# Optical flow sensors based on moiré effect

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DOI: 10.13111/2066-8201.2025.17.4.12

*Received: 07 October 2025/ Accepted: 10 November 2025/ Published: December 2025*


***Abstract:*** *This paper continues recent research of the author on the applications of dynamically generated moiré patterns in gaseous and transparent fluid flows. Moiré patterns are special interference patterns that appear when two or several quasi-aligned periodic structures are superposed. Depending on the detector, geometrically unrelated macro patterns emerge in the shape of darker and lighter areas as an effect of optical interference of the overlapping patterns as well as aliasing of the resulting pattern with the sensor's elements. A series of well-known antialiasing practices such as low pass optical filtering can be used to counter this effect when normally imaging everyday objects but on a careful analysis the moiré pattern itself has merit as a tool of investigating small displacements in transparent fluids without any interference. The system described in this paper is able to detect minute changes in velocity of a fluid without perturbing it -unlike the traditional methods where classic flow sensors are placed within- and is therefore a good addition to the experimental aerodynamicist. It also can be extended to work for larger displacements/ lower sensitivities by adjusting the forming grid patterns as will be shown.*

***Key Words:*** *optical method for fluid flow measurement, moiré patterns, very slow speed fluid flows,non-intrusive sensing of very low speed fluid flows, simple optic fluid flow sensor with error correction*

## 1. MOIRÉ PATERNS AND THEIR APPLICATIONS

Moiré patterns are optical phenomena that appear at the imperfect superposition of periodic patterns in optics. These are sometimes called optical matrices, and consist in repeated patterns of transparent and opaque zones, usually in the shape of bars or grids of various designs [1]. The phenomenon got its name after the first practical observation in textiles, where two roughly woven layers of silk were superimposed at a slight angle between fibres to obtain a wet or cascading look. The moiré pattern is a so-called macro pattern- light interference creates geometric shapes with characteristic sizes far larger than the periodic elements of either of the two optical matrices.

These special characteristics allowed the use of moiré patterns in deformation, material stress and strain and flow visualization, as they tend to amplify motion amplitude and apparent speed (the so-called optical speedup of moiré patterns simply states that when two moiré lattices move with respect to one another, the resulting interference pattern is easily observable- much larger than any of the two structures- and appears to move faster than the two structures).Optical methods in highly sensitive, easily perturbed flows are preferable because of their non-invasive nature.

Optical methods for displacement measurement include photogrammetry -the precise measurement of contour parallax. With the properties of optical displacement amplification and optical speedup, moiré patterns help increase the precision of such methods. Numerous applications exist ranging from macroscopic methods using normal light and macroscopic lattices printed on mobile or deformable part faces and compared to a paired static lattice attached to a camera system of appropriate construction, but also microscopic crystallographic methods that observe naturally occurring or artificially constructed crystal layers with geometric imperfections or misalignment forming micro lattices and exhibiting moiré effects when compared to undisturbed regions of the same crystal [2]. Digital micrometres are one of the more common applications of the effect -the stationary lattice is superimposed on the moving vernier lattice and the interference moiré bands that form when moving the mobile piece with respect to the stationary part give a greatly improved precision reading of the displacement.

Moiré patterns occur in nature also – sometimes imperfect crystals show this kind of effect between atomic layers containing slight imperfections leading to partial mis-alignment of crystalline layers. This is also observed and exploited in artificially micro structured 2d plane graphene (known in the field as magic angle MSL graphene) or other carbon derivatives (quasi-crystalline graphene or the compressed variety) where interference due to moiré effects extends in all regions of the electromagnetic spectrum, opening paths to development of new sensors and active materials (semiconductors, enhanced Seebeck and photovoltaic effect materials etc as a result of emergent moiré interference properties).Such complex metamaterials are often referred to as moiré superlattices -and taking into account the very definition of the moiré effect, material scientists found ways to build them using a technique that rotates the layers with a screw displacement mechanism while the crystal is forming [3].

The simplest implementation of moiré sensors is a pair of Ronchi gratings. These are bar patterns of alternating opaque and transparent lines in the case of the transmission Ronchi gratings – or light and dark stripes on reflecting patterns in the case of the so-called “reflective” Ronchi patterns.

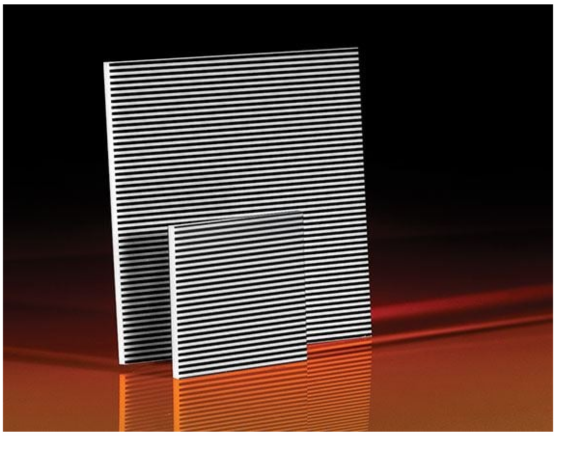

Figure 1a. Reflective Ronchi gratings example an Edmund optics offering from its current catalogue

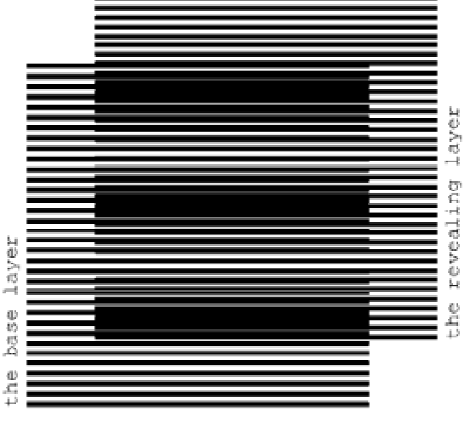


Figure 1b. A two Ronchi grating superposition showing the moiré effect as thick lines-image from [1]

In figure 1a we can observe reflective Ronchi plates of 1x1 in offered as optical targets by the optics lab and academic demonstrator company Edmund Scientific. These are used in conjunction with a transmission Ronchi grating of a different or similar frequency to observe optical superposition effects- the moiré. The left side of the picture shows two superimposed transmission Ronchi plates- and the moiré effect that arises in the form of thicker black lines. To observe fine motion or distortions, one of the gratings is fixed on the reference surface and the other is free to move above it. The fixed plate is often called the base layer, while the mobile plate is called the revealing layer [1].

To use moiré plates as motion and deformation sensors we must find the superposition laws for the two linear gratings, so let us analyse a portion of the enlarged figure 1b to reveal what happens at the superposition of the two gratings. See Figure 2 for details and notation. Let us consider two superimposed Ronchi gratings like the ones shown in Figure 1, b and let the spacing be different (like in most applications). The vernier effect then when one is moved above the other ensures the superposition is periodic, with period $p_m$. If we denote the spacing of the base layer $p_b$ and the spacing of the revealing layer $p_r$ we will see the following situation (refer to fig. 2 below).

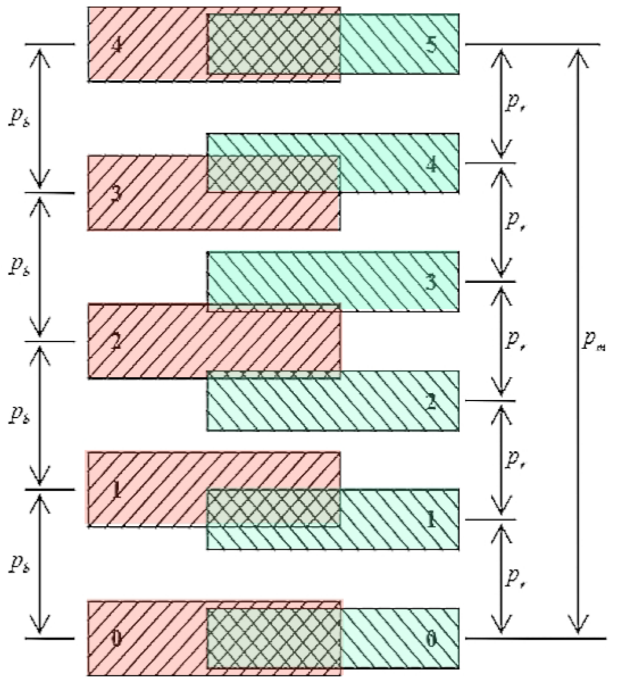


Figure 2. The spacing of two superimposed moiré grids and the geometric parameters. The fixed base layer is in orange and the revealing grid in light green. Redrawn after [1] keeping the notations.

When superimposed, the two patterns with periods $p_b$ for the base grid and $p_r$ for the revealing grid align perfectly after a period $p_m$. The partial superimpositions can be thought of as aliasing due to non-Shannon sampling.

The period of the superimposition can be found as:

$$p_m = \frac{p_b * p_r}{p_b - p_r} \tag{1}$$

The formula holds for the case when the base plate has a shorter period than the revealing plate but the value is taken in modulus as absolute [1] as in (2):

$$p_m = \left|\frac{p_b * p_r}{p_b - p_r}\right| \tag{2}$$

If we use a complete superposition of the two grids then we can make a corelation of the opacity of the resulting image, with the non-aligned zones covering the transparent area and the perfect alignment zones keeping the adjacent zones transparent. The immediate application of the effect is a light transmissivity-based sensor for displacement in transparent media. Of course, the pattern changes and the periodicity of the phenomenon mean the sensor will register an overhead and reset – but we can use multiple spacing grids to account for these higher periods and extend the measuring range of the instrument as required.
Similarly, if the revealing layer moves with respect to the base layer, a thickened fringe moiré pattern is formed, but it moves in the same direction with a greater speed than that of the revealing layer- in fact its speed holds a direct correlation to the speed of the revealing layer. The effect is called optical speedup and states the relationship between the speeds of the apparent moiré pattern $v_m$ and the speed of the mobile revealing layer that actually moves, denoted by $v_r$ is;

$$\frac{v_m}{v_r} = \frac{p_m}{p_r} \tag{3}$$

But considering (2) we obtain:

$$\frac{v_m}{v_r} = \frac{p_b}{p_b - p_r} \tag{4}$$

With the observation that if the base layer's period is longer than the revealing layer's the motion sense will be inverted (1).
Similar formulae cand be deduced for inclined patterns and for rotational superpositions (and combinations thereof) (1), (5).

## 2. MOIRÉ PATTERNS AND OPTICALLY DETECTED FLUID FLOWS

Once we established the common uses of moiré patterns in motion detection [1],[2], I feel necessary to draw a parallel with the background oriented Schlieren method (BOS). In a general sense, the BOS method uses at least two images of the object around which the flow is examined- one without the flow and the other in presence of the said flow. By doing so we can compute the displacements by numerically comparing the two images taken at different moments in time and identifying background pattern distortion and displacement as a measure of the variations of the refraction index, and ultimately as a function of the local fluid density. By a series of stacked approximations, one then calculates back from the local density and time between frames parameters such as flow speed and direction, as well as the resulting pressure field.
A moiré pattern emerges if optically superimposing the two images -and a second order moiré, or moiré of a moiré- appears if one takes into account sampling the film of the flow at a certain, implementation specific temporal resolution. By comparing two sets of superimposed images that reveal the local flow direction and magnitude of local displacement ultimately related to speed, one gets information about the displacement of the flow field itself- i.e. "contours of derivatives of displacement" [4] – or the local acceleration of the flow. This method is in use in other branches of fluid dynamics research such as ship hull design and water channel analysis but using a simple experimental apparatus that the author describes in this paper the method can be extended to air flow visualization in wind tunnels.
The basis of fluid motion detection with all optical methods is the observation that light speed itself is different when passing through a medium that is itself in motion with a relative speed

v to the static observer, described by the approximate formula derived from general relativity equations:

$$u_x = \frac{c}{n} + v\left(1 - \frac{1}{n^2}\right) \tag{5}$$

where $u_x$ is the speed of light in the moving medium with the speed $v$
$v$ is the speed of the moving medium, along the x axis
$n$ is the refractive index of the medium
$c$ is the speed of light in vacuum

Based on this we can predict the image of the pattern that is immersed in the flow will show deformations due to the speed of the light traversing it being changed as a function of the refraction index of the medium. And the refraction index itself changes with local density- this being the basis of the Schlieren methods as well. To summarize, the author proposes a non-intrusive flow sensor using moiré patterns formed between a fixed base layer grid and a revealing grid that is placed on a transparent window on the other side of the flow as it passes a tunnel, as is the case in the test section of a regular wind tunnel. The setup is then completed by a digital optical sensor with enough resolution and of such magnification that a moiré pattern appears. If the revealing grid has a different frequency than the base grid we have an expanded sensitivity moiré sensor, and if the resolutions are chosen so that the overlay is perfect, we get a so-called Zebra Schlieren (high sensitivity large area Schlieren setup). What is essential is that the two methods are related and by varying the spatial frequency of the revealing grid one can increase sensitivity for low-speed detection. The equation (4) then will allow to calculate the speed of the flow by measuring the speed of change of the emergent moiré macro pattern lines. Apparent displacements due to image deformations of the base grid viewed through the interference effect with the revealing grid are also magnified and therefore easily detected by a standard resolution camera [5].

**Why bother with moiré if we have BOS/ regular Schlieren of various types?**

Typical displacements of the light due to density effects in a non-laminar flow are very small, hence the disturbances must be serious in order to be sensed by a typical Schlieren system. Most subsonic speeds are considered too low to produce sufficient light deflection with their pressure fronts so a very high sensitivity Schlieren system is needed. This is usually accomplished with using powerful optics with great magnification- but the downside is that the longer the focal length the smaller the field of view. For large field sensitive Schlieren systems the superimposed stripe technique is used-but again we find two superimposed grids. The technique is more sensitive if the gratings are larger and imaged appropriately so that the optical density of the grids is high on the sensor. All that being said, all flow visualization methods are related and based on the optical flow theory.

**What is optical flow?**

Optical flow has been defined by the American psychologist James J. Gibson in the 1940s [6] as a perception phenomenon relating to the detection of motion by changes in the field of view, relating the apparent motion of the observer to changes in objects shape brightness and scale and their apparent displacement in the field of view.

This phenomenon also can be used to simulate motion and also to detect real, physical motion using patterns that are made to move in relation with the flow. All methods currently used in machine vision and flow visualization are based on the detection of gradients and discontinuities in optical flow patterns that are generated using the physical flow properties-i.e. by correlating refractive index and local density and following the optical gradient jumps (regions of nonlinearity or discontinuity). Once such an image is obtained by various means- Schlieren, shadowgraphy, moiré pattern displacement etc- dedicated algorithms for motion computing are used to transform the apparent pattern motion in fluid motion vectors, such as those described in [7]. Simpler methods use a colour pattern shift as a basis for optical gradient methods identifying solid, coloured objects motion by checking pixel colour shift in addition to the traditional variations in image brightness in space and time within pre-defined pixel matrices (windows) [8]. Optical flow is deemed valid if the gradients of the nearest pixels correlate to their previous values for brightness and colour within 20%, each frame being compared to the previous one. It is essentially a numerical method based on camera sensor framerate and digitization of the observed optical flow.

Going back to flow visualization- flow is different from a fixed rigid object in motion and to make use of the same principles as before we must correlate it with observable and repeatable motion related image artifacts that appear similar to solid objects and process those as a measure of the flow. One way to achieve this is by using moiré patterns that are affected by the flow and quantize those changes.

**Moiré patterns and optical flow sensors**

As previously established, moiré patterns have an apparent optical flow amplification [1]- i.e. they tend to react greatly to the smallest changes in apparent relative grid motion so that they can be used to detect small changes in the refractive index of a fluid flow between them and observe large movements in the interference pattern they create.

Therefore, a simple sensor for transparent fluid flows can be constructed from two transparent plates with a superimposed grid or stripe pattern between which we cause the fluid to flow. Such a setup can easily be adopted in wind tunnels and bears similarity to background oriented Schlieren installations. Both transparent and reflecting and transparent plates can be used, with the light transmitted through the flow sample or side- illuminated from the transparent grid (revealing layer) and reflected by the other base layer represented by an opaque plate. To complete the arrangement, a digital camera is needed- and here we separate two cases. The first is the trivial one- providing enough resolution and field of view to image the observed moiré patterns formed by the images of the two superimposed grids. A second, more interesting case is when a single grid (base layer) is used, and the camera sensor and focal length of the lens chosen so that the pattern forms directly on the sensor. A moiré pattern is easily formed if the image size of the grid is a sub/multiple of the number of pixels on the axis of interest. This case is no longer an interference moiré but an optical aliasing phenomenon.

## 3. CONCLUSIONS

The phenomenon of moiré pattern formation and their properties -optical speedup and macro pattern motion with the slightest motion of the revealing grid or its image, have been long studied and used in optical metrology [5], [7] but also in machine vision and optical flow sensors [7], [8]. With some modification, the principle can be used to measure transparent fluid flows in a non-invasive way and therefore sensors for small speed low Reynolds flows can be built using the principles shown. In a follow-up to this presentation, an experimental prototype and method will be explored in detail. The procedure is now in its experimental phase and a practical example will be soon analysed in a follow-up work.

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