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On the application of BOS

Gerd E. A. Meier[1]

[1]Formerly DLR Göttingen and Leibniz Universität, Hannover

[2]Am Menzelberg 6, 37077 Göttingen, Germany

*geameier@web.de

Abstract

In 2019 BOS is celebrating its 20th birthday. On this occasion the main BOS experiences and new applications of the author and his colleagues are mentioned. In the first part the numerous applications by authors from DLR-Göttingen after the invention of BOS by the author in 1999 are recalled. There were results in supersonic tunnel and jet flow, helicopter vortex shedding and high speed aero acoustic wave tests. Then some newer results on water film flow, water waves and exhaust plumes are shown. Finally MBOS (Moire BOS) using electronic pixel pattern interference is described together with first results.

1 Introduction

Since next year BOS (Background Oriented Schlieren) is celebrating its 20th birthday it is now time to resume its major applications, its future possibilities and its impact on optical flow measurement.

BOS was invented as a subset of the very general optical tool called BOOT (Background Oriented Optical Tomography) invented by the author working in Caltech in spring 1999 on the search for an optical tool for detecting "clear air turbulence" Meier (1999). The idea of using a laser beam backscatter system for this purpose was not successful immediately. During verification tests of the laser tool BOS was detected as a method with the invers optical ray path of the laser setup. The first fluid dynamic experiment with BOS at Caltech Lab, Pasadena, USA, was the recording of a hot jet of air by Meier (1999).

Independently by Dalziel, Hughes and Sutherland (2000) a number of novel synthetic schlieren techniques for obtaining both visualization and accurate measurements of a density field were proposed at that time. One of their proposed three refractometry techniques is familiar to the main idea of BOS. This technique they have named PMR (Pattern Matching Refractometry).

The first publication of "Hintergrundschlierenverfahren" was a German patent application by Meier (1999). Finally patented was BOOT (Background Oriented Optical Tomography). This name already pointing to the wide range of possible tomographic density field investigations. Later on for simpler applications the name was shortened to BOS (Background Oriented Schlieren) because of the use of only one projection in the most setups. The following review of applications describes some main steps in the progress of BOS.

2 The advantage of BOOT over BOS

As already mentioned above, BOS is a subset of the more general optical tool BOOT. Background oriented optical tomography is a method reproducing a density field in three dimensions locally. As shown in Fig. 1 (right) the flow field in front of a deliberate background is imaged with many cameras from as much as possible but sufficient number of different directions. For comparison a second set of images without the object is taken. Those image pairs are evaluated with PIV (C. Willert 1985) or other pattern matching tools for density gradient. From each evaluated gradient image by Poisson or line integration a density projection can be won. Since any of those images is a projection from a different viewing angle,

by the usual mathematical procedures as convolution back projection the local density values can be achieved. This also solves the problem of undefined position of objects in simple BOS use finally. One application of BOOT without naming it is found in Goldhahn (2006). Probably there are more in between.
In a simpler version of BOOT the setup of Fig. 1 (right) can be used with less cameras for stereoscopic reconstruction of gradient fields. Often schlieren objects like shockwaves or vortices can be accurately localized this way also.

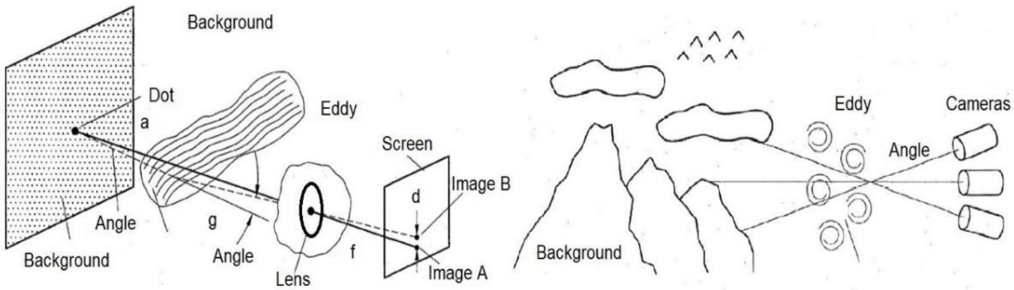

Fig. 1: Setup for ordinary BOS (left) and setup for BOOT (right)

2 Early work with BOS in DLR-Göttingen on different flow types

In DLR Göttingen the exploration of BOS was started by the author in a wide range of applications with many coworkers. These coordinated activities gave BOS a strong initial impact. First early experiments were performed with a supersonic jet from a Laval Nozzle by Rein et al. (1999). Here for the first time the gradient field of the jet achieved by BOS was integrated up to the density field projection (Fig.2). The integration of the BOS data was done numerically crosswise over the jet and also by a Poisson integration of the gradient field projection. The left image in Fig. 2 shows the error sensitive crosswise gradient data line integration. The right one shows the more smooth picture of the field integration. In both the images the cellular structure of the jet becomes imaged. Also the typical decay of the density variations and cells lengthwise in the structure is clearly visible. This decay is due to turbulent mixing which is not visible because of the long exposure times of the background images.

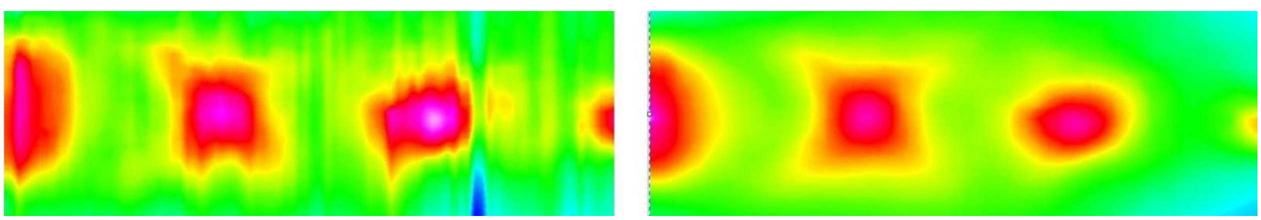

Fig. 2: Left line integration, right Poisson field integration of BOS data of a supersonic jet.

The power of BOS investigating schlieren objects of unlimited extension in three dimensions found application in observing the tip vortices of the rotor blades of a flying helicopter. This elaborate tests with stereo BOS were performed by Raffel et al. (2000) with a real flying helicopter in the backyard of the DLR institute in Göttingen (Fig. 3 left). This work was a major contribution in helicopter rotor noise research. Results testified vortex structure interaction being the major pulse noise generation mechanism.
Further on the combined application of BOS and PIV in DLR Göttingen brought another fundamental progress in flow measurement. Early experiments provided the density gradient field and the flow velocity field in one image and at one instant of time. One example is the wind tunnel recording of a transonic flow field (Fig. 3 center) by Stasicki, Willert, Raffel, Kompenhans and Meier published in Meier (2002). Another is the simultaneous recording of density gradient and velocity of the turbulent wake flow downstream of a cylinder (right image in Fig. 3). The first ever made High Speed BOS video was made by Stasicki and Meier in 2004 for a conference in London (Fig. 3 second row) and was published in Stasicki

et al. (2004). This video was made with flash illumination of the background for about 1ms sufficient for the camera.

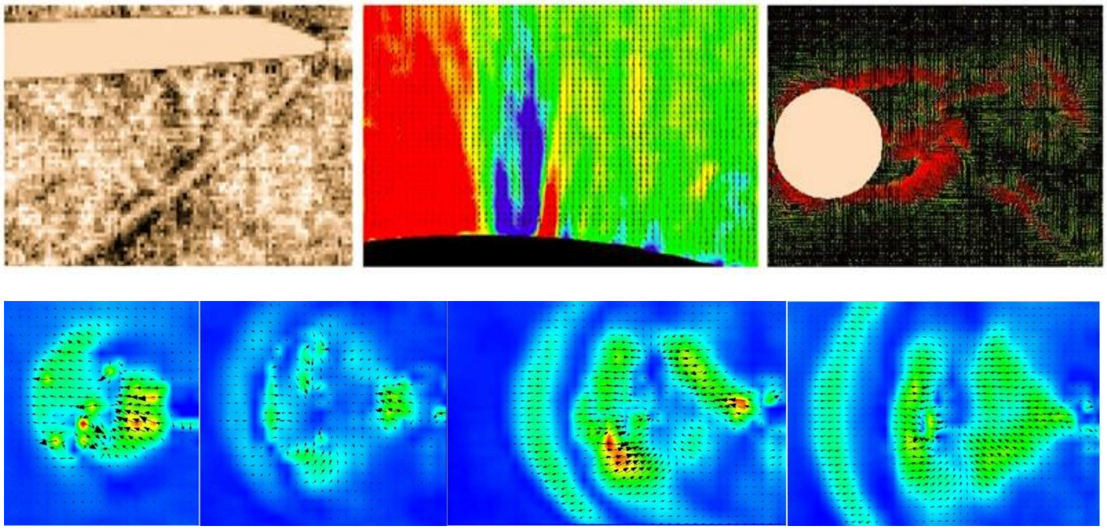

Fig. 3: Tip vortex of a helicopter blade, transonic tunnel flow and wake flow of a cylinder (top). Bottom: Time resolved gun shot from left to right, gas and shock waves (Interframe time 0,1ms)

3 Numerous applications of BOS by other authors

A good impression of the numerous later developments and applications of BOS give the proceedings of the ISFV and ICEFM conferences since 2000. The author is delighted about more than 5000 citations of BOS and 15000 for Background Oriented Schlieren found by Google in the open literatur. Main impact is visible for applications with compressible flow, special background structures and for use of natural backgrounds especially for large outside objects.

4 Recent applications of BOS

Newer experiments of the author are concentrated on the applicability of BOS for natural gas flow, fume detection, jets, liquid films on surfaces (Rieselfilm), water waves, vapor and, exhaust plumes and fire.

Fig. 4: A jet of natural gas (left three images) and a fume bubble from a smoke stack (right two images)

In Fig. 4 in front of a regular background a smooth first part of a jet of natural gas from a circular nozzle is shown. At the upper end of the jet image a vortex caused by instability and gravity influence is observed. This BOS application demonstrates that in case of moderate local density variations a regular background (left) is adequate. In case of large variations the danger of aliasing is present.
The right series of two pictures in Fig. 4 shows a smoke stack and the BOS visualized smoke bubble. Right image is received by correlation of images of the wood in the back with and without the smoke

bubble. This technique is applied in environmental studies for observation and detection of polluting emissions.

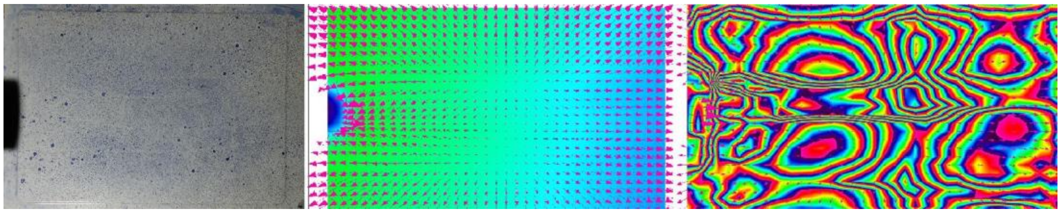

Fig. 5: Time averaged jet of hot air: left setup, middle gradients, right correlation coefficient

By a longer exposure time of the background image during presence of an unsteady flow a time average of the density variations can be achieved if the spots are not too much blurred for the correlation procedure of the images. So the gradient image of the jet in Fig. 5 center shows two symmetric vortex centers. The right image where the correlation coefficient is colorful displayed also shows the long time symmetric structure.

Fig. 6: Water films on a glass plate

The two images with short time exposure of water films running down on a glass plate in Fig. 6 show the wavy surface and thickness of the film as well as the possibility of evaluation of speed and structure variations of the waves. The right background shows as image structure a Moire interference of the dot pattern (left background) with the camera chip pattern. This effect is already visualizing the water film more distinct than the left background image without Moire effect (see MBOS below).

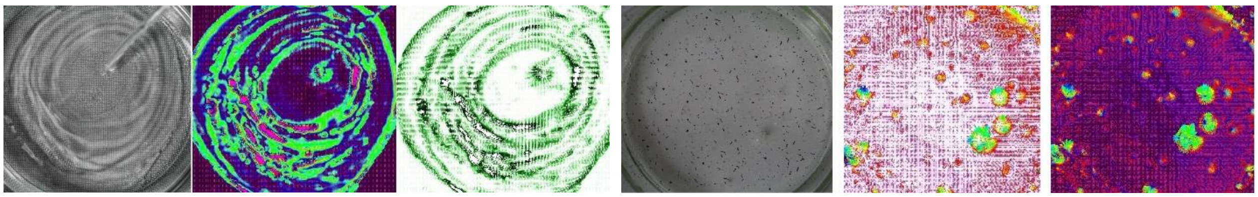

Fig. 7: Water waves on the surface after impact of a jet and oil spots on a water film

For wave studies the left three images in Fig. 7 show the background, a colored BOS evaluation and the vector field of gradients of the water film thickness. This series demonstrates once again the possibility of wave measurement in height and velocity. The right series shows oil droplets on a water film. Both BOS evaluations concern a thickness measurement instead of a density measurement. This way demonstrating another field of applications. The vectors are not resolved in this small images but clearly visible in original size. The center image in the right series shows a distinct aliasing effect which is due to narrow spot pattern. In both the series the background distance is 1cm only, essential in case of high gradient values.

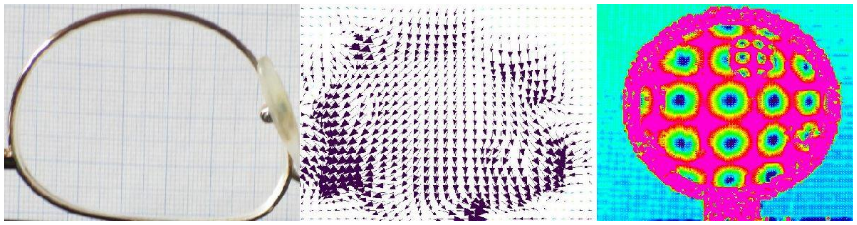

Fig. 8: Left: refraction measurement of an eye glass, right: aliasing for too large distance of a lens.

A side look to investigations of transparent solid media is presented in Fig. 8. Here two glass objects of daily use are tested. The left two images show refraction index measurement of an eye glass, the right image shows a looking glass. For large variations of refraction index or material thickness the adequate background distance is important. In the right image of a lens curious aliasing effects occur.

5 New applications with electronic MBOS (MoireBOS)

A system consisting of a TV screen and a video camera (Fig. 9) is able to produce a distinct fringe pattern (Moire) in the camera image by a certain interaction and superposition of the dot or line pattern of both their imaging elements. The basic pixel structure of the monitor is imaged by the lens on the camera chip. If then a schlieren object (Eddy in Fig. 9) is put into the imaging beam path the image of the dot matrix of the TV monitor in the camera is distorted and dot images change from A to B (see Fig. 1). Consequently a distortion of the pixel pattern and a shift of the pale fringe output of the camera results.

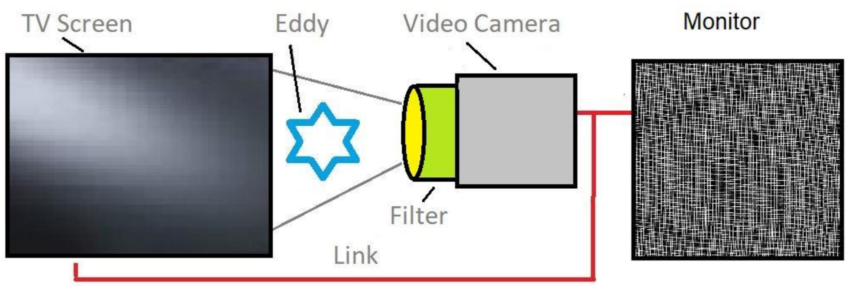

Fig. 9: Electronic MBOS setup with pixeled elements interfering in Moire fringes

A Moire fringe method was already used by Burton 1949 and Mortensen 1950. They have realized Moire deformation being an optically simpler alternative to the classical schlieren method. Nowadays the Moire method is applied in micro circuit checking (Miao et al. 2016). The electronic MBOS method employs instead of the printed or engraved mechanical backgrounds and filters two controllable pixel raster.

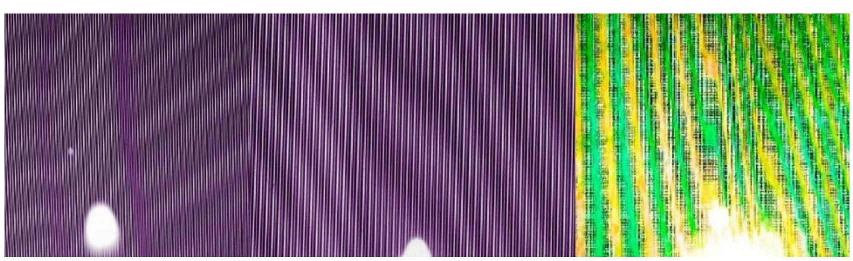

Fig. 10: Three MBOS results for candle flames in front of a monitor screen

The production of the fringe images stems from the output of the digitally recorded camera images. By a monitor the Moire fringe picture is visualized permanently (see Fig. 10). The image recorded in this way then is a superposition with an already apparent fringe image of the background alone (see also Fig. 11).

Fig. 11: Fringe images of an oil schlieren and two eye glass images with different basic fringes

Due to the pixel structure of the visualizing monitor it comes to further superimposed Moire effects unfortunately (Fig. 11). Not only refractive index gradients may generate the fringe image distortions finally. Also bias pattern occur together with the deformed basic pattern. A suppression of the third order distortions is possible by filtering or choosing a monitor display with different or less pixeled resolution.
The main advantage of MBOS over classical BOS is the permanent visibility of a schlieren image without evaluation by a computer. So far it is - back to the roots – similar to the old Toepler Schlieren Method.
The sensitivity of electronic MBOS is connected with the pixel displacement d illustrated in Fig. 1.
This is increased with background distance a, focal length f of the imaging lens and object grad(n), but diminished by large camera distance g from the background (d ~ a f grad(n)/g). But of course the system parameters like pixel density, commensurability of raster frequencies and screen adjustments are important anyway.

6 Conclusion

BOS has become a very valuable tool in fluid dynamics. Compared to the old Schlieren Setups it is extremely simple, can be used with cheap tools, has no field limitations and delivers quantitative two dimensional or even three dimensional density gradient fields. Many authors have contributed to the development, refinement and application of BOS. Especially in combination with other optical flow measurement tools like High Speed Photography, Particle Image Velocimetry and Pressure Sensitive Paint BOS has become an inevitable tool. Simplicity is one main of several advantages compared to the more qualitative and humble Toepler Schlieren Method and the elaborate classical or differential interferometry.

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