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 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.
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]:

\[
\tan(\varepsilon_y) = \int_0^\infty \frac{1}{n} \frac{dn}{dy} \, dz
\]

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

\[
\Delta y = Z_D M \varepsilon_y
\]

with the magnification factor of the background \(M = z_i / Z_B\) and the distance of the background and the phase object \(Z_0\).

According to the above equation, large image displacement is obtained for large \(Z_0\). On the other hand \(Z_0\) 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 \((Z_0=6R, Z_D=5R)\) 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 $c=54$mm, $\alpha=17^\circ$ collective pitch) at a tip Mach number of $Ma=0.37$ (a) and fully stalled flow at the same blade tip at $Ma=0.46$.

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 40×80ft$^2$ 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).
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 3908×2602px 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 1/8000s 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 5×5px area of interest, where a multi-grid evaluation scheme was used (initial and final interrogation window size: 96×96px and 8×8px 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=400mm) 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
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 256×256px 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
32×32px 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.

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 70m²
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 ψ=360° 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
was to develop a hand-operated paraxial BOS sensor, consisting of two commercial cameras (Nikon D50 fitted with f=500mm 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
visualized 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.

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Figure 8 Full-scale, in-flight reference-free BOS tip vortex visualization from aboard a chaser airplane. A microlight 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 $180^\circ$ 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.


