Lund University

Master's Thesis

# Dynamic interferometry and high-speed imaging

*Author:*
Lars Sjödahl

*Supervisor:*
Johan Nilsson

*in the*

Department of Biomedical Enginering

June 2015

LUND UNIVERSITY

# *Abstract*

Faculty of Engineering LTH
Department of Biomedical Enginering

Master of Science

**Dynamic interferometry and high-speed imaging**

by Lars SJÖDAHL

At the Department of Biomedical Engineering work has been done on micro-dispensers - micro-mechanical devices used for handling extremely small volumes of fluid, which is used in the pharmacological industry. The main part of these devices is a membrane which moves distances on the order of micrometers, and vibrates with natural modes at frequencies over 10kHz, and there was a desire to image the motion in high time-resolution. The idea was to use interferometry to measure the shape of the membrane and an interferometric set-up had been constructed to prove the concept on a stationary membrane, but the vibration modes when the membrane was in motion could not be imaged with this set-up since the vibrations were several orders of magnitude to fast for the camera to capture. This thesis covers the construction and optimization of a suggested set-up that might be capable of imaging the high-frequency vibration modes of such a membrane in motion, and to investigate its capacity and give recommendations for further development.

# Contents

# List of Figures

# Abbreviations

| | |
|---|---|
| **BE** | **B**eam **E**xpander |
| **BS** | **B**eam **S**plitter |
| **SiM** | **Si**licon (wafer) **M**irror |
| **SNR** | **S**ignal (to) **N**oise **R**atio |
| **fps** | **F**rames **P**er **S**econd |
| **tilt** | A change in angle in the plane up/down along the facing directions. |
| **yaw** | A change in angle in the plane left/right along the facing direction. |
| **roll** | A change in angle around the axis parallel to the facing direction. |
| **target** | The membrane as the part being imaged in the optical set-up. |
| $\lambda$ | lambda, used to denote wavelength |

# Chapter 1

# Introduction

## 1.1 Background

This purpose of this thesis is to investigate if a set-up can be made, which images the way small membranes, which vibrate with high frequency, move.

### 1.1.1 Micro-dispensers

These membranes are designed to be used in micro-dispensers, which are small mechanical devices used to eject small drops of a fluid. This is done by moving the membrane which constitutes one wall of a fluid holding chamber, so that the fluid gets pushed towards and out of an opening (nozzle) on the opposing wall. By controlling the path of the drops after they emerge from the nozzle, the drops can be steered to hit specific areas on an adjacent plate, where small reaction "wells" have been made. The fluid can then be analyzed with a unique mixture of reagents in this place. By controlling the size of the drop precisely, it is possible to perform quantitative tests on the fluid using only very small

volumes. Conversely it makes it possible to use a small volume of a sample fluid to perform many different tests, which is of course useful if it is difficult to obtain larger quantities of the sample fluid.

In order to decrease the time required to perform such a set of tests, the latency time you need to wait between ejecting two such drops, with controlled size, should be minimized.

The way the membrane is moved, or "actuated", is by physically connecting it to a piezoelectric actuator, which is a small electrically controlled moving bar. That the material it is made of is "piezoelectric" means that it changes shape when an electrical voltage is applied to it. It also works backwards, so that if a pressure is applied to it, or it in any other way is made to change shape, a voltage is produced over opposing sides in one orientation of it. That an object made from a piezoelectric material has a physical vibrational resonance frequency, which causes an electrical voltage of a specific frequency over them, is the basic principle used in many time-keeping circuits using piezoelectric crystals like Quartz. However, in micro-dispensers the resonance causes a problem.

### 1.1.2 Vibration modes

If a simple square-wave pulse is used to actuate the membrane, then after the drop is produced the membrane will keep oscillating afterwards with dampened resonance modes that depend on the shape of the membrane. The time profile of the force applied to it, i.e. the electrical waveform applied to the actuator, will also affect how fast the membrane comes to a rest. If an identical pulse to create a new drop is started again before the membrane has come to a rest, the membrane will start with an unknown position, velocity, and shape, and the

size of the resulting drop (if one is even created) will vary significantly depending on the exact time since the last pulse started. This is highly undesirable as it puts much higher demands on the time precision of the equipment, which translates to higher cost. There is therefore a desire to develop the shape of the membrane, and suitable actuation waveforms, to instead make the membrane come to a rest as quickly as possible, so that conditions are the same as before you produced the first drop in a long time.

## 1.2 Earlier work

Suitable shapes and waveforms to produce this result has been developed theoretically, and can be simulated, but the developed shapes needed to be verified in practice. However, there was at the start of this project no way of imaging a membrane, which was a millimeter in width, and moving with an amplitude on the scale of micrometers, at frequencies predicted by the models to be in the range of 10-100kHz, with a time resolution high enough to observe the resonance modes of the membrane. This is the problem that this project intended to solve. Since the motion of the membrane is too small to be imaged directly with a microscope, the idea was to use laser interferometry, and a proof-of-concept demonstration has been built, which is described in the next chapter.

## 1.3 Intended result

The scope of this thesis is to try to improve the performance of the current set-up, and try to modify it so it can be used to image the membrane when it is

in motion, on a limited budget. This will require a time resolution of less than the time it takes for any part of the membrane to move less than $\lambda/4$. The intended set-up is one where you can set a specific point in time relative to the actuation moment and immediately get a sufficiently sharp interferogram to verify the shape of the membrane at this point in time, with a height resolution of less than $\lambda/4$ of a wavelength.

## 1.4 13 year hiatus

The thesis was started 2001 and some promising results were obtained. There was then a 13 year hiatus due to financial considerations, and during this time the equipment was regularly packed away, used for other experiments, and occasionally assembled. Some parts were broken and had to be replaced or repaired. When the set-up was then reassembled for the conclusion of this project, configuring it proved more troublesome, which has affected the result and some of the conclusions of this thesis.

# Chapter 2

# Theory

## 2.1 Interferometry

Before this project started, an existing set-up had already proved the concept of imaging the membrane this way, but only when the membrane was at rest. Interferometry is based on the wave properties of light, which makes it behave in counter-intuitive ways when the light is coherent, such as the light from a laser. In coherent light, the photons not only have (almost) exactly the same frequency, but they are also in phase as they propagate. When coherent light from a laser is split into two beams by passing a semi-reflective, semi-transparent surface, both the new beams will have the exact same frequency. If the beams are then subsequently mixed together again, e.g. by falling on the same object, a pattern will form. In those points on the object where the difference between the two light beams' paths is near an integer number of wavelengths, the two beams will amplify each other, which is called "constructive interference", but in the points where the difference between the two light beams paths is far from an integer number of wavelengths, so that the waves

are in counter-phase, the two beams will instead cancel each other out, which is called "destructive interference". So in some locations you will get bright light, but in other you will get little or no light at all. The more equal the beams are in amplitude (and hence intensity), the more they cancel each other out.

In an interferometer, such as the one constructed in this project, typically a collimated (neither diverging nor converging) laser beam is split up into two equally intense parts using what's appropriately called a beam splitter. One part is then reflected on a perfectly flat surface like a mirror, and the other part hits the object you want to image, in this case the membrane. The membrane and the mirror are both angled so that the reflected beams go back to the beam splitter, where again half the intensity of each beam goes through and half is diverted. By careful calibration you then make one part from the mirror line up with one part from the object, so they are mixed. Since the beam from the mirror has reflected off a flat surface, every part of the beam is still in phase. The beam from the membrane on the other hand, has been reflected off a non-flat surface, so when the two beams mix, some parts of the mixed beam will be cancelled out while others will still be bright, depending on the difference in the distance the beam has travelled. By projecting the beam on a white matte screen, an image with a characteristic look containing alternating dark and bright fringes, is produced. These fringes each represents microscopic differences in height on the membrane's shape. (It is very much like the height curves of a topographic map.) Such an image is called an interferogram.

In the proof-of-concept setup, which uses a (continuous) Helium-Neon laser, an image of the membrane could be projected on a white screen, where the interference fringes could be seen clearly. Each dark-to-dark fringe represents a total path length difference of one wavelength ($1\lambda$ = "one lambda") but since

the laser beam has to travel in both directions, before and after reflection, a dark-to-dark distance represents a movement in height of $\lambda/2$ of the membrane. The finest resolvable resolution is between a bright fringe and a dark one, and that represents $\lambda/4$, which for this laser is equivalent to 158.2nm, but in reality it's not possible to pinpoint the exact center of the bright or dark fringes, so the height in each point can not be determined with such precision. However, the integrated height difference over several fringes has the same absolute error margin, because it's only the exact phase that has uncertainty. Each full dark-to-dark center really is 158.2nm apart.

The position of the fringes in a interferogram of a membrane can be predicted if you know the topography of membrane, i.e. the height for each point. From the interferogram it is not trivial to interpret backwards to the topography of the membrane, because it can't be discerned from the fringes whether they represent a positive or negative difference in height. In most cases (except in some inflection points) it should however be possible rule out all but one interpretation of the shape by accepting some reasonable assumptions about the strains and the physical properties of the material, i.e. how the material can bend and how physical objects move. From these you can derive boundary conditions for the first and second order derivatives of the shape. Such an interpretation is not in the scope of this project. The interferograms can still be compared to the predicted interferograms of the modelled membrane in different stages of its motion, to analyse deviations and evaluate the models.

## 2.2 Amount of light

The pre-existing set-up generated a high intensity interferogram. This is easier to accomplish because the membrane is not moving, and a continuous laser can

be used to illuminate the membrane without interruptions. Moving a point of the membrane during the time it takes for the camera to record an image with continuous light (ca 40-70 milliseconds depending on frame rate) will blur the interference fringes in that point. In continuous illumination, a height movement of more than $\lambda/4$ will make the fringes difficult to discern, and at $\lambda/2$ the interference fringes have been smeared to an even intensity and can't be interpreted at all. This time-limit is so short that no camera with such high-speed capacity is available without a very large budget. One available option is to reduce the time that the membrane is illuminated by pulsing the laser so it acts like a stroboscope. The camera will then capture the image during 1/25s but the membrane will only be illuminated during a much shorter time, so only this will be recorded in the image. We can easily produce laser pulses with shorter duration than 1us, and it will be investigated how short pulses are needed and if that results in enough light.

If the pulses are bright and short enough, then the recorded image shows as sharp, high contrast fringes as possible. However, even if the blur from motion is reduced by having short illumination, the thermal noise in the camera and undesired light reaching it from other sources will not decrease, and hence the SNR between bright and dark fringes will drop.

The crucial question is this: is there a "Goldilocks" time for illumination that is long enough to get enough light in the image to cause discernible interference lines over the background noise, but short enough that the membrane doesn't move to far? Obviously, this also depends on the intensity of the laser source, but only intensities available in reasonable price range (ca 10-50mW) are considered, and with higher intensities there might still be trade-offs which diminishes performance.

## 2.3 Multiple Exposures

One possible way to increase the contrast between bright and dark fringes without having longer pulses, is by recording several shots (actuation followed by one delayed laser pulse), each with short pulses, in the same image frame. The time-scale for the membrane to settle had been predicted to be on the order of 1ms, so with a frame rate of 25 fps, you could do up to 40 shots integrated in the same image. This would require that the process is reproducible, but we're counting on that anyway, since a specified delay between actuation and illumination is expected to show the membrane having the same shape. I will investigate if this can indeed be used to increase the contrast without the images becoming blurred by uncertainties in how the membrane moves after subsequent actuations.

The number of shots in one image frame has an upper limit, which is yet to be determined. As long as the membrane has time to come to a rest between consecutive actuations, more shots in one image should just increase the contrast by increasing the bright fringes while not adding to the dark ones, and given that the motion is repeatable the fringes should not smear. However, when the number of shots in each image becomes too large, the time between two shots will become too short for the membrane to come to a rest, the motion will become unpredictable, and the fringes will start to smear or differ from where they are if the membrane had been allowed time to come to a rest. If several shots per frame is practical, I will try to determine the upper limit for a membrane, which translates to the practical settle time for the membrane.

## 2.4 Diode lasers

Laser diodes need a minimum current to start actually lasing. At currents below this threshold current, they act as ordinary LED:s, which means that the light they produce is not coherent, and hence does not produce interference fringes. When a diode laser is configured to be switched on and off with as low latency as possible (to be very responsive to the control signal), its "off" state is set to be the highest current possible without lasing, which still gives off a bit of light. Using a diode laser calibrated like this in this set-up, would mean that the fringes produced by the short laser pulses, might be completely drowned by the non-coherent light produced during all the rest of the time. I will investigate if this setting needs to be modified.

# Chapter 3

# Equipment

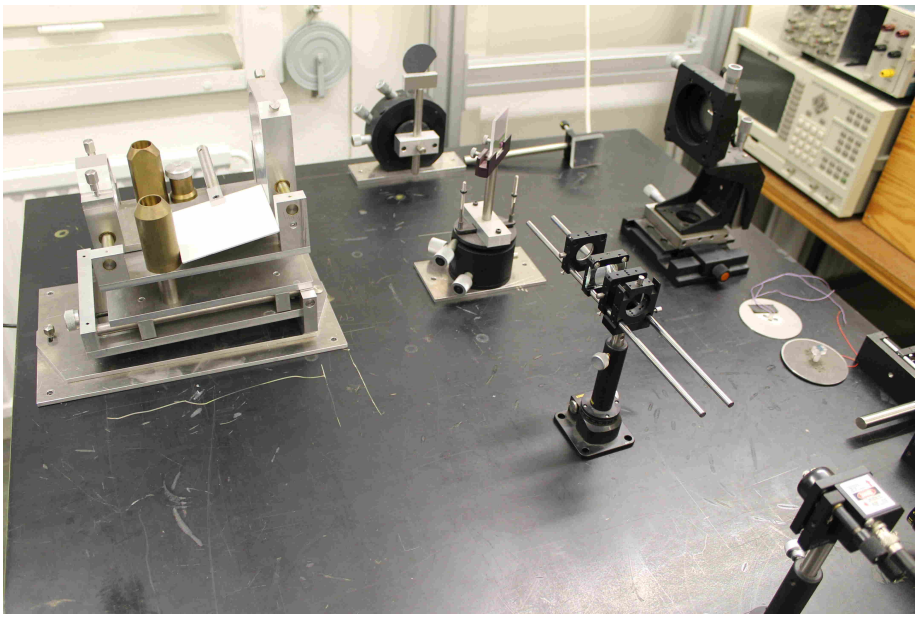

FIGURE 3.1: The setup - a basic interferometer, with a diode laser as light source.

## 3.1 Optical components

### 3.1.1 Laser

The new diode laser with housing, collimator and driver electronics from Thorlabs, model HL6320G. It contains a Hitachi Laser Diode, made of InGaAsP, and it produces 10mW laser light at a wavelength of 635nm (red)-


FIGURE 3.2: The new fast-switching diode laser.

### 3.1.2 Beam expander

A 20x beam expander from Melles Griot, which is used to increase the area that is hit by the beam, so it covers the whole membrane, and the radial intensity profile of the beam is smooth, i.e. the intensity will vary less over different parts of the images.

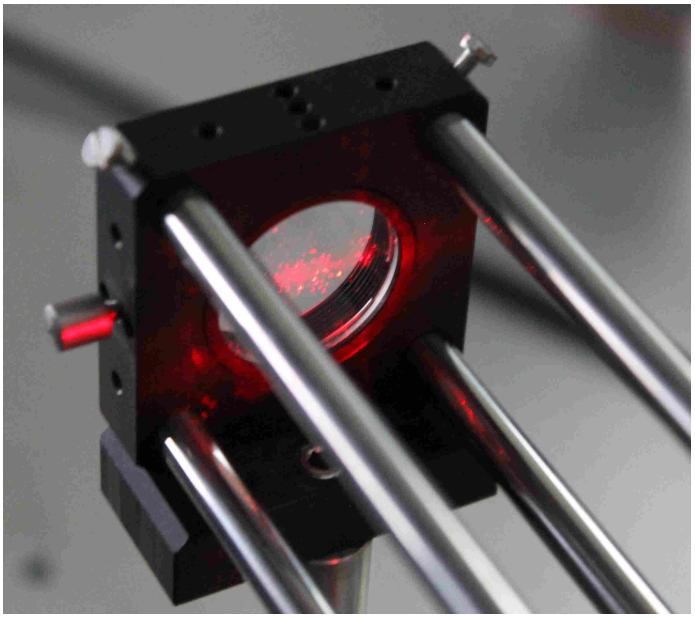

FIGURE 3.3: The initial, self constructed, Beam Expander. At this high intensity the scratches on the cleaned lenses become apparent.

### 3.1.3 Beam Splitter

This is the most important component in any interferometry, and serves two purposes. First, it splits the beam from the laser into two beams which are exactly in phase, and later on it allows the two reflected beams to be mixed together again. It should be ca 50 percent intensity in both beams, but since both legs are transmitted and reflected once each, and it doesn't matter which order the intensity diminishes, the exact reflectivity doesn't matter either.

### 3.1.4 Mirror(s)

In the proof-of-concept set-up, a highly reflective mirror was used. This was later replaced by a 2 inch diameter Silicon wafer, mounted on a metallic holder,

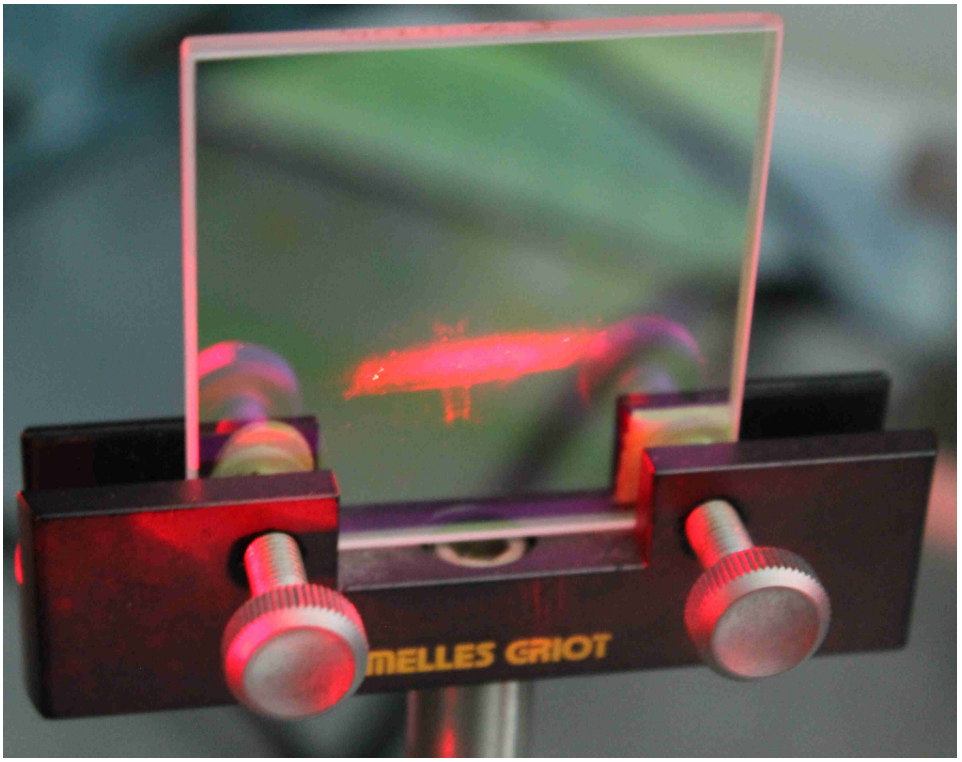


FIGURE 3.4: Beam splitter. Ideally it shouldn't scatter this much light.

which allowed it to be mounted in standard mechanics on the optical table, which allowed it to be angled in both "tilt" and "jaw" directions.

### 3.1.5 Target

This is the membrane that should be imaged, set in a holder with 4 degrees of motion: it translates left/right and up/down relative to the incident beam, and can also be angled in both tilt and yaw.

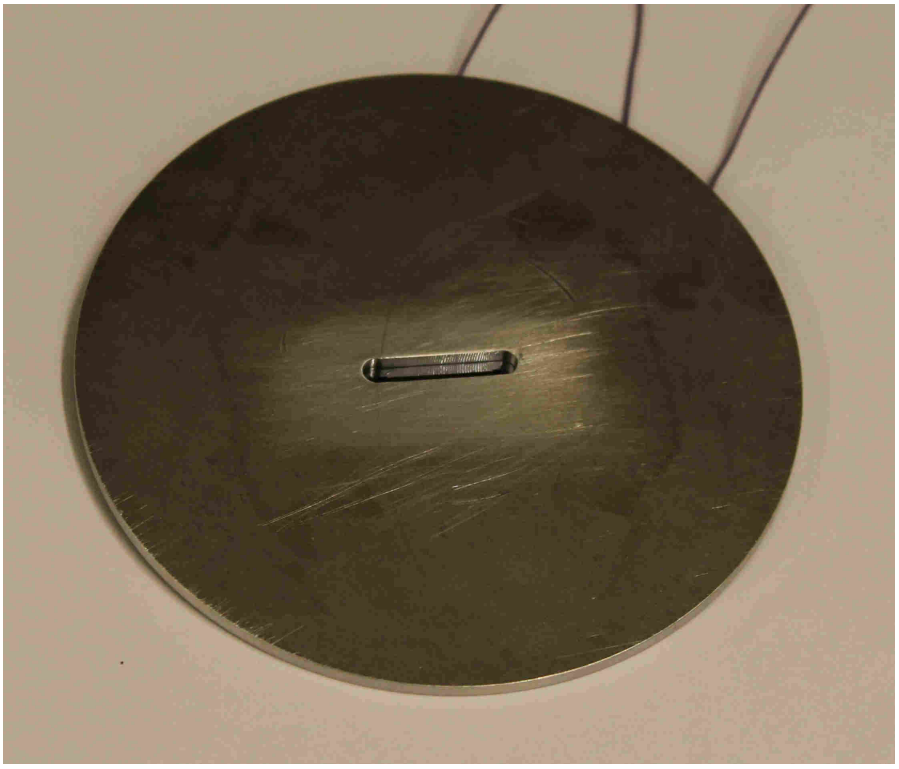

FIGURE 3.5: The target (membrane) mounted on its aluminium back plate.

### 3.1.6 White projection screen

Just a simple white, matte, plastic plate that the laser beam can be projected on. It is also useful to temporarily block a part of the beam path, or protect the camera when you set the laser on full intensity.

### 3.1.7 Microscope

This was used in the beginning of this project, but later on it was eliminated in favor of direct projection on the camera sensor.

### 3.1.8 Microscope "cradle"

While not an optical component as such, it was part of the mechanics used to line up the optics. The pre-existing set-up used a mounted microscope with a camera to record images, but there weren't many degrees of freedom which made the calibration a big hassle. The resulting mixed laser beam had to be directed so the camera could positioned to catch it. A new cradle to mount the camera on was therefore ordered from the faculty tool-smith Lennart Nilsson who then constructed it. The new cradle has a whopping 5 degrees of freedom to center the image better. It translates in 3 perpendicular directions, and can be angled in tilt and roughly in yaw.

### 3.1.9 Shear Plate Collimation Tester

From Melles Griot. This instrument is used to see visually if the beam is collimated, convergent or divergent. The beam is split into two parts that can be seen in the viewing window, and if the beam is large enough for the parts to overlap, the angle of the interference fringes in the overlap region gives a measurement of the collimation.

## 3.2 Electronics

### 3.2.1 Actuator

The actuator on the membrane is pushed by applying a voltage over the connector wires. It is typically operated with a voltage of 60 volts, but in this setup a maximum of 10Vpp was available to drive it. The motion of the membrane is

clearly audible, so when driven with an alternating voltage at audible frequencies, even an amplitude of 10Vpp creates a sound so loud that ear protection is required for working near it for extended periods.

### 3.2.2 Function generator

Tektronix AFG3022B, capable of 250MS/s , with a bandwidth of 25MHz. It has a max output voltage of 10Vpp, which limits the amplitude of the actuator's motion. It was used in the range of 25Hz to 20kHz.

### 3.2.3 Pulse generator for driving the laser

Phillips PM5715 Pulse Generator. It can create pulses from 1Hz to 50MHz. In the set-up the function generator that drove the actuator, also triggered this pulse generator to output its pulse after a manually controllable delay. This delay was set with analog knobs, and the exact delay could not be discerned from this alone.

### 3.2.4 Oscilloscope

A 2-channel digital Tektronix TDS1002 (60MHz , 1GS/s) . This was used for measuring the actual delay of the pulse generator, and the pulse length.

### 3.2.5 Camera

A small USB-connected digital camera from Edmund Optics, capable of 14-25 fps. The specified sensitivity is unknown.

## 3.3 Software

### 3.3.1 Camera driver

Camera driver and demo program: supplied by IDS: Demo program "uEye ActiveX". This had limited functionality, but allowed images to be captured and saved in file formats .bmp, .jpg or .png . Since further manipulation of the images was desired, images were saved in the non-compressed BMP format (BitMaP).

### 3.3.2 Octave

Using the BMP file format for the images, they could be imported to the free math utility software Octave. They could then be analyzed and contrast could be artificially stretched so it is easier to judge with your eyes. The functions used to do this are found in Appendix B and C.

# Chapter 4

# Modifications and optimizations

## 4.1 General improvements to contrast and image quality

To get a sense of what images I could expect in the camera, I had the image be projected on a white screen in front of the camera, and increased the effective intensity of the laser by increasing the pulse length.

As clearly seen, the part of the membrane of highest interest seems very dark, while there is a round halo of scattered light around the image. I believe this is an effect of that part of the membrane being so curved, the reflected light from these parts become so divergent it reduces the intensity. This is a big limitation on what shapes can be imaged, but for this purpose of this thesis, I decided to focus on imaging the parts of the membrane that gave a strong direct reflection.

### 4.1.1 Matching reflectivity

The highly reflective mirror that had been purchased for the proof-of-concept setup was replaced with a simple silicon wafer from the same lab that made the micro-dispensers. This was to lower the reflectance of the mirror to closer match the reflectance of the membrane, so the contrast of the fringes would be greater. The silicon wafer is extremely flat from manufacturing, but since it is very thin it is easily warped by tension. It also cracks very easily. The first wafer was glued into a grove in a holder which could be tilted in both directions, pitch (up/down) and jaw (side to side), but during the 13 year hiatus it had broken. A new wafer was glued into the grove, but within a few days it to was snapped off by accident in the lab. When the large remains of this was glued to the side of the holder for added stability instead of into the groove, the large contact surface connecting it to the holder with the glue warped the wafer visibly, so it became useless. A new wafer was then glued to the other side, and attached only by the tip of a corner, to minimize warp. When this was accidentally snapped off the next day, only a small part of the tip came off, and the rest could be attached anew using the other corner. [IMAGES]

### 4.1.2 Cleaning optics

The optics had been collecting dust for various lengths of time, and all needed cleaning. It took a while before I realized that dirt on the objective of the microscope, which is mounted a bit into the microscope and a bit out of sight, was causing a lot of the artefacts. After I cleaned that carefully, I started to get some interference patterns to speak of. In my quest to clean all optical parts, I unfortunately made the mistake of using ethanol to clean the protective glass in from of the camera sensor, inside the camera. It turned out to not be ethanol

resistant, and the images became misty, and there were more artefacts in the image than before. The glass was removable, but using the camera with the sensor exposed for long periods was not acceptable considering the amount of dust in the environment. I got help by Axel Tojo, who fabricated a new sensor window for me, out of ethanol-resistant polycarbonate. The new window was free from scratches and work could continue.

### 4.1.3 Proper beam expander

When this project was initially started, a very simple beam expander was constructed out of one concave and one convex lens, mounted firmly coaxially. This turned out to then produce a sufficiently collimated, expanded beam, and was used during that part of the project, and it was possible to create interference pattern good enough to see the progression of a membrane movement. After the hiatus, when the setup was reassembled, a similar lens combination was constructed, but interference patterns resulting from mixing the two beams could not be produced. It might be that the lenses are different or that they have been to worn out and scratched, but no matter why, a working beam expander was still needed. I therefore used the best we had available, which was the dedicated 20x BE from Melles Griot, that was used for the HeNe laser in the original set-up.

### 4.1.4 No microscope - direct projection

After the 13 year hiatus, it was found that the optics of the microscope caused so many artefacts that it was much more efficient to project the beam directly on the naked camera sensor. Since the microscope is removed but the degrees

of freedom with the possibility of fine-tuning is still desired, the camera was simply taped in place on the cradle, and the cradle's knobs are used normally. This is much less elegant mounting-wise, but it is effective. At one point, when I was cleaning all the optics with ethanol and paper wipes, I learned that the protective window that covers the camera sensor isn't resistant to ethanol and instead of removing some dust, I ended up creating terrible small scratches and made the surface slightly misty, or milky. The effect on image quality was a disaster. Leaving the image sensor unprotected for long times was unacceptable, so a replacement window was milled from ethanol-resistant polycarbonate, and the image quality was improved to normal as far as I can tell. The original window is visibly tinted, so color representation was probably affected, but in monochromatic light, this is not noticeable. With direct projection on the camera sensor, it was clear that the full projection of the membrane, which is ca 20mm wide, wouldn't fit on the camera sensor all at once. This still seemed like a reasonable trade-off to bypass so many artefacts.

### 4.1.5 Black backplate

While trying to calibrate the set-up to get good images, I kept seeing stray reflections in different places all over the set-up (and quite often they ended up in the camera image) which I traced back to the aluminium back-plate that the membrane is mounted on. Aluminium is a sturdy material to mount things on so I don't want to replace it, but the reflections had a unpredictable effects on the images, so in order to get rid of artefacts from the metallic back-plate, it was painted matte black with model paint.

## 4.2 Imaging the membrane in motion

### 4.2.1 Re-optimized threshold current on laser

The diode laser driver from ThorLabs, that the Hitachi laser diode was mounted in and driven by, was calibrated to respond very quickly, meaning it had an "off" current just below its lasing threshold.
In order to increase the contrast, the threshold current "$I_{thr}$" was therefore simply minimized as much as possible. This is adjustable to the user by a small trim potentiometer on the laser housings side. The light coming from the laser in the off mode was the decreased to undetectable by the camera.

### 4.2.2 Can pulses be made sufficiently short?

The laser pulses that illuminate the membrane must be shorter than the time it takes for membrane to move $\lambda/4$ . There was a concern that any laser pulse that would give enough light to create a detectable pattern in the camera, would have to be so long that the membrane would have time to move significantly and hence be blurred.
Actual pulse shape and length is difficult to measure with the oscilloscope because the control pulse it's so short it was unknown how the laser driver's logic would react to the pulse. An idea was to measure the time profile of the laser intensity directly, and a fast photo diode with only 5ns rise time was obtained to investigate the actual laser pulse, but I didn't have the time to construct the surrounding electronics, and later on the question also lost relevance. Longer laser-pulses are acceptable if the membrane moves with lower velocity=fewer fringe cycles in an image position per second, i.e. lower amplitude, since the frequency shouldn't be different.

### 4.2.3 Repeatability of the membrane's motion

Is the image stable at a later stage of the motion, i.e. given a specified delay between membrane actuation and laser pulse, is the shape always the same (for imaging purposes)? If the interference pattern begin to blur as the delay is increased, this would indivate that the motion isn't identical between different actuations. It was trivial to check that the patterns are stable for at least hundreds of $\mu$s. This led to the following idea and investigation.

### 4.2.4 Multi-exposure

If the motion progresses in the same way during different actuations, it should be possible to record many exposures in the same image frame that the camera snaps. With the camera running at 25 fps, I reduced the laser pulse length to a minimum. I then set the repetition rate of the function generator to frequencies at different multiples of 25Hz and increased it until I first started to see the pattern in the camera image, noticed it become increasingly intense, and then eventually the pattern shifted between two frequency settings, which should represent when the actuations come so short after each other that the membrane hasn't settled since the last one yet. This becomes one of the limiting factors for how many exposures you can get per frame, with frame rate being the other.

# Chapter 5

# Results

## 5.1 General shape of projection

Photos taken of projection on white screen. You can see that the actual membrane part in the middle is dark, and there is a halo around the whole picture. The membrane is probably not very flat, and reflects the light all over.

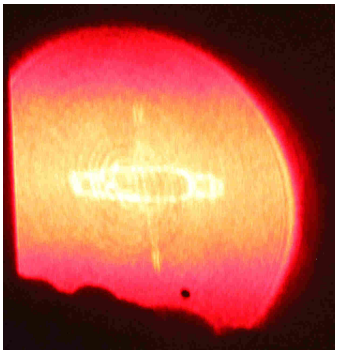

FIGURE 5.1: Projection of the mixed reflections from both mirror and target. Interference patterns are visible, but also lots of other patterns.

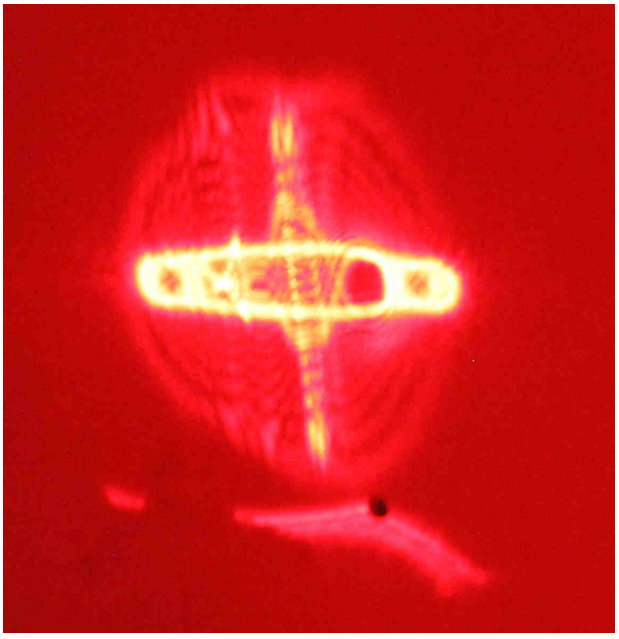

FIGURE 5.2: Projection of just the reflection from the target.A lot of the disturbing patterns come from just this without the "mirror beam" to create interference with the way that was intended.

## 5.2 Through the microscope

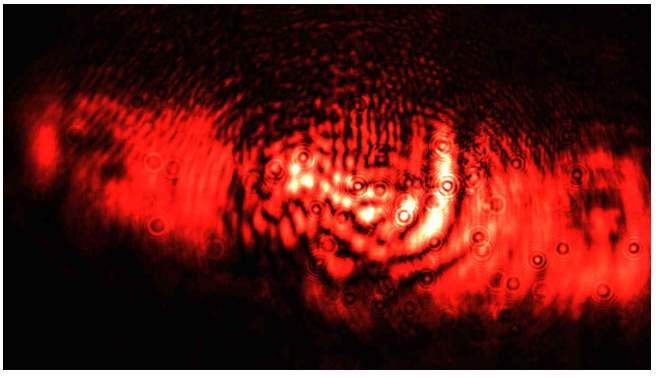

FIGURE 5.3: Image of just the beam from the target, through the microscope after it was cleaned. Still full of artefacts.

## 5.3 Multi exposure, different repetition frequencies

### 5.3.1 Comparison in stretched images

Contrast-stretched. Contrast increases with repetition frequency, but patterns shift at higher frequencies.

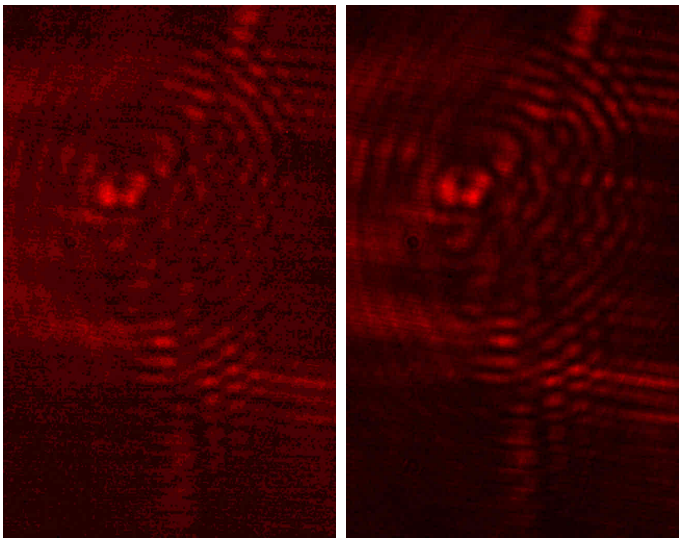

FIGURE 5.4: Difference in contrast between 200Hz and 900Hz. Intensity is normalized.

### 5.3.2 Comparison of Intensity along line

You can see a difference that the pattern starts to shift between 400 and 500Hz. The left peak, representing one of the bright fringes, shifts slightly to the left in the image.

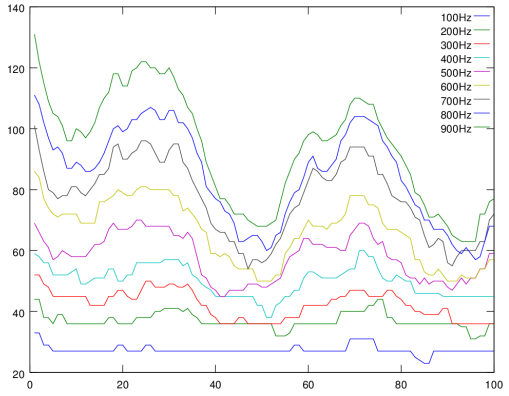


FIGURE 5.5: Intensity along a 9px thick horizontal line in top left corner, for different repetition rates.

## 5.4 Interference sources

With no optics other than the very essential, and using the dedicated beam expander from M-G, the cleanest images possible were recorded. A series of images at different times after actuation were taken to illustrate how well the movement up and down can be pinpointed, even though the complexity of artefacts currently makes it difficult to interpret the actual shape. The pulse is set to the minimum possible by the pulse generator, according to the oscilloscope ca 12-15ns, but this is below its time resolution, so the exact pulse length is unknown. It is also not know how the laser driver reacts on this short an input.

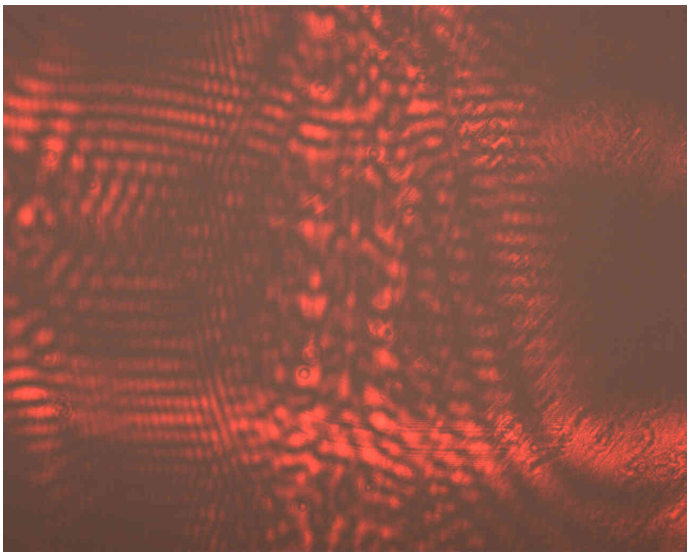

FIGURE 5.6: This is what just the beam from the target looks like, when the beam from the mirror is blocked and there shouldn't be interference fringes. The misty haze is because the cameras sensor window was damaged.

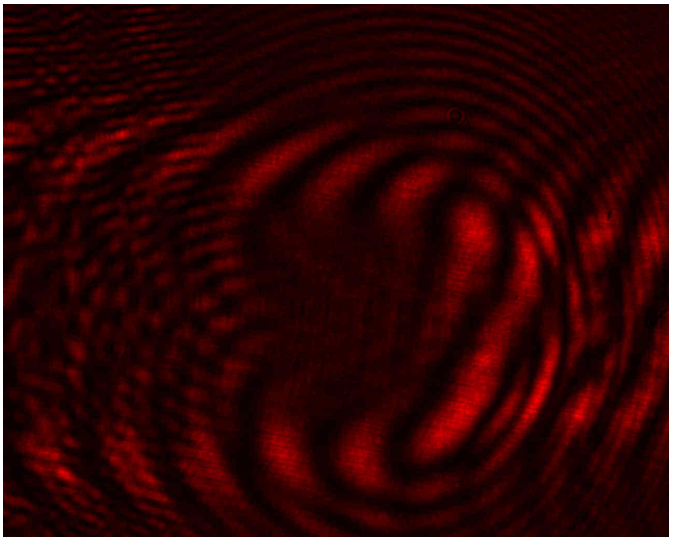

FIGURE 5.7: High contrast interference patterns from mixed beams, with position that varies with time-after-actuation.

# Chapter 6

# Conclusions and Discussion

## 6.1 General

Even if images from different points in time after the actuation produces strong interference patterns, which progress clearly and resolved in time, the artefacts from other sources with this equipment make it difficult to use the resulting images for the intended use. Optical components display scattering scratches that become visible under intense illumination.

## 6.2 The system is fast enough to capture the motion

- It was shown that the movements of the membrane can be imaged with time resolution of the motion at least down to single microseconds.

- It was also demonstrated that this resolution will be sufficient for the intended use in verifying the predicted vibration modes.

- In the trade-off for the pulse length, between the membrane not moving too far during one image, and getting enough light in the image to discern the interference fringes, it turns out that a work-around with multiple exposures in the same image is inherent in the assumption of nearly identical vibrations, i.e. if the membrane always has a certain shape after a specified time, then the contrast can be increased by a factor that's inversely proportional to the settle time for the membrane. For the membrane that was tested, a repetition frequency of 400Hz, but not one of 500Hz or more, could be achieved without difference in the vibration mode compared to lower repetition frequency, and only resulted in more contrast.

- The contrast achieved at the highest repetition rate that preserved the vibration modes was sufficient, even at the shortest selectable laser pulse length, to create discernible fringes in the image frames.

## 6.3 Too many artefacts from current optics

- The images are hard to interpret, not because of problems with the time-resolution or the amount of light required, but because of defects in the optics, and artifacts due to the difficulty in calibrating the optics.

- However, even with quite bad images with lots of artefacts, in which it is difficult to interpret the shape of the membrane, it is still very simple to measure the settle time for the the membrane, by comparing images.

## 6.4 Feasability

A system for dynamic interferometry can be made with a relatively cheap laser and camera, as long as the optics is clean and undamaged enough to make static interferometry. The motion of the membrane during each actuation is so identical, that each point in time after actuation can be imaged separately. Even with affordable laser intensity and camera with normal shutter time, it was possible to generate images of the moving membrane at any point in time, with easily discernible interference fringes.

When the optics was newer, a simple beam expander worked well enough to get strong interference patterns, but after several years of collecting dust and more than a few small scratches, the produced images are so ridden with artefacts they can not be used to verify the shape of the membrane. It becomes apparent that having clean, undamaged optics with as few defects as possible really is important to get good images with few artefacts.

# Chapter 7

# Recommendations for further development

Based on the assumption that you still only have limited budget...

## 7.1 Replace optics

Replace the optical components and get protective storage for all of them. Make sure your cleaning material is doesn't damage it.

## 7.2 Light cover

Build a simple cover to shield off not only ambient light but also to keep dust out. This is especially useful when there are more people attending other things in the same lab, and could also attenuate a the noise from the moving membrane significantly.

## 7.3 Reduce path length

For imaging the highly curved parts of membrane as well, it probably helps to reduce the distance between the membrane and the camera, so the diverging light isn't reduced in intensity as much. To maximize the contrast, an even less reflective mirror would be better suited to cancel out the less intense light.

## 7.4 Customized laser driver

Use better (customized) driver electronics for the laser diode. Take the diode's driver electronics into consideration before designing an input signal. Don't waste money on one carefully calibrated for other applications, where off-light is accepted. Optimize for this purpose, with few, short, intense pulses.

## 7.5 Automated image capture

If you can control the camera driver and save images from an external program, it would be convenient to automate the setting of delays, and collection and processing of images. Even if the camera has a normal slow frame rate, you could easily record a sequence which you would then be able to browse back and forth through at a replay speed of your own choice.

## 7.6 X/y scanner

Build a computer controlled motor driver that can move the camera in two directions, so that the camera sensor can scan the projection i 2 directions.

By controlling this motion from the computer that records images it would be much easier to build a composite image of the full target.

# Appendix A

# Calibrating the setup

This instruction includes steps for sliding individual lenses of the beam expander. That is because the beam expander can be constructed of 2 high quality lenses if such are available. If a dedicated beam expander is available, these steps can be omitted with some reasoning, and the rest of the instruction should still be helpful in adjusting things in the right order. It's recommended to get all the optical components really just as clean as you want them before you start this procedure. It's easier to adjust the angles when the beams go through clean optics, and you're really likely to mess up your calibration when you clean the components in place.

Steps to line up:

## A.1 First line, first leg

1. Laser correct height (if you can't set other heights later due to their restrictions, you might have to start over here). The optimal height is

the average of the mid-range height for the target, and the mid-range heigh of the camera.

2. Position the closest beam expander lens centered in front of the laser aperture.

3. Make the distant beam expander lens centered in height: move BE up/-down to center in

4. height the laser beam from the closest lens, on the holder for the distant lens.

5. Swing BE until closest BE lens is centered in front of laser.

## A.2 First line, second leg

1. Si-mirror: adjust to correct height, so laser beam hits it in flattest part

2. slide the closest lens of the collimator so the laser focuses near the distant side of the distant lens, so it's easier to tell the reflected beam apart from the direct beam.

3. Si-mirror: adjust angles so the beam hits the distant side of the BE lens holder evenly/centered

4. First line is now done and should not be adjusted, only collimated later. reflected laser into cavity accidentally seems ok.

## A.3 Second line, first leg

The pair laser-BS-target and SiM-BS-Camera. If the Si mirror reflects straight back to the laser (it should or the set-up won't work), then this line will be straight regardless of how the BS is tilted and turned. It is roughly perpendicular to the first line, but should now be adjusted so the direct and (SiM) reflected laser beams hit the target and the camera, respectively. The height range is restricted for both.

1. Put the target at it's maximum height.
2. Tilt BS so the beam hits just about a millimeter below the target. Move the target sideways if necessary.
3. Turn the BS so the beam is lined up sideways with the camera, restricted to its degrees of freedom.
4. Move the camera up/down until the beam hits right in through the lens. If the beam is too low for the camera to reach, then tilt the BS until the camera can hit and you get a picture on the image sensor. The beam aimed at the target will now be lower, so (move and) lower the target until the beam hits it straight on.
5. Slide the BE lens to expand the beam to make sure the target is really centered.
6. If the height restriction prevent you from creating a line, they estimate how far from the limit you are, and and how far you are from the middle of the range. Then go back to creating the first line, starting by adjusting the laser height accordingly. Try for "mid range", but as long as you're inside the adjustable range it should work.

## A.4 Second line, second leg

From the target, through he BS, to the camera.

1. Put a screen in front of the camera. Slide the nearest BE lens to focus the laser on the screen. This makes the next step much easier.
2. Adjust the angles of the target to make it coincide on the screen with the beam SiM-BS-camera.
3. Slide the nearest BE lens slightly to expand the beam again.
4. Put the screen "before" the BS, and mount the Collimation Tester between the BE and the BS.
5. If you're not wearing safety glasses yet, you probably want to put them on for this step
6. Crank up he laser good and proper, and line up the CT so the two beam images overlap.
7. In the overlap, look for interference fringes as you slide the nearest BE lens slowly. When you see the fringes, slide the lens until the finges are parallel to the guide line in the CT observation window. The beam should now be collimated and you might want to fix the lens in place. Then remove the CT from the beam.
8. Turn down the intensity
9. Remove the screen from the beam and watch the interference pattern on your computer screen.

# Appendix B

# Octave function contrastStretch

```
function stretchContrastRed(nme)
Iny=zeros(1024,1280,3, "single");
fiver=[2:5:252];
pth="C:/Users/Lars/Documents/ExJobb/img/";
#set your directory where you have your images
I=imread([pth, nme,]);
Ir=single (I(:,:,1));
lowest=single(min(min(Ir)))
highest=single(max(max(Ir)))
fakt=single(255/(highest-lowest))
Irfl=Ir.-lowest;
Irstr=Irfl.*fakt;
Iny(:,:,1)=Irstr;
InyInt=uint8 (Iny);
imwrite(InyInt, [pth, substr(nme,1,-4), "stretched", ".bmp"])
IrLin=Irstr'(:);
```

```
myHistAfter=hist(IrLin,fiver);
ILin=Ir'(:);
myHistBefore=hist(ILin,fiver);

plot(fiver,myHistBefore,"-;before;",fiver,myHistAfter,"+3;after;")
#saveas (1, [pth, "BeforeAndAfter", nme, ".png"]);
endfunction
```

# Appendix C

# Octave function intensityProfile

```
function intensityProfiles
Iny=zeros(1024,1280,3, "single");
x=[1:200];
pth="C:/Users/Lars/Documents/ExJobb/img/";
#set your directory where you have your images

nme="626_0100Hz.bmp";
Ired1=sum(imread([pth, nme,])(296:304,1:100,1));# the selected strip

nme="626_0200Hz.bmp";
Ired2=sum(imread([pth, nme,])(296:304,1:100,1));# the selected strip

nme="626_0300Hz.bmp";
Ired3=sum(imread([pth, nme,])(296:304,1:100,1));# the selected strip

nme="626_0400Hz.bmp";
```

```
Ired4=sum(imread([pth, nme,])(296:304,1:100,1));# the selected strip

nme="626_0500Hz.bmp";
Ired5=sum(imread([pth, nme,])(296:304,1:100,1));# the selected strip
#21
nme="626_0600Hz.bmp";
Ired6=sum(imread([pth, nme,])(296:304,1:100,1));# the selected strip

nme="626_0700Hz.bmp";
Ired7=sum(imread([pth, nme,])(296:304,1:100,1));# the selected strip

nme="626_0800Hz.bmp";
Ired8=sum(imread([pth, nme,])(296:304,1:100,1));# the selected strip

nme="626_0900Hz.bmp";
Ired9=sum(imread([pth, nme,])(296:304,1:100,1));# the selected strip
plot(x, Ired1,"-;100Hz;", x,Ired2,"-;200Hz;", x,Ired3,"-;300Hz;", x,Ired4,"-;400
saveas (1, [pth, "MultiExposuresIntensityProfiles", ".png"]);
endfunction
```