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Anwendung der ILIDS-Technik zur Tröpfchengrößenbestimmung in Hyperschallströmungen

Application of the ILIDS technique for droplet sizing in hypersonic flows

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Tröpfchen, ILIDS, Hyperschall, Spray
Droplet breakup, ILIDS, hypersonic, spray

Abstract

For the investigation of mechanisms of liquid atomization the final droplet size is of great interest. The secondary break-up of a liquid spray has been studied in the hypersonic blow-down windtunnel of the von Karman Institute for Fluid Dynamics at a Mach number of 6 with the ILIDS-technique.

The ILIDS-technique uses a Laser-sheet, which illuminates the two-phase flow. The light is partly reflected at the surface of the droplet and refracted inside the droplet, creating a circular fringe pattern. With the resulting fringe pattern it is possible to reconstruct the droplet size.

For detecting the circular fringe patterns a Hough-transform has been used, the fringe frequency was calculated by an autocorrelation method. To distinguish fringe patterns created by the interference of the light from spurious signals, the band-averaged autocorrelation function is compared with the theoretical, ideal one.

Reynolds numbers ranging from 9.7E6 to 26E6 have been investigated. The droplet size distributions for the different flow conditions have been compared to the log-normal distribution.

Introduction

A measurement technique using the interference pattern of two from a droplet reflected/refracted light was first proposed by König in 1986. Since then great progress has been made and it is now possible to measure the droplet size in a 2-dimensional area for a wide range of scenarios.

The ILIDS technique uses the fact that glare points of a sphere under coherent light produce interference fringes if they are photographed out of focus. These interference fringes then can be used to calculate the droplet size. It is therefore possible, if all geometric quantities are known, to skip the calibration. This is in praxis not feasible, there are several semi-experimental ways to calibrate the setup (Dehaeck). Here the two step theoretical calibration was used because of its simplicity, and suitability for the used camera, a commercially DLSR. The minimum droplet size can be easily obtained by simple considerations and gives for water droplets in air a minimum diameter of 5µm. Preliminary experiments with water droplets and theoretical assumptions gave an estimation about 100µm.

To have a good signal to noise level, the reflected and the refracted light should be in the same order of magnitude. Using geometrical optics, one can conclude, that the optimal scattering angle has to be 69°. This indeed means, that also the lens and the CCD-chip have to be tilted to obtain the same off-focus distance in the whole field of view. This is called the Scheimpflug setup. A setup with the optimal scattering angle was installed inside the wind tunnel, whereas the Scheimpflug condition is not satisfied, so that there corrections have to be applied to the data.
The image analysis consists of several steps: First the circular fringe patterns are detected, then the frequency of the fringe pattern is calculated. Spurious signals have to be discarded and finally the droplet size is calculated using the calibration parameters.
The formula for the droplet size is (Dehaeck):
$D = \lambda\, \alpha\, F\, C$ with λ: Wavelength, α: Conversion factor depending on geometrical properties, F: fringe frequency, C: Calibration factor.
As it is the aim to capture the secondary breakup, a spray will be directly injected into the flow by an atomizing nozzle. This makes it easier to generate a reproducible, continuous spray at a defined test section. The nozzle is mounted in a housing with a blunt front, pointing in flow direction, emulating a bulk of liquid.

Droplet breakup

As usually in fluid dynamics non-dimensional parameters are introduced to classify the flow. For multiphase flows, especially with strongly curved surfaces the Weber number is the most important. The Weber number expresses a fluid's inertia compared to its surface tension.

$$\mathrm{We} = \frac{\rho v^2 l}{\sigma}$$

Where ρ is the density of the fluid, v its velocity, l its characteristic length and σ the surface tension. For describing droplet breakup, the diameter of the droplet is chosen as characteristic length.
The other important number is the Ohnesorge number, which includes the effect of viscosity:

$$\mathrm{Oh} = \frac{\mu}{\sqrt{\rho \sigma l}} = \frac{\sqrt{\mathrm{We}}}{\mathrm{Re}}$$

Where μ is the viscosity of the liquid.
The breakup can be divided into two regimes: the primary breakup, where a bulk of liquid is fragmented into droplets and the secondary, where the droplets are disintegrated into smaller droplets. Primary instabilities start deforming the bulk liquid into more or less corrugated ligaments, which then breakup and induce the droplet size of the resulting spray. In the present case we are investigating the secondary breakup after the liquid has been disintegrated by a atomizing nozzle into droplets.
Early measurement techniques were high-speed shadowgraph photographs, which allowed to characterize different drop deformation properties prior to breakup. It was possible to identify different qualitative descriptions of breakup mechanisms for different Weber number regimes. Pilch and Erdman give an excellent overview.
It is intuitively clear that a droplet with low Weber number, i.e. high surface tension and low inertia will better resist disintegration. A droplet in a high-speed flow will eventually reach a diameter, where it is stable enough to resist further breakup. This diameter is the maximum stable diameter, the corresponding Weber number the critical Weber number We_c.
The conventional approach to estimate the maximum stable diameter is to assume a simple multistage breakup. This approach too crude to be in line with the experiments. More sophisticated estimates have been proposed and proven to be successful by Pilch and Villermaux. In order to understand the breakup mechanisms and also for practical applications it is necessary to acquire the final droplet size distribution.

Experimental Setup

The experiments were conducted in the Hypersonic wind tunnel H3 of the von Karman Institute for Fluid Dynamics. This windtunnel is a blow down facility, where the flow has to be established during an initial phase of several seconds. The probe is then swiveled into the flow. This is necessary to avoid blockage; nevertheless blockage still can appear, especially at low stagnation pressures, as it happened during the campaign. The H3 provides a jet with a diameter of 12 cm and a speed of Mach 6. The Reynolds number can be varied from 3E6 to 30E6.
The laser is deflected by a prism and enters the windtunnel. There is a metal beam attached to the inside, where a mirror and the cylindric lens is mounted; in this way a laser sheet is obtained with an angle of 69°. The graphic in fig. 1 illustrates the setup. The laser sheet thickness is about 2-3mm.

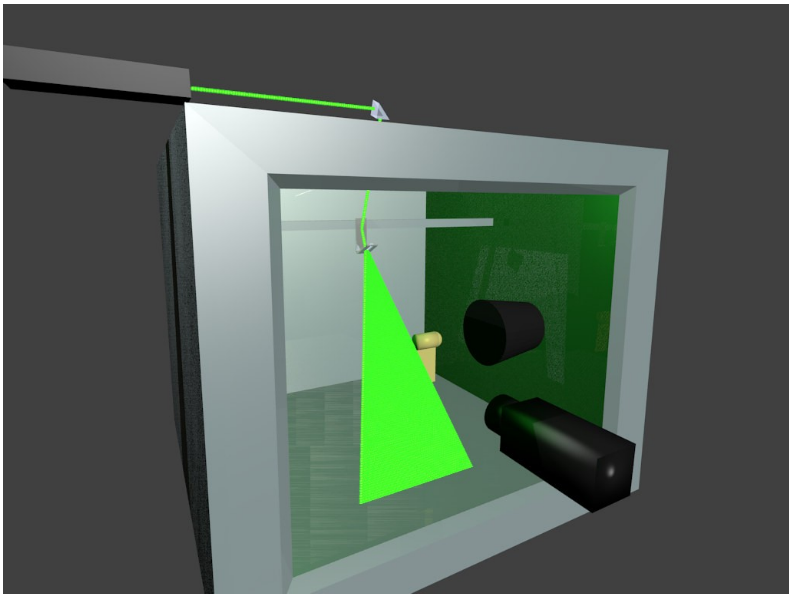

fig. 1: Computer graphic of the setup

The spray was introduced by a nozzle, that produces directly small droplets. The fairing was designed to produce a flow similar to the flow over a bulk of liquid.

Image Analysis

Circle detection: There are several pattern matching algorithms that are suitable. For basic shapes as the circle the Hough-Transform provides a simple, but robust global method. The disadvantages as high memory consumption are solved by methods explained later. T. Peng provides a sophisticated implementation for the circle detection using Hough Transform. It returns directly the radius and the location of the detected circles. As input it accepts the grayscale image matrix, the range of circle radii that should be searched for, a smoothing filter a general threshold parameter and a threshold for deciding, when two overlapping circles should be discarded, treated as one circle or as two circles.
Striping: As the laser sheet is inclined by 67.5° and due to the fact, that no Scheimpflug setup was used, the size of the circles is changing across the y-axis of the image. For optimal performance the circle radii search range should be adapted accordingly. To achieve

this, the image is cut into several stripes. Another advantage is that the memory consumption decreases considerably and that it will be easy to parallelize the processing.

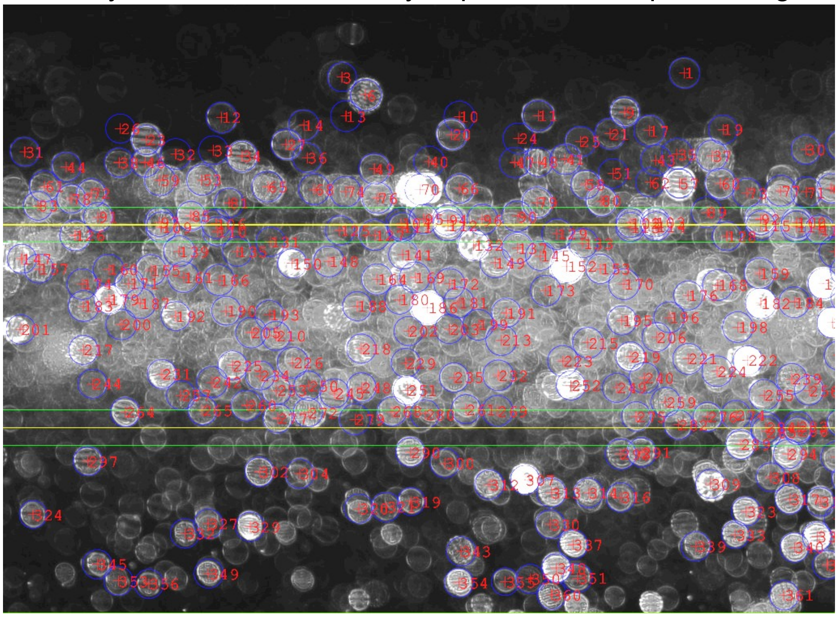

fig. 2: Detected circles in an image section. The full size pictures have been cut in 10 stripes. The image was cut in three parts at the yellow lines with an overlap region between the green lines.

For the frequency analysis, autocorrelation has been chosen. Autocorrelation is the cross-correlation of a signal with itself and, applied on the pictures of the detected circle, provides a 2-dimensional map. This auto-correlation map indicates, how similar the fringe pattern of an overlay of a displaced pattern and a the original pattern compared to the original pattern is.
Since we are interested in the spatial frequency in y-direction, one could make a cut in y-direction of the autocorrelation map and analyze the resulting one-dimensional function. Instead, to use the information of the neighboring pixels, a rectangular band has been cut out of the map and the mean values inside this band in x-direction were taken. This has the advantage, that the noise is reduced and that it is possible to detect if a fringe pattern has been rotated. Figure 3 shows a theoretical fringe pattern with the autocorrelation-map and the band-averaged autocorrelation function. The band size was 50% of the image width. The error caused by the spurious rim is 1%.
Discarding: Before we can then obtain the fringe spacing, we have to make sure that the pattern is the original fringe pattern created by the interference of the reflected light and not by spurious effects. This step is very important, because with relative low statistics a complete bogus fringe pattern can significantly distort the result. To do this one can compare the actual autocorrelation function with the theoretical, ideal one. Therefore criteria based on the existence and position of maxima and minima have been formulated.

- Circle size: A peak at a position large that the circle size is obviously a spurious signal.
- Existence of minima and maxima. If none are found it is not possible to obtain any frequency information. In the classification scheme the existence is repeatedly checked.
- Saddle point: If there is a saddle point before the first peak it is very likely that there is complete or almost complete overlap of circles.
- y-distance between consecutive minima/maxima
- x-distance between consecutive minima/maxima

Typical spurious effects are the circular border, overlapping, distortion from phase changes and rotation.

Calculation of the fringe spacing: The maxima and minima in the band-averaged autocorrelation-function are calculated using a marching algorithm and parabolas are fitted to obtain subpixel precision. The positions of the minima and maxima give the fringe spacing. The inverse of the fringe spacing is the fringe frequency used in the formula above. Another approach is to use a least square fit with a theoretical function of the band-averaged autocorrelation function. Such a function could be in the form of:

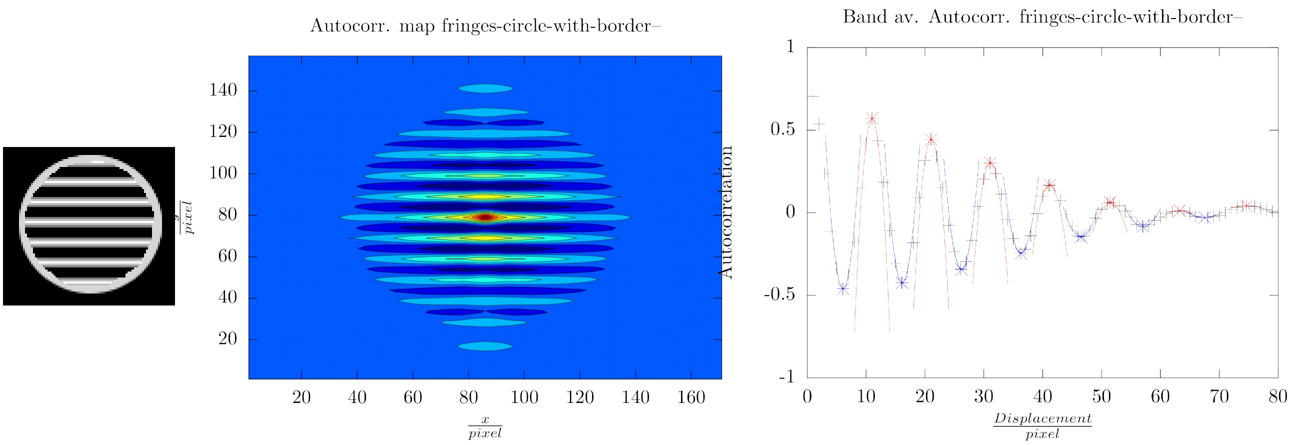

fig 3: Image, autocorrelation map and band averaged autocorrelation function of an artificial circular fringe pattern with border. The calculated frequency has less than 1% difference to the ideal pattern.

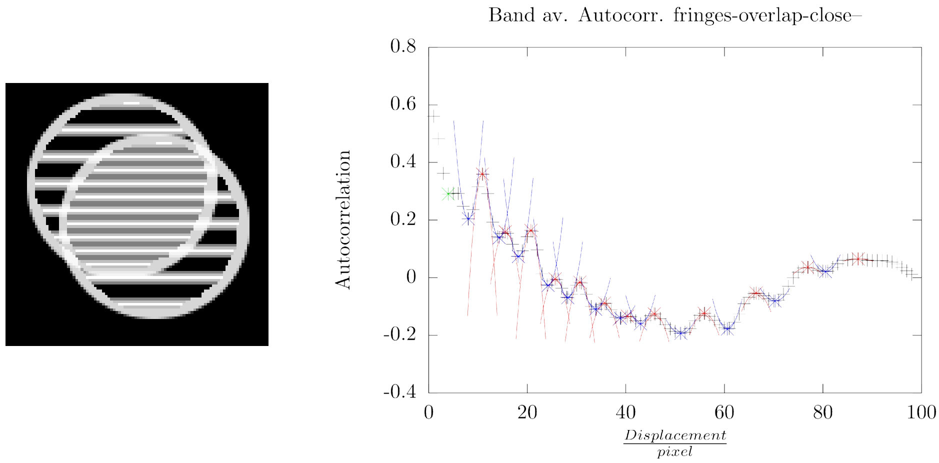

fig 4: Image and band averaged autocorrelation function of two circles with same frequency. One can clearly see the doubled frequency. The circular fringe pattern is rejected by the saddle criterium (first green star), but would clearly also fail by the minima/maxima consistency check at the 2nd maximum

$$y = (1 - a) \cdot \cos(b \cdot x) + b \cdot \cos(c \cdot x) + d \cdot (x - e)^2$$

Results

Experiments were conducted under following (freestream) conditions:

P0 / Pa	ρ	U / m/s	Re	T	SMD / µm
0	1.01E-01	-	-	66.9	115
30	1.10E-01	940.9	2.60E+07	61.1	88
20	7.36E-02	950.3	1.71E+07	62.3	99.3
10	4.10E-02	933.5	9.77E+06	60.1	101

The droplet size distributions are plotted in fig 5. The measurements are compatible to the log-normal distribution. From the fit it is possible to obtain the median diameter and the statistical error on it. One can also see clearly, that for slower speeds we have more good circles, because of less overlapping due to the broader spray.
In the vacuum, the droplet diameter distribution is broader (σ = 0.45). Due to the asymmetry of the log-normal distribution, the mean- and median-diameters are smaller than with the flow, but the Sauter mean diameter is larger. The fact, that the mean-diameter is larger in the vacuum without flow seems contradictory, since the there is no aerodynamic force to disintegrate the droplets. Since the conditions are very different, other mechanisms like evaporation may occur, though.
The largest uncertainty originates from the displacement distance of the camera, which was estimated to approx 5% for that setup.

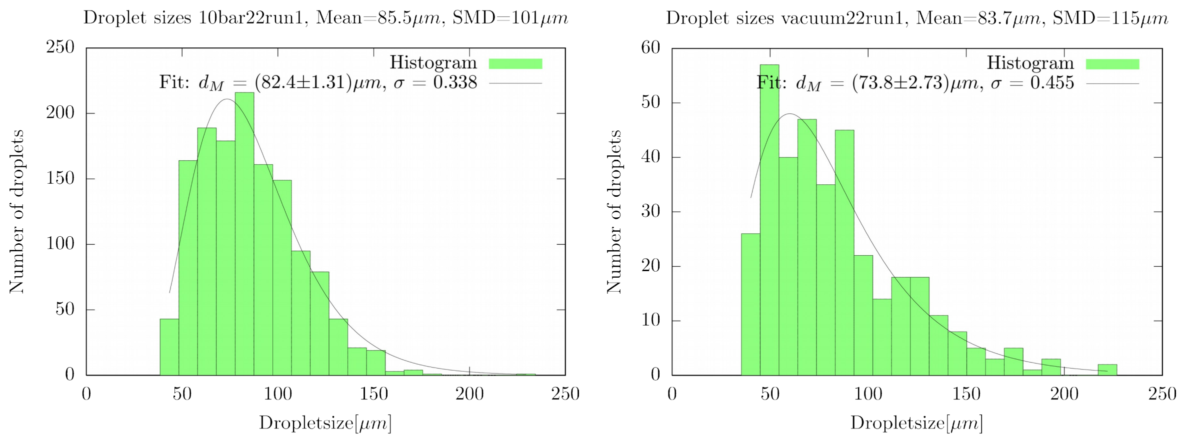

fig 5: Size distribution under the 10 bar and vacuum conditions with log-normal fits

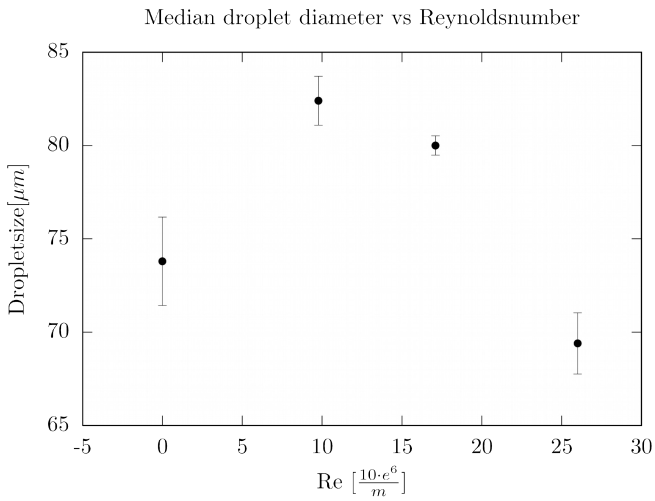

fig 6: Median droplet diameter vs Reynolds number

Conclusions and outlook

In this study the breakup and atomization of water droplets in hypersonic flow has been investigated experimentally.
The first step was to inject a nozzle into the flow by an atomizing nozzle. This produces already small droplets, which will be further disintegrated by the hypersonic flow. The size of the droplet has been measured by the ILIDS technique. Therefore the necessary optical setup has been implemented in the H3 hypersonic windtunnel.

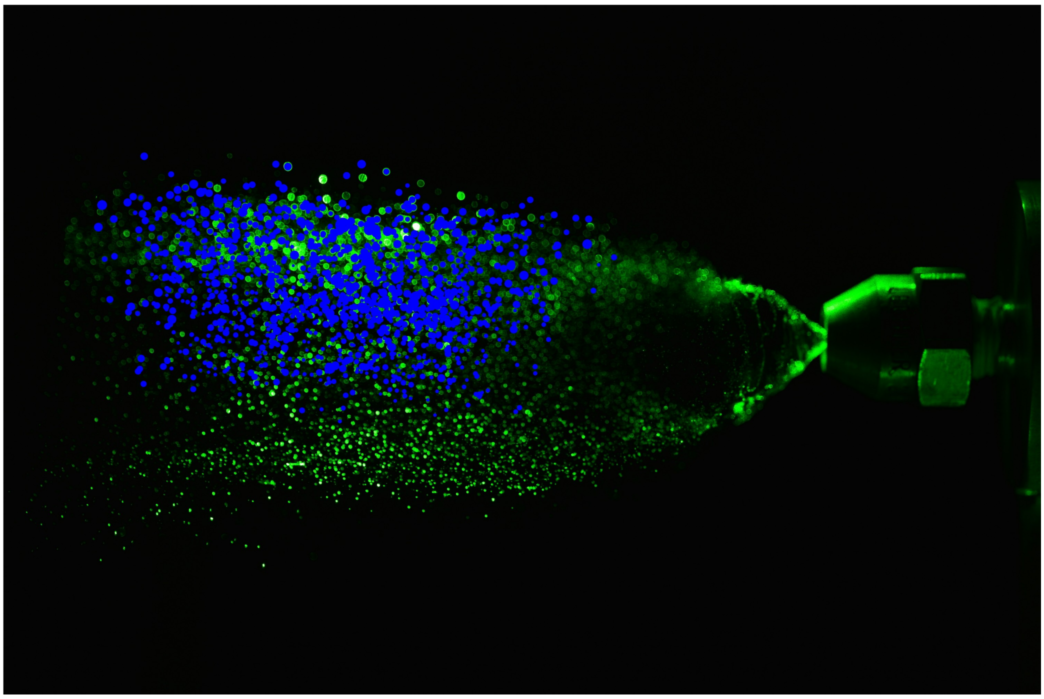

fig 7: Picture acquired by the camera with overlay of the droplet sizes under the 10 bar conditions. The bigger the blue circle, the bigger the droplet (the data for the droplet sizes was acquired by 7 images). In the lower part the fringe-patterns were discarded due to the smaller off-focus distance, and therefore smaller circular fringe pattern sizes.

The off-focus images obtained were analyzed in several steps. First an automatic detection algorithm was implemented to detect the circle positions and radii. As pattern matching method the Hough transform was used, which proved to be very reliable. This also has the advantage that it is easier to treat non-Scheimpflug images, where the off-focus distance and therefore also the circle size depends on the position in the image. The second step is to analyze the detected circles found in the image. For this an autocorrelation map was computed; the horizontal average of a band of this map provides a periodical function, in which the positions of the minima and maxima give the fringe spacing. The discarding of circles can be adjusted by several criteria, which makes it possible to reliably get rid of almost all circles resulting from spurious effects. The false positive rate was roughly estimated to be less than 0.1%.

The experiments were conducted at freestream Reynolds numbers ranging from 9.7E6/m to 26E6/m. The droplet size distributions for the different flow conditions have been compared to the log-normal distribution and different characteristic sizes have been calculated. The results are compatible with estimations from the nozzle characteristics, in focus measurements and a simplified minimum droplet size estimation. The dependence of the droplet size in different flow conditions is consistent with the expectations: At higher Reynolds numbers the forces on the droplet are higher and the resulting droplets smaller. However for zero flow and in vacuum the droplet size is smaller than with flow. This is caused by a different breakup mechanism in the vacuum. However, it is not possible to make a qualitative description within the scope of this study.

In the future a validation with a commercial PDA is desirable. Improvements in the image processing can be achieved by several methods:

- Using 2d FFT on the autocorrelation map. With this method it would be possible to find rotated circles.
- Using a Hough-transform to find lines in the images to calculate the rotating angle of fringes.
- Using an analytical function for the fringe spacing calculation as described before.

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