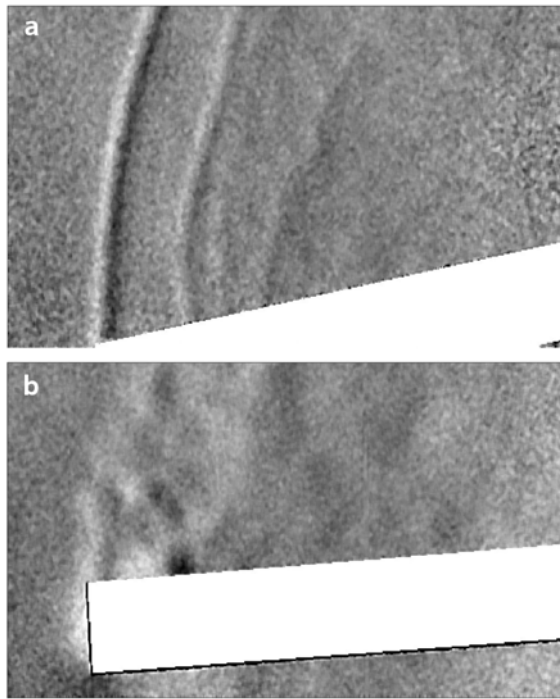


Figure 2 An example of state-of-the-art reference-free BOS visualizations of blade tip flows. Blade tip vortex shed from a subscale rectangular rotor (chord length $c=54\text{mm}$, $\alpha=17^\circ$ collective pitch) at a tip Mach number of $\text{Ma}=0.37$ (a) and fully stalled flow at the same blade tip at $\text{Ma}=0.46$.

much less localized compressible structures associated with fully separated flow at the blade tip of subscale models (Fig.3).

3. LARGE-SCALE APPLICATIONS

When it comes to large-scale BOS applications, even in favorable laboratory conditions, illumination becomes one of the limiting factors. The use of retro-reflective materials for BOS backgrounds greatly enhanced the efficiency of short-duration pulsed light sources, which are generally rather dim. Illumination is important in two ways: First, the more light is available, the higher the f-number can be chosen (small lens aperture), i.e. the higher the system's sensitivity. Second, rotor blade motion should be "frozen", i.e. motion blur is to be minimized (which depends on exposure times only).

Furthermore, the use of on-axis lighting facilitates much larger Schlieren fields at larger distances because direct reflection along that incident path does not follow the inverse-square law of lighting that a diffuse background is subject to.

The combination of retro-reflective backgrounds and on-axis pulse illumination was recently utilized to

visualize tip vortices shed from a full-scale helicopter in the world's largest wind tunnel. A dedicated light source was designed and prototyped for this experiment by Lightspeed Technologies (USA). New high-intensity LED were used that operated in pulsed mode, with electronic drivers pushing the amperage to five times the level of continuous operation. As a result, exposure times were greatly reduced. The 18 LED on the prototype ring light were fitted with condenser lenses and prisms. A condenser lens focused the output of the individual LED and the prisms directed the output in a circle. Thus the light output in total was focused and formed to illuminate only the background.

A testing program of full-scale UH-60 blades in the NFAC $40 \times 80\text{ft}^2$ low speed wind tunnel at NASA Ames was conducted in 2009. As part of the very comprehensive testing program, blade displacement photogrammetry, and BOS measurements were carried out, to capture the complex vortex structures in forward flight along the span of the blade. Two cameras were required to obtain photogrammetric imagery of the volume of interest. The photogrammetry is accomplished using the Schlieren rendering of the each camera, locating the vortices in each and using the calibration along with epipolar analysis. One camera was placed in an existing window port but the second camera had to be inserted in a 5ft deep and 1ft diameter tube that accommodates a wind tunnel light (Fig.3).

The rotor operated at 4.3Hz for the one-per-rev synchronizing signal. The retro-reflective BOS data were acquired using this synch signal. The rotor operated with an absolute encoder that output both a one-per-rev signal and 1024 n-per-rev signal stream. The blade azimuth for the moment of the exposure was established using a receiver box that used both outputs to create a delay from the one-per-rev signal.

The tip vortices were successfully visualized over a distance of X_m (Fig.3).

4. NATURAL BACKGROUNDS

The qualification of natural formation backgrounds can be illustrated drawing on single frames extracted from the movie "Top Gun" (Paramount Pictures, 1986). At the time computer animations were unavailable, i.e. real airplanes were recorded with desert-like terrain in the background (Fig.2a). Although a certain lack of non-high-definition video media resolution prevents evaluation by correlation methods simple image subtraction of successive images reveals tip vortices and hot exhausts from the engines (the mean displacement of subsequent images was determined by cross-correlating larger areas in the four corners of the image and corrected for prior to subtraction) (Fig.2b).

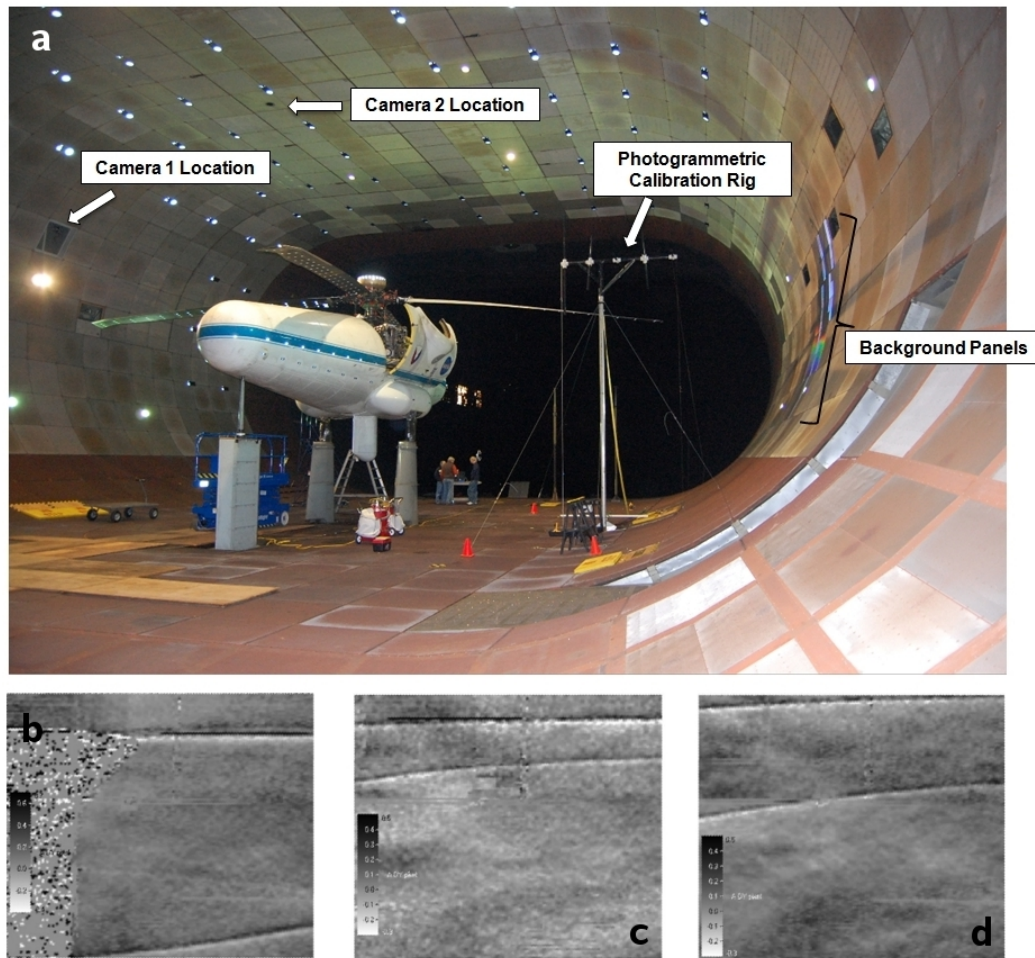


Figure 3 Photograph of 40ft by 80ft wind tunnel test section with LRTA and photogrammetric calibration rig (a). Monoscopic results for $\psi=95^\circ$, 105° , and 120° (b-d), with $\alpha=0$, and $\mu=0.15$.

The very same approach was used to probe the tip vortices shed from a MBB Bo105 helicopter hovering in ground effect (Fig.5). A commercial single-reflex camera with a resolution of 3908×2602 px was used at a frame rate of 5Hz. From a distance of 38m (approximately 7.4 main rotor radii R) from roughly 12m ($2.4R$) above the ground BOS data were acquired using grass as a natural background with high spatial frequencies and sufficient contrast. With exposure times of $1/8000$ s and inter-framing times of 0.2s tip vortices could clearly be identified during departure of the helicopter. Computing the image displacement, standard cross-correlation routines, as developed for PIV, were supplemented with improved peak-fitting routines taking into account larger image areas. The best results were obtained with least square fits of a Gaussian to a 5×5 px area of interest, where a multi-grid evaluation scheme was used (initial and final interrogation window size: 96×96 px and 8×8 px within 3 passes) [15]. In Fig.5, the youngest vortex shedding from the blade just passed the observation area along with vortices generated by previous blades. Note that each vortex is seen twice as it appears at different locations in the two images correlated.

5. IN-FLIGHT TESTING

Proceeding with an earlier approach [7], one way of taking reference-free BOS into flight is to install a stereoscopic camera system within a helicopter. An example for this approach is an airborne camera system installed in a BELL UH 1D helicopter, probing young blade-tip vortices directly downstream from the blade tip (Fig.6). The setup consisted of two high-resolution commercial cameras (Canon OES 1 Ds Mark II) with zoom objectives (focal distance $f=400$ mm) mounted on an optical rail which is fastened to the fuselage in the cabin.

The distance between the background and the cameras varies between 2 and $20R$ (Fig.6). The measurements were carried out during a hover flight close to the ground with skirts of wood serving as the background. In principle, any non-correlating but homogeneous natural background appears usable for BOS. However, as obvious from Fig.6b the lack of flatness (or two-dimensionality) of the leave distribution diminishes similarity of the pattern seen



Figure 4 An illustration of flow visualization by natural background oriented Schlieren imaging, using footage from the movie "Top Gun" (Paramount Pictures, 1986). Relatively low image resolution (when compared to scientific imaging) hinders the correlation analysis of still images (a), where normalized differences of color tones of successive image pairs clearly uncover wing tip vortices and hot exhausts from the engines (b).

by the two different cameras even at small stereo-angles, which translates into large "dark" spots in the resulting displacement field (Fig.6c). Interrogation window sizes of 256×256 px were used. To mitigate the three-dimensional aspect of the background and to extract the blade tip vortices, a second evaluation with an interrogation window of 32×32 px was added. The main deflections were observed in the vertical direction, indicating vortex development to be complete closely behind the trailing edge of the blade.

To improve the evaluation a color-separation procedure was used taking advantage of the fact that commercial single-lens reflex cameras acquire multiple colors [9,18]. Images were decomposed into the three primary colors, 8 elementary dot patterns can be extracted from the image: one pattern for each of the primary colors (red, green and blue), one pattern for all secondary colors, 3 patterns of dots containing R, G, and B, respectively and one pattern for the uncolored areas. The assessment of the image distortion is achieved by treating each of the 8 elementary patterns separately by using the cross-correlation method already applied in the PIV technique. To increase the precision of the common BOS technique, the further processing can either be performed by a gliding interrogation window as described by Leopold [9] or by a pairwise ensemble correlation.

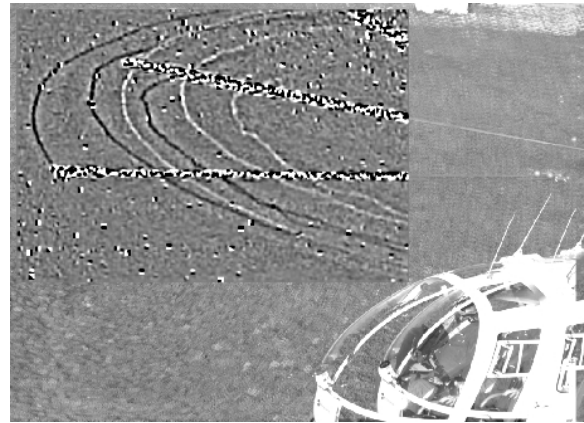


Figure 5 Main rotor blade tip vortices shed from DLR's MBB Bo105 test helicopter (in hover in ground effect) visualized by reference-free natural background oriented Schlieren (grey values depict displacement magnitude). The Bo105 features rectangular blades of $R=4.92$ m in radius, with a chord length of $c=0.27$ m and a blade tip Mach number of $Ma=0.63$.

The latter was shown to significantly enhance the signal-to-noise ratio in case of statistically independent samples windows containing similar displacement information [10,17].

Our second example of in-flight testing leads us back to artificial pattern and image acquisition from the ground. With regard to open issues concerning brown- or white-out situations, large scale vortex field investigations covering the whole wake flow down to the ground are particularly desired. In an attempt to probe the wake flow below DLR's Bo105 test helicopter in a rather traditional manner, a 70m^2 retro-reflective, random dot pattern was fixed to a hangar wall at Braunschweig Airport. Only ambient sunlight provided illumination. Using the paraxial imaging sensor introduced in Sec.2, Schlieren images of the entire wake flow were acquired during approach and departure. Tip vortices were observed up to $\psi=360^\circ$ in vortex age, i.e. down to approximately $0.5R$ below the rotor disk, where the signal vanishes (Fig.7). Apparently, the optical configuration in use, with the helicopter and the background pattern being $5R$ and $9R$ away from the camera system vortices cannot be detected closer to the ground. This might partly be due to hot exhausts from the turbines entering the wake or may have to be attributed to the density signal within the vortex cores relaxing (Fig.7).

The third and final example for in-flight measurements brings together reference-free BOS imaging, natural formation backgrounds and very large-scale optical arrangements. The initial idea

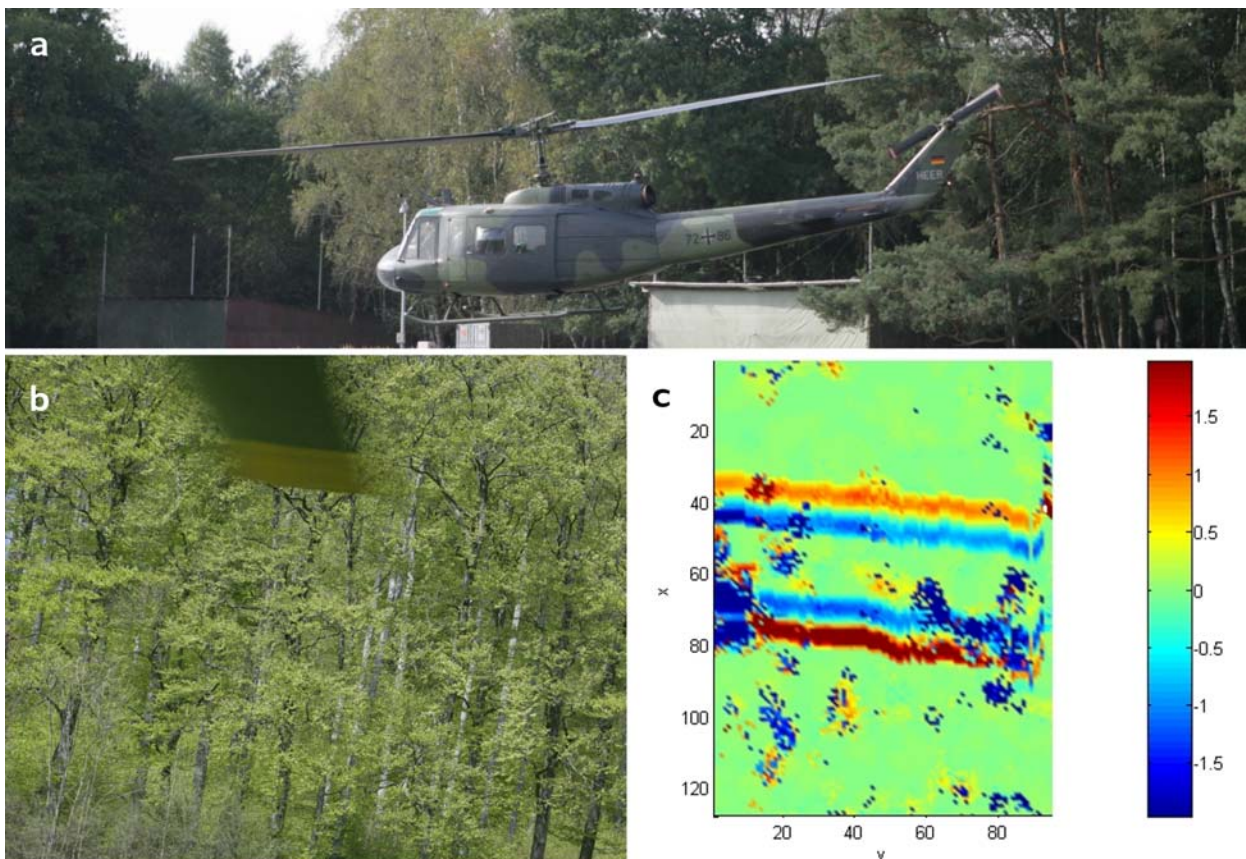


Figure 6 Reference-free, color BOS from aboard a Bell UH 1D helicopter in hover in ground effect (a) using skirts of wood as natural backgrounds (b). Two cameras in stereoscopic configuration acquired images simultaneously, yielding two separated displacement traces of the same tip vortex within the field of view (c). The UH 1D features also rectangular blades of $R=7.315\text{m}$ in radius, with a chord length of $c=0.53\text{m}$ and a tip Mach number of $Ma=0.72$.

was to develop a hand-operated paraxial BOS sensor, consisting of two commercial cameras (Nikon D50 fitted with $f=500\text{mm}$ lenses) with a trigger system that allows inter-framing times of the order of $O(1\text{ms})$, to visualize rotor tip vortex structures of DLR's Bo105 from aboard a chaser aircraft during flight. Data acquisition in cruise flight conditions requires extremely small inter-framing times to capture similar parts of the background in both images, while motion blur of the main rotor restricts exposure times to less $1/1000$ corresponding to approximately $1c$ of blur for individual rotor blades.

As the chaser aircraft, a RANS S7 microlight was chosen, offering an acceptable range of cruise speeds. Operating 152m above the helicopter leveled at 91m above ground, agricultural areas were imaged (Fig.8). In contrast to tree structures, especially corn fields were found to be adequate BOS backgrounds. Their flatness and homogeneity facilitates simple cross-correlation analysis with exceptional signal-to-noise levels.

Figure 8 shows an example result of in-flight

visualizations in cruise flight conditions (the velocity of the helicopter was approximately $u_\infty=50\text{kt}$, i.e. 25.7m/s indicated airspeed). Tip vortices can clearly be differentiated up to vortex ages of $\psi=180^\circ$ as well as a very dominant signal from the hot exhaust gases is seen.

This first attempt of taking helicopter blade tip vortex field studies into the air turned out to be very encouraging. Careful analysis and optimization of speed, position and optical arrangement will further improve image quality as well as systematic studies of background quality will contribute to advance in-flight testing.

6. CONCLUSIONS

Feasibility of reference-free BOS methods for full-scale, in-flight visualization of helicopter blade tip vortices was demonstrated for a variety of measurement configurations. Using paraxial or stereoscopic imaging in connection with suitable artificial or natural backgrounds, the main rotor tip vortices of a Bo105 test helicopter were successfully



Figure 7 Full-scale tip vortex visualization in low-speed forward flight in ground effect ($u_\infty \approx 10 \text{ m/s}$ corresponding to 20kt indicated airspeed at $h \leq R$). The Bo105 operated at a distance of approximately 4R in front of a 70 m^2 speckle pattern suspended from a hangar wall at Braunschweig airport. Images were acquired with a paraxial camera system from a position another 5R away from the helicopter at inter-framing times corresponding to $\psi = 45^\circ$ to 90° in main rotor azimuth. In the image domain undisturbed by exhaust gases, four tip vortices of increasing age can be differentiated (i.e. vortex ages up to $\psi = 360^\circ$ were visualized), also indicating the forward slip stream boundary. The increase in concretion of the vortex core signal with increasing vortex age indicates dissipation of the core density incursion and, additionally, secondary instabilities seem to become visible at $\psi \geq 180^\circ$.

visualized in in hover, with and without ground effect, and in cruise flight. With this, *in situ* measurements of vortex locations relative to blades, relative to the rotor plane, vortex trajectories and orientations become available, providing unique insight into the field characteristics of these dominant structures.

Major limitations of measurement fidelity were identified as proper arbitrariness of natural backgrounds, sufficient two-dimensionality and sufficient illumination or ambient light conditions (which determine motion blur and dynamic range of the recording). Future work will include the development of a generalized background quality factor to assess measurement resolution and uncertainty systematically. Once satisfactory spatial resolution is obtained, field topology information can be supplemented by vortex core density estimates using tomographic reconstruction algorithms. In parallel, a GPS based positioning system will be developed to track the helicopter and chaser aircraft position in space along with the angle of view of the camera during in-flight acquisition. Simultaneous BOS acquisition and precise allocation of the helicopter including derived quantities concerning flight attitude will open up new vistas in experimental helicopter aerodynamics.

Having demonstrated the feasibility of the concept, experiments dedicated to several aerodynamic problems can be envisaged. Experiments corroborating and validation aeroacoustic prediction codes for helicopters can be taken directly into the field as well as computational fluid dynamics will be confronted with in situ test cases at least on the overall vortex field level. Reference-free BOS is perfectly suited for full—scale, in-flight studies owing to its fairly simple sensor units and robust, easy-to-use evaluation methods with a vast variety of future applications for studying maneuvering aircrafts, propagation of shockwaves around supersonic and hypersonic vehicles.

ACKNOWLEDGEMENTS

The authors are indebted to A. Bauknecht, G. Ertz, P. Munier and M. Krebs for their contributions to the preparation and conduction of the hover measurements as well as to A. Dillmann, T. Wilmes, A. Müller, U. Göhmann, M. Gerber and F. Wojton from DLR for their commitment during the flight tests. This work was partly supported by the US/German Memorandum of Understanding on Helicopter Aerodynamics, Task VIII “Rotor Wake Measurement Techniques” and the DLR-ISL cooperation.

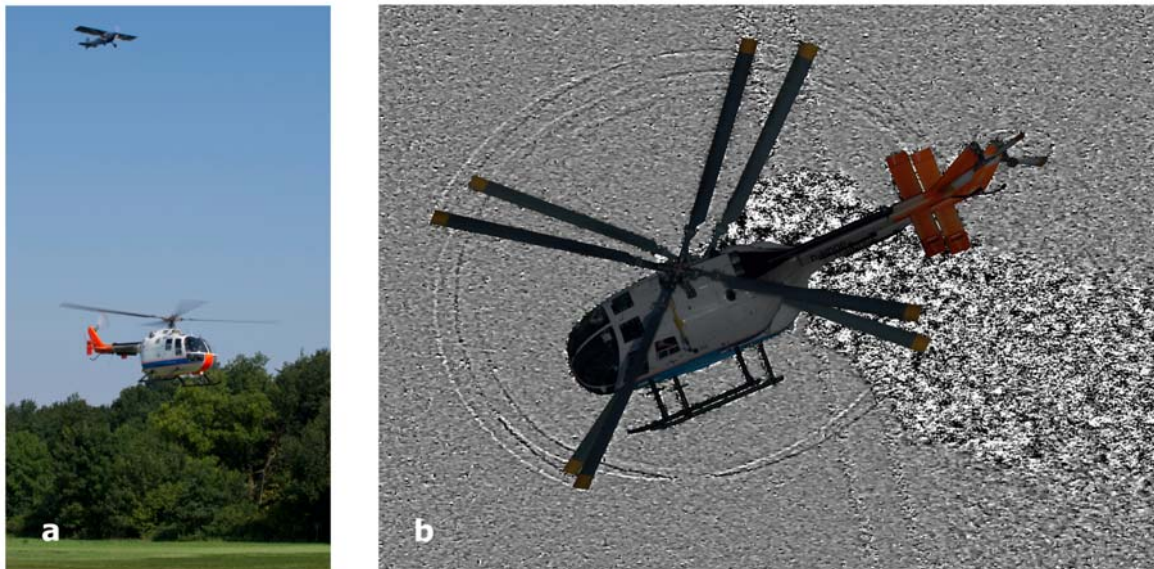


Figure 8 Full-scale, in-flight reference-free BOS tip vortex visualization from aboard a chaser airplane. A microflight aircraft (RANS S7) with cruise speeds ranging from approximately 22 to 36m/s (43 to 70kt indicated airspeed) was kept 152m (500ft) above DLR's Bo105 experimental helicopter which in turn operated at an altitude of 91m above ground (300ft GND) (a). At inter-framing times corresponding to $\Delta\psi=90^\circ$, tip vortices can be traced up to 180° of vortex age by simple cross-correlation analysis of backgrounds like cornfields or flat grass lands (except for the region blurred by hot exhaust gases) (b). Note that the nearly vertical image distortion closely behind the fuselage in b originates from farm machinery tracks on the ground.

REFERENCES

- [1] A. Bagai and J. G. Leishman. Flow visualization of compressible vortex structures using density gradient techniques. *Experiments in Fluids*, 15(6):431–442, 1993.
- [2] S. B. Dalziel, G. O. Hughes, and B. R. Sutherland. Whole-field density measurements by synthetic Schlieren. *Experiments in Fluids*, 28:322–335, 2000.
- [3] S. Debrus, M. Francon, C. P. Grover, M. May, and M. L. Robin. Ground glass differential interferometer. *Applied Optics*, 11:853–, 1972.
- [4] S. Doric. Ray tracing through gradient-index media: recent improvements. *Applied Optics*, 29(28):4026–4029, 1990.
- [5] N. Fomin, E. Lavinskaja, W. Merzkirch, and D. Vitkin. Speckle photography applied to statistical analysis of turbulence. 31:13–22, 1999.
- [6] M. J. Hargather and G. S. Settles. Natural-background oriented Schlieren imaging. *Experiments in Fluids*, 48:59–68, 2010.
- [7] K. Kindler, E. Goldhahn, F. Leopold, and M. Raffel. Recent developments in background oriented Schlieren methods for rotor blade tip vortex measurements. *Experiments in Fluids*, 43:233–240, 2007.
- [8] U. Köpf. Application of speckling for measuring the deflection of laser light by phase objects. *Optics Communications*, 5:347–350, 1972.
- [9] F. Leopold. The application of the colored background oriented schlieren technique (CBOS) to free-flight and in-flight measurement. *Journal of Flow Visualization and Image Processing*, 16: 4, 2009.
- [10] C. D. Meinhart, S. T. Wereley, and J. G. Santiago. A PIV algorithm for estimating time-averaged velocity fields. *Journal of Fluids Engineering*, 122:285–289, 2000.
- [11] W. Merzkirch. *Flow visualization*. Academic Publishing, New York, 1974.
- [12] M. Raffel, H. Richard, and G. E. A. Meier. On the applicability of background oriented optical tomography for large scale aerodynamic investigations. *Experiments in Fluids*, 28:477–481, 2000.
- [13] M. Raffel, C. Willert, S. Wereley, and J. Kompenhans. *Particle image velocimetry, a practical guide*. Springer, 2007.

- [14] H. Richard and M. Raffel: Principle and applications of the background oriented schlieren (BOS) method. *Measurement, Science and Technology*, 12: 9, 1576-1585, 2001.
- [15] F. Scarano and M. L. Riethmüller. Advances in iterative multi-grid PIV image processing. *Experiments in Fluids*, 29(1):51–60, 2000.
- [16] G. S. Settles. *Schlieren and shadowgraph techniques*, Springer, Berlin, Heidelberg, New York 2006.
- [17] A. Sharma, D. V. Kumar, and A. K. Ghatak. Tracing rays through graded-index media: a new method. *Applied Optics*, 21(6):984–987, 1982.
- [18] F. Sourgen, F. Leopold, and D. Klatt. Reconstruction of the density field using colored background oriented Schlieren technique. *Optics and Laser Technology*, 2011. (in press).
- [19] L. Venkatakrishnan. Density measurements in an axisymmetric underexpanded jet by background-oriented Schlieren technique. *Optics and Lasers in Engineering*, 43(7):1574–1579, 2005.
- [20] L. M. Weinstein. Large field schlieren visualization - from wind tunnels to flight. *Journal of Visualization*, 2:3–4, 2000.
- [21] U. Wernekinck and W. Merzkirch. Speckle photography of spatially extended refractive-index fields. *Applied Optics*, 26:31–32, 1987.