

# **Flow Visualisation by Means Of Electronic Speckle Pattern Interferometry (ESPI)**

**Eli Michal**

A research report submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg in partial fulfillment of the requirements for the degree of Master of Science in Engineering

August, 2007

## **Declaration**

I declare that this research report is my own unaided work. It is being submitted to the Degree of Master of Science to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other university.

---

E. Michal

\_\_\_\_\_ day of \_\_\_\_\_ year 2007



## **Abstract**

This research report details the design, construction, implementation and optimization of a quantitative movable flow visualization technique named Electronic Speckle Pattern Interferometry (ESPI).

ESPI is a powerful visualisation technique that can allow for full flowfield analysis. It is thus possible to quantitatively determine the refractive index variation and hence the density variation in a compressible gas flow.

Complementary results between previous work done and the current work shows the integrity of ESPI results

Flowfields that were investigated included – candle flame, axis symmetric and non-axis symmetric nozzles.

Due to advanced CCD technology, there have been improvements in the overall image quality. Post processing of the images produced clearer images and hence better results.

The technique was applied on multiple test rigs, proving its versatility.

## **Acknowledgments**

I would like to extend my thanks to my supervisor Professor Beric Skews, his constant source of funding and information proved to be invaluable throughout this study.

Thanks are also due to Dr Filipe Barbosa for his support and guidance.

To all students and staff from the flow research group at the University of the Witwatersrand I owe thanks, for their time and advice.

To my current employer Professor Clive Gray, thanks are due for his support and guidance.

Finally thanks are especially due to my parents and siblings especially my father Rabbi Gavin Michal, for his constant practical and physical support in all aspects of design and construction of the numerous experiments conducted.

## Table of Contents

|                                         |                         |
|-----------------------------------------|-------------------------|
| <b><i><u>Declaration</u></i></b>        | <b><i><u>2</u></i></b>  |
| <b><i><u>Abstract</u></i></b>           | <b><i><u>3</u></i></b>  |
| <b><i><u>Acknowledgments</u></i></b>    | <b><i><u>4</u></i></b>  |
| <b><i><u>Table of Contents</u></i></b>  | <b><i><u>5</u></i></b>  |
| <b><i><u>List Of Figures</u></i></b>    | <b><i><u>8</u></i></b>  |
| <b><i><u>List of Symbols</u></i></b>    | <b><i><u>11</u></i></b> |
| <b><i><u>1. Chapter 1</u></i></b>       | <b><i><u>12</u></i></b> |
| Introduction                            | 12                      |
| <b><i><u>2. Chapter 2</u></i></b>       | <b><i><u>13</u></i></b> |
| General Introduction to Interferometry: | 13                      |
| 2.1. Simple harmonic motion             | 13                      |
| 2.2. Superposition of waves             | 14                      |
| 2.3. Intensity                          | 14                      |
| 2.4. Fringes                            | 15                      |
| 2.4.1 Two beam interference images      | 17                      |
| 2.4.2 Correlation fringes               | 18                      |

### **3. Chapter 3** **19**

|                                                   |           |
|---------------------------------------------------|-----------|
| <b>Electronic Speckle Pattern Interferometry</b>  | <b>19</b> |
| 3.1 The speckle effect                            | 19        |
| 3.1.1 Speckle size                                | 20        |
| 3.2 Speckle generators                            | 20        |
| 3.2.1 Angular distribution of the scattered light | 21        |
| 3.3 Speckle recorder                              | 22        |
| 3.4 ESPI set-up                                   | 23        |
| 3.5 Optics calculations                           | 24        |
| 3.5.1 Thin Lens equation                          | 24        |
| 3.5.2 Imaging lens                                | 24        |
| 3.6 Dust Diffraction Patterns                     | 26        |

### **4. Chapter 4** **27**

|                                                   |           |
|---------------------------------------------------|-----------|
| <b>Image processing</b>                           | <b>27</b> |
| 4.1 Interferogram generation by Image subtraction | 27        |
| 4.2 Introduction to pixel size                    | 28        |
| 4.3 Transformations and point processing          | 29        |
| 4.4 Filters                                       | 29        |
| 4.4.1 Linear Filters                              | 30        |
| 4.4.1.1 Spatial Filter                            | 30        |
| 4.4.1.2 Gaussian filters                          | 31        |
| 4.4.2 Non linear filters                          | 32        |
| 4.5 Fourier transforms                            | 32        |
| 4.6 Abel Transform                                | 33        |

## **5. Chapter 5** **35**

|                                          |           |
|------------------------------------------|-----------|
| <b>Experimental Set-up</b>               | <b>35</b> |
| 5.1 Holographic Interferometry           | 35        |
| 5.2 Out of plane interferometer          | 37        |
| 5.2.1 Test specimens                     | 38        |
| 5.2.2 Set-up details                     | 39        |
| 5.2.3 Image processing details           | 40        |
| 5.3 Optimisation of set-up               | 41        |
| 5.3.1 Soldering iron                     | 41        |
| 5.3.2 Candle                             | 42        |
| 5.4 Axis-symmetric Air compressor Nozzle | 48        |
| 5.5 Rocket Nozzle                        | 50        |
| 5.6 Non axis-symmetric nozzle            | 51        |
| 5.7 Missile Geometry                     | 57        |

## **6. Chapter 6** **61**

|                               |           |
|-------------------------------|-----------|
| <b>Results and discussion</b> | <b>61</b> |
| 6.1 Soldering Iron            | 61        |
| 6.2 Candle                    | 62        |
| 6.2.1 Calculations            | 62        |
| 6.2.2 Analysis                | 65        |
| 6.3 Air Compressor Nozzle     | 68        |
| 6.4 Non axis-symmetric jet    | 71        |

## **7. Chapter 7** **73**

|                   |           |
|-------------------|-----------|
| <b>Conclusion</b> | <b>73</b> |
|-------------------|-----------|

## **References** **74**

## List Of Figures

|                                                                                                                                                                                        |           |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------|
| <i>Figure 2.1 – Constructive and Destructive Interference .....</i>                                                                                                                    | <i>14</i> |
| <i>Figure 2.2 – Circular waves expanding outward.....</i>                                                                                                                              | <i>15</i> |
| <i>Figure 2.3 – Viewing screen placement.....</i>                                                                                                                                      | <i>15</i> |
| <i>Figure 2.4 – Two beam interference of two plane wavefronts .....</i>                                                                                                                | <i>17</i> |
| <i>Figure 3.1 – a) Formation of objective speckle b) Formation of subjective speckle ..</i>                                                                                            | <i>20</i> |
| <i>Figure 3.2 – Speckle field diffuser with intensity distribution .....</i>                                                                                                           | <i>21</i> |
| <i>Figure 3.3 – Intensity vs. Divergence angle</i><br><i>(<a href="http://www.rpcphotonics.com/engineer_diffuser.htm">http://www.rpcphotonics.com/engineer_diffuser.htm</a>) .....</i> | <i>22</i> |
| <i>Figure 3.4 – ESPI Set-up .....</i>                                                                                                                                                  | <i>23</i> |
| <i>Figure 3.5 – Thin lens.....</i>                                                                                                                                                     | <i>24</i> |
| <i>Figure 3.6 – Imaging lens .....</i>                                                                                                                                                 | <i>25</i> |
| <i>Figure 3.7 – Dust Diffraction Patterns (Klein, 1970) .....</i>                                                                                                                      | <i>26</i> |
| <i>Figure 4.1 – Transformation.....</i>                                                                                                                                                | <i>29</i> |
| <i>Figure 4.2 – a) Original pixel values with mask applied b) Output matrix.....</i>                                                                                                   | <i>30</i> |
| <i>Figure 4.3 – a) Unfiltered Image b) Filtered image using Gaussian blur.....</i>                                                                                                     | <i>31</i> |
| <i>Figure 4.4 – Image matrix.....</i>                                                                                                                                                  | <i>32</i> |
| <i>Figure 4.5 – 3 x 3 mask.....</i>                                                                                                                                                    | <i>32</i> |
| <i>Figure 4.6 – Light ray passing through test field.....</i>                                                                                                                          | <i>33</i> |
| <i>Figure 5 – Holographic Interferometry set-up.....</i>                                                                                                                               | <i>35</i> |
| <i>Figure 5.1 ESPI Set-up .....</i>                                                                                                                                                    | <i>37</i> |
| <i>Figure 5.2 – Spatial Filter and Beamsplitter .....</i>                                                                                                                              | <i>39</i> |
| <i>Figure 5.3 – ESPI image of soldering iron .....</i>                                                                                                                                 | <i>41</i> |
| <i>Figure 5.4 – ESPI Set-up with candle.....</i>                                                                                                                                       | <i>42</i> |
| <i>Figure 5.5 – ESPI candle interferogram .....</i>                                                                                                                                    | <i>43</i> |

|                                                                                           |           |
|-------------------------------------------------------------------------------------------|-----------|
| <i>Figure 5.6.....</i>                                                                    | <i>44</i> |
| <i>Figure 5.7.....</i>                                                                    | <i>45</i> |
| <i>Figure 5.8 a) Speckle pattern after paste applied    b) Before paste applied .....</i> | <i>46</i> |
| <i>Figure 5.9 – Subtracted ESPI image using the newly ground glass .....</i>              | <i>46</i> |
| <i>Figure 5.10 – Candle Flame with best ground glass.....</i>                             | <i>47</i> |
| <i>Figure 5.11 – Nozzle with a jet exiting .....</i>                                      | <i>48</i> |
| <i>Figure 5.12 – Nozzle interferogram .....</i>                                           | <i>49</i> |
| <i>Figure 5.13 – Rocket Nozzle Interferogram.....</i>                                     | <i>50</i> |
| <i>Figure 5.14 – Shock cells.....</i>                                                     | <i>50</i> |
| <i>Figure 5.15 – Non axis-symmetric nozzle .....</i>                                      | <i>52</i> |
| <i>Figure 5.16 – Candle illustrating fringes .....</i>                                    | <i>52</i> |
| <i>Figure 5.17 – Improved image with fringes.....</i>                                     | <i>53</i> |
| <i>Figure 5.18 – Constant fringes.....</i>                                                | <i>54</i> |
| <i>Figure 5.19 – Refocused image.....</i>                                                 | <i>54</i> |
| <i>Figure 5.20 – Refocused image after pressure increase.....</i>                         | <i>55</i> |
| <i>Figure 5.21 – Refocused image with fringes.....</i>                                    | <i>55</i> |
| <i>Figure 5.22 – Higher fringe resolution.....</i>                                        | <i>56</i> |
| <i>Figure 5.23 – Best fringes .....</i>                                                   | <i>56</i> |
| <i>Figure 5.24 – Super Sonic Blow Down Tunnel.....</i>                                    | <i>57</i> |
| <i>Figure 5.25 – ESPI supersonic set-up .....</i>                                         | <i>58</i> |
| <i>Figure 5.26 – Candle Interferogram without fringes .....</i>                           | <i>58</i> |
| <i>Figure 5.27 – Candle Interferogram with Fringes .....</i>                              | <i>59</i> |
| <i>Figure 5.28 – Missile Interferogram .....</i>                                          | <i>60</i> |
| <i>Figure 6.1 – Comparative pictures.....</i>                                             | <i>61</i> |
| <i>Figure 6.2 – Filtered pictures .....</i>                                               | <i>62</i> |

|                                                                                         |    |
|-----------------------------------------------------------------------------------------|----|
| <i>Figure 6.3 - Holographic Interferogram of a candle flame (Vest, 1977)</i> .....      | 63 |
| <i>Figure 6.4 – Original image</i> .....                                                | 64 |
| <i>Figure 6.5 – Filtered Image</i> .....                                                | 64 |
| <i>Figure 6.6 – Cropped image</i> .....                                                 | 65 |
| <i>Figure 6.7 – Candle with flame colours</i> .....                                     | 65 |
| <i>Figure 6.8 – Superposition of candle images with fringes</i> .....                   | 66 |
| <i>Figure 6.9 – Nozzle Interferogram with different filtering techniques</i> .....      | 68 |
| <i>Figure 6.10 – Underexpanded jet with a large pressure ratio (John, 2006)</i> .....   | 69 |
| <i>Figure 6.11 – A Mach Reflection at a plane wall (John, 2006)</i> .....               | 69 |
| <i>Figure 6.12 – Nozzle interferogram for an underexpanded axis-symmetric jet</i> ..... | 70 |
| <i>Figure 6.13 – Traced fringes</i> .....                                               | 70 |
| <i>Figure 6.14 – Non axis symmetric Interferograms</i> .....                            | 71 |
| <i>Figure 6.15 – Circular orifice nozzle interferogram (Van Dyke, 1982)</i> .....       | 72 |



## List of Symbols

Due to the interchangeability of symbols, only the main ones are identified below. The others are highlighted in the text

$\lambda$  - Wavelength of light

$I$  – Intensity

$n$  – Refractive index

$P$  – Pressure

$R$  – Gas Constant

$T$  – Temperature

$\rho$  - Density

$N$  – Number of fringes

# 1. Chapter 1

## *Introduction*

Flow visualisation is a vast field comprising of many different techniques. These can be divided into two main categories:

Qualitative  
Quantitative

The qualitative techniques that are generally employed (Shadowgraph, Schlieren), can only yield results that identify what the flow appears like. However quantitative flow visualisation reveals data about the flow. This report deals with the latter as it is a powerful visualisation technique that can allow for full flowfield analysis.

The original research topic that was to be investigated was that of holographic interferometry, which included the recommissioning of the double pulsed ruby laser housed in the Flow Research Group at the University of The Witwatersrand.

After many attempts the pulsed ruby laser was found to be unrepairable and therefore the research topic had to be changed to that of Electronic Speckle Pattern Interferometry (ESPI). The purpose of this was to establish the ESPI set-up and to improve upon previous work done. Improvements included being able to move the ESPI rig to different test locations, as well as enhancing the resolution of the pictures taken previously. Previous ESPI rigs had been set up with older digital camera technology, and with the rapid advances in CCD technology in the past 5 years, it was decided to use ESPI with these new CCD chips.

Several flowfields were investigated and their temperature and gradient profiles were recorded using ESPI. Post processing allowed for optimisation of the image.

Chapters 2 to 4 give a holistic literature review of ESPI:

Chapter 2 outlines general interferometric principles used in ESPI as well as other interferometric techniques.

Chapter 3 details the specifics relating to ESPI; it includes the speckle effect as well as all the optical components needed.

Chapter 4 highlights the main image processing techniques used in ESPI.

Chapters 5 to 7 detail the experiment and analysis of the results.

Chapter 5 outlines the experimental procedure used including preliminary results, and the different test specimens that were investigated. It also details the optimisation process followed for the ESPI set-up.

Chapter 6 details the analysis of the results and Chapter 7 concludes the report.

## 2. Chapter 2

### ***General Introduction to Interferometry:***

A general introduction to interferometry is presented below, for an in-depth study consult listed references by Fomin (1998), Merzkirch (1987) and Vest (1977).

#### **2.1. Simple harmonic motion**

When light is propagated through a medium such as air it is assumed to exhibit simple harmonic amplitude variations, this is due to the fact that light is considered to be an electromagnetic wave with the form of:

$$y = A \sin\left(\frac{2\pi}{\lambda} x\right) \quad (2.1)$$

Where:

A = amplitude of the wave  
 $\lambda$  = wavelength of the light

Now if the wave moves to the right with a velocity  $v$  then equation 2.1 becomes:

$$y = A \sin\left(\frac{2\pi}{\lambda}\right)(x - vt) \quad (2.2)$$

In order for interferometry to occur one has to have two coherent light beams interfering, as interferometry relies upon the fact that these two beams will interfere and either superpose or subtract from one another, resulting in fringe patterns. This is due to the fact that *their amplitudes combine and thus* due to the phase changes that occur (between the two combining waves) they can then combine to interfere as opposed to incoherent light sources that will interfere due to intensity as opposed to amplitude. (Tolansky, 1973)

The general expression for a sinusoidal wave is given by:

$$y = A \sin(kx - \omega t + \phi) \quad (2.3)$$

Where:

$k$  = angular wave number  
 $\omega$  = angular frequency  
 $\phi$  = phase constant

## 2.2. Superposition of waves

Since interferometry records both the amplitude (intensity) of the wave and the phase change, one therefore has to superpose two light waves in order to derive interferometric results.

Two individual wave functions, which differ in phase but are the same in both amplitude, frequency and wavelength can be written as:

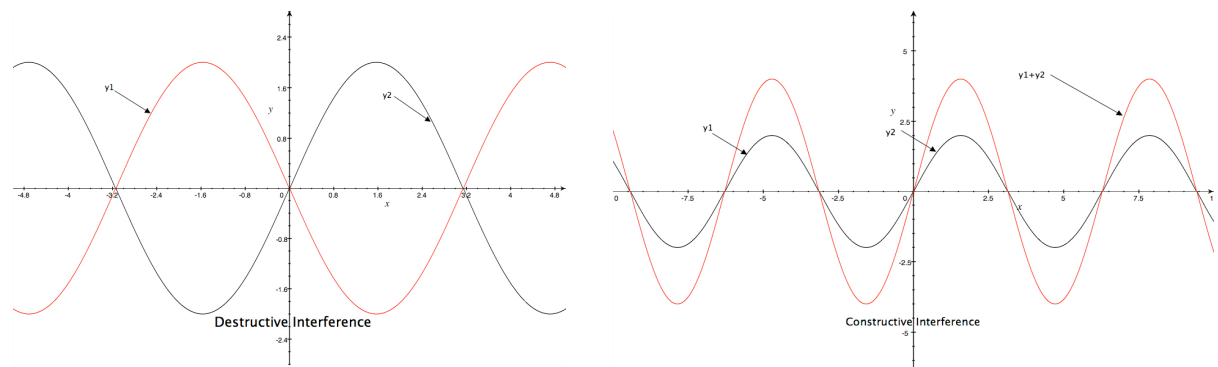
$$y_1 = A \sin(kx - \omega t)$$

$$y_2 = A \sin(kx - \omega t + \phi)$$

Combining both those equations results in:

$$y = 2A \cos\left(\frac{\phi}{2}\right) \sin\left(kx - \omega t + \frac{\phi}{2}\right) \quad (2.4)$$

The amplitude is therefore  $2A \cos(\frac{\phi}{2})$  and depending what the phase constant is will determine whether or not the waves have constructive or destructive interference.



**Figure 2.1 – Constructive and Destructive Interference**

## 2.3. Intensity

Intensity ( $I$ ) of the wave is directly proportional to the square of the amplitude (Smith, 2001) of the wave function. Since the amplitude is  $2A \cos(\frac{\phi}{2})$  and  $\cos \phi$  will fluctuate between +1 and -1, resulting in  $I$  varying from  $4A^2$  to 0.

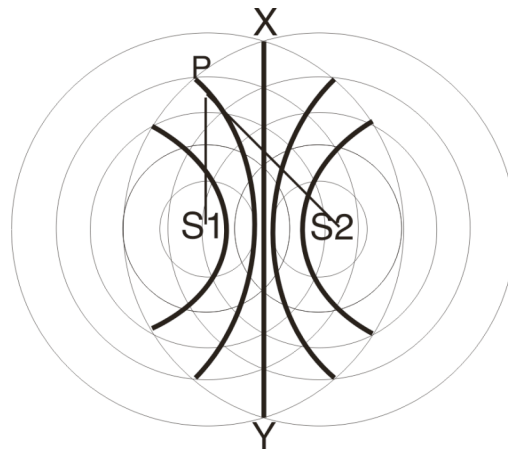
In order for  $I$  to be a maximum  $\cos(\frac{\phi}{2})$  must equal one resulting in  $\phi = 0^\circ$ , and hence for  $I$  to be a minimum  $\phi = 180^\circ$

Therefore for  $\phi = 0^\circ, 360^\circ, 720^\circ$  etc.  $I$  will be a maximum (i.e.  $4A^2$ ), and for  $\phi = 180^\circ, 540^\circ, 900^\circ$  etc  $I$  will be a minimum (i.e. 0).

Therefore the waves will superpose to a maximum when they are in phase, and will form a zero effect when they are  $180^\circ$  out of phase.

## 2.4. Fringes

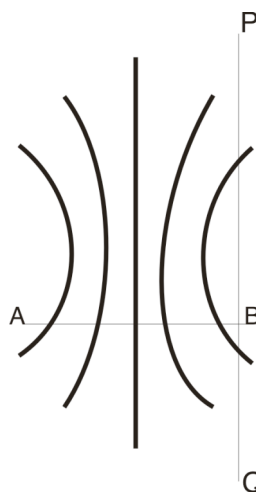
In order to understand how fringes are formed it is useful to think of it in terms of a hydrodynamical analogy.



**Figure 2.2 – Circular waves expanding outward**

As explained in Tolansky (1973), it is useful to think of light and optics in the same manner as hydrodynamics. As if two needles (attached the ends of a tuning fork) are dipped into water, each needle will then produce its own circular wave patterns which will be in phase with each other.

Therefore consider figure 2.2. Sources S1 and S2 produce circular waves spreading outwards. Let each circle be a peak of the wave and therefore when these waves intersect they will be interfering at a maxima (outlined by the heavy black lines in figure 2.2)



**Figure 2.3 – Viewing screen placement**

Figure 2.3 shows the formation of fringes and how the placement of the viewing screen will affect the shape and size of the fringes formed. The viewing screen is what will allow for visualisation of the fringes, i.e. the projection of the fringes onto a screen at a specific point will produce specific types of fringes, i.e. if the viewing screen is placed in the A-B direction straight narrow fringes will be formed whereas if the viewing screen is placed in the P-Q direction circular thick fringes will be formed.

In order to produce fringes there has to be changes in phase between the two wave fronts i.e. two waves must intercept and produce either constructive or destructive interference. Placement of the viewing screen will affect the shape of the fringes formed (Figure 2.3)

Visibility of the fringes depends upon the intensities of the different light waves, therefore:

$$V = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} \quad (2.5)$$

As described in section 2.3 the total intensity is given by:

$$I = 4A^2 \cos^2\left(\frac{\phi}{2}\right) \quad (2.6)$$

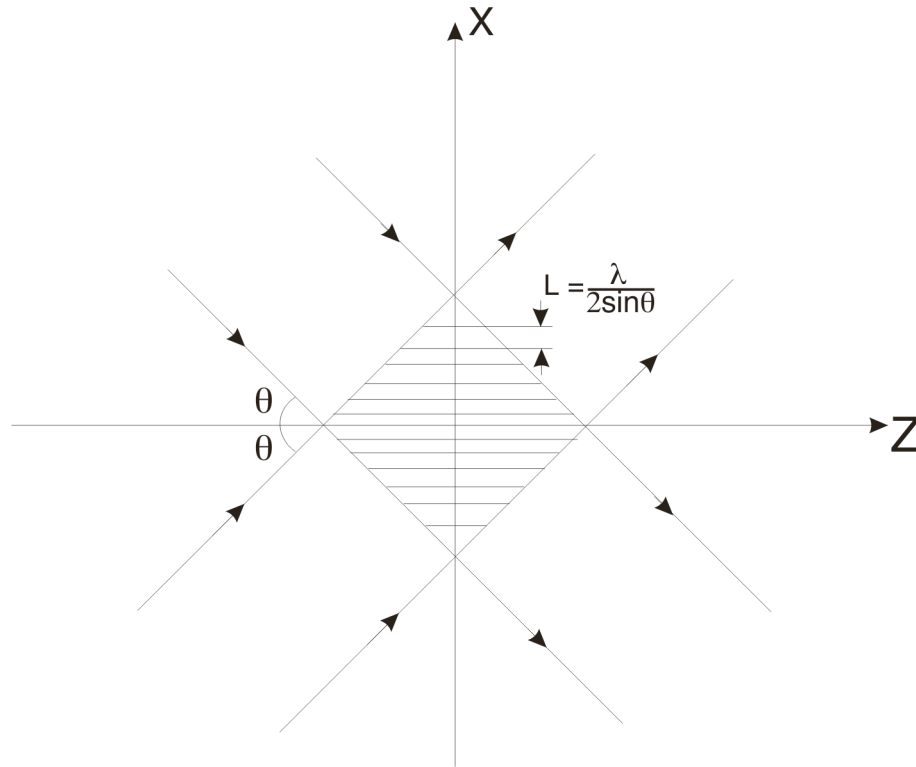
The above equation yields a cosine curve and therefore the intensity of these light waves will form fringes known as *cos squared* fringes.

The above solution holds only true if the amplitude of the light waves are the same, however if they are not, complex number representation of light waves is needed.

This results in the following equation (Jones & Wykes, 1989):

$$I_T = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos(\phi_1 - \phi_2) \quad (2.7)$$

### 2.4.1 Two beam interference images



**Figure 2.4 – Two beam interference of two plane wavefronts**

If two plane wavefronts interfere they will have the following intensity function (Jones & Wykes, 1989):

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos\left(\frac{4\pi}{\lambda} x \sin \theta\right) \quad (2.8)$$

resulting in the fact that the intensity function will vary sinusoidally from  $I_1 + I_2 + 2\sqrt{I_1 I_2}$  to  $I_1 + I_2 - 2\sqrt{I_1 I_2}$ , thus forming a fringe pattern.

### 2.4.2 Correlation fringes

Correlation fringes will occur when two waves which have the same phase interfere, this is given by the following equation (Jones & Wykes, 1989):

$$\Delta\phi = 2N\pi \quad (2.9)$$

Where:

$N$  = Fringe number

Therefore the fringes will be uncorrelated when:

$$\Delta\phi = (2n + 1)\pi$$

Therefore one can quantitatively determine the density of the air (due to the number of fringes), by making use of the following relationships:

The Gladstone Dale equation states that the refractive index of a gas is directly proportional to its density (Fomin, 1998):

$$n - 1 = k\rho \quad (2.10)$$

Where:

$n$  = Refractive index of the gas

$k$  = Gladstone Dale constant

The phase difference between two different states of a gas is given by (Jones & Wykes, 1989):

$$\Delta\phi(y) = \frac{2\pi}{\lambda}(n_2 - n_1)dy \quad (2.11)$$

Where  $n_2$  represents the refractive index of the gas once it has been disturbed and  $n_1$  represents the refractive index before disturbance,  $dy$  is the length of the disturbed field.

By substitution of equations 2.9 and 2.11, the following relationship is derived:

$$N = \left( \frac{n_2 - n_1}{\lambda} \right) dy \quad (2.12)$$

Where  $N$  is the number of fringes.

Therefore once an interferogram has been taken, and the number of correlation fringes have been counted, the refractive index, and hence the density, of the disturbed gas can then be calculated.



### 3. Chapter 3

#### ***Electronic Speckle Pattern Interferometry***

The discussion of ESPI will be limited to those of out of plane displacement interferometers. A brief description of the speckle effect will be explained as well as design considerations.

In order to produce speckle interferograms the following components are needed (Fomin, 1998).

Light source and optics (Laser, mirror's, beamsplitters etc)

Speckle field generators (Ground glass)

Speckle field recorders (CCD camera)

Automated data processing system (Image processing software, e.g. Matlab)

#### **3.1 The speckle effect**

Any surface illuminated by a laser beam (coherent light source), exhibits speckle. Speckle is best described as having a granular appearance. This speckle effect only occurs on optically rough surfaces, laser speckle will occur randomly on this surface and its intensity will vary along its scattered path.

In order for speckle formation to occur the following conditions must take place (Fomin, 1998):

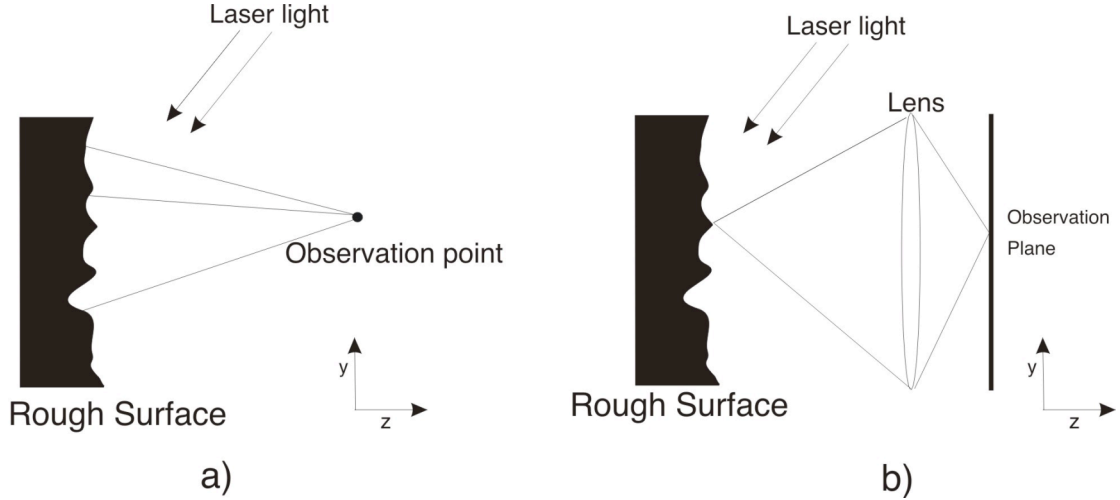
The light must be perfectly coherent

The rough surface must introduce phase fluctuations greater than  $2\pi$

The surface must not depolarize the light

A large number of scattering centers must contribute to the intensity at the point in the observation plane.

There are two types of speckle that can be formed, namely objective and subjective speckle (Figure 3.1). Objective speckle is speckle as described in the above paragraph, whereas subjective speckle is when an imaging lens is added to the abovementioned system.



**Figure 3.1 – a) Formation of objective speckle b) Formation of subjective speckle**

### 3.1.1 Speckle size

Objective and subjective speckle will form different sizes; thus the size of objective speckle (Figure 3.1 a) is given by (Fomin, 1989):

$$\sigma_{sp} = 1.22\lambda \frac{z}{D} \quad (3.1)$$

Where  $z$  is the distance from the rough surface to the observation point and  $D$  is the diameter of the illuminated section on the rough surface.

Subjective speckle is formed when an imaging lens is added to the system (Figure 3.1 b) with a finite aperture, the size of the averaged speckle is governed by the aperture ratio ( $F$ ) of the lens and the magnification ( $M$ ) of the system (Fomin, 1989) Therefore:

$$\sigma_{subj} = 1.22\lambda(1 + M)F \quad (3.2)$$

Thus it is possible to adjust the speckle size by modifying the aperture ratio of the lens. In ESPI one tries to make the speckle size approximately equal to the pixel size of the CCD array (Andrag, 2000).

## 3.2 Speckle generators

In order to produce the speckle an optically rough surface is needed whose surface roughness is greater than that of the wavelength of the laser light being used.

In order to produce the speckle effect a diffuser has to be introduced in the path of the coherent light beam.

Etched ground glass can be used as an optical diffuser (Andrag, 2000). The glass is etched by means of hydrofluoric acid. Ground glass is placed in this acid bath for a set time period, with one side covered by wax. This will then create an optical diffuser with one side of the ground glass having a different surface roughness to the other (Dyson, 1959), the degree of surface roughness will be determined by how long the glass is left in the acid bath.

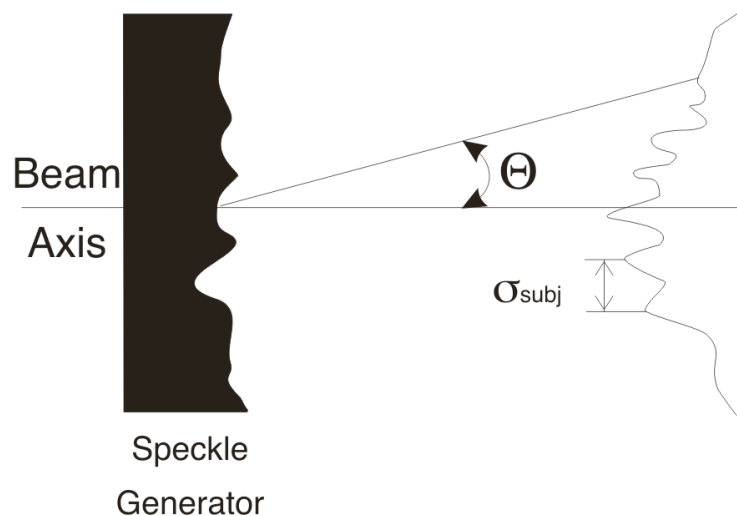
Sandblasting of the one side will also enable the ground glass to act as a diffuser.

Another method, which photographers use to produce optical diffusers, makes use of two pieces of glass and placing the one piece on a flat surface and then wetting the glass and adding 600 grit carborundum abrasive powder onto the glass. The other piece of glass is placed above it now and grinding then occurs between the two surfaces (Klein panorama magazine, 1998).

Fomin (1998) discusses other techniques that can be applied

### 3.2.1 Angular distribution of the scattered light

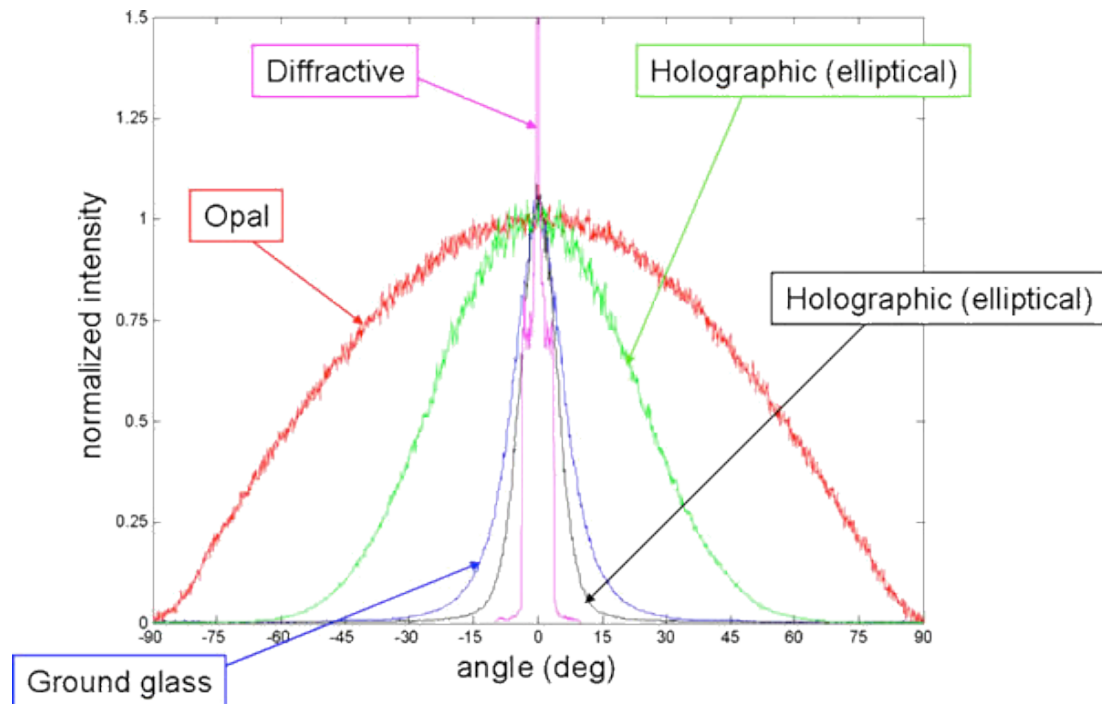
The mean intensity of the light is inversely proportional to the angle at which it is emitted from the speckle generator (Figure 3.2).



**Figure 3.2 – Speckle field diffuser with intensity distribution**

Therefore as the polar angle  $\theta$  increases the intensity of the emitted light will decrease. In order to diffuse the light so that it has the right peak intensity, the diffuser must therefore not increase this angle over a critical limit.

As the light generally used in ESPI is of a collimated nature, a mid range diffuser such as ground glass can therefore be used, as the divergence angle  $\theta$  will have a low value.



**Figure 3.3 – Intensity vs. Divergence angle**  
[http://www.rpcphotonics.com/engineer\\_diffuser.htm](http://www.rpcphotonics.com/engineer_diffuser.htm)

Figure 3.3 illustrates how the peak mean intensity differs for different types of diffusers at different divergence angles, as one can see, the maximum divergence angle for ground glass must be  $\pm 7.5^\circ$ , in order for it to be used as a speckle generator. The two different graphs for the holographic diffusers represent results from two different manufacturers.

The ground glass diffuser tends to have a Gaussian profile (figure 3.3). For an in-depth analysis of the angular distribution of scattered light consult Fomin (1998).

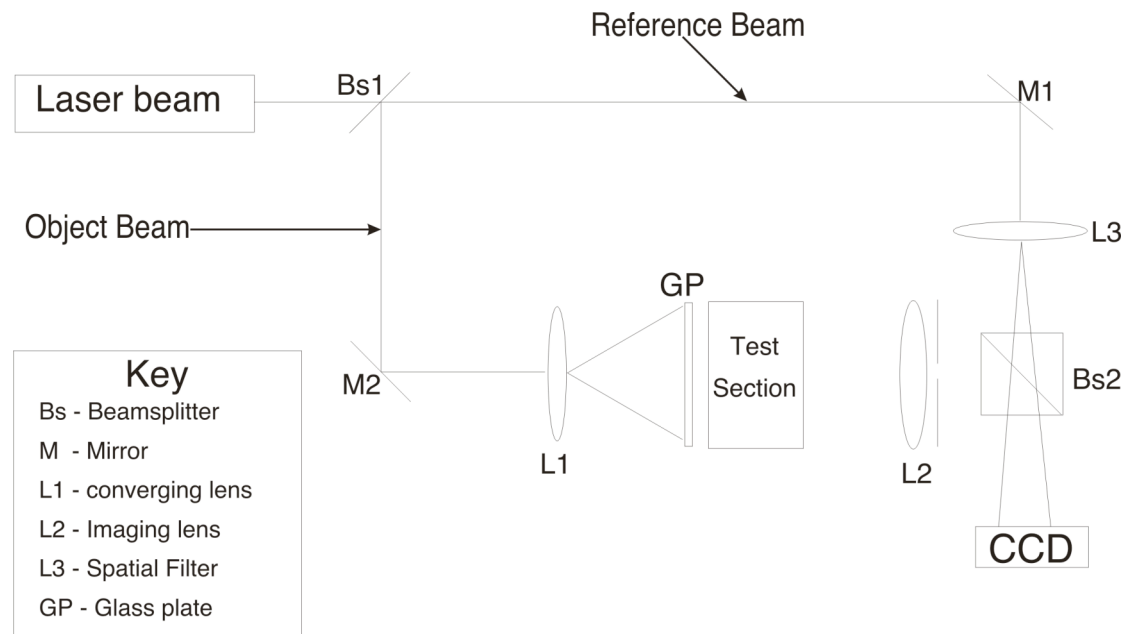
### 3.3 Speckle recorder

In order to record the speckle patterns photographic techniques need to be employed. Before the advent of digital cameras specklegrams were taken using photographic films or plates. In holographic interferometry film and plates are still used extensively.

CCD (charge coupled device) cameras are the most commonly used recording devices in ESPI. In the last ten years these cameras have advanced rapidly.

A CCD is generally a two-dimensional metal-oxide-semiconductor rectangular array of closely spaced independent sites (pixel), which allow for a photon-induced charge to be stored and then read into memory (Fomin, 1998).

### 3.4 ESPI set-up



**Figure 3.4 – ESPI Set-up**

Figure 3.2 illustrates a typical ESPI set-up; monochromatic coherent light (laser beam) is directed into a variable beamsplitter, which then allows for the light to be split into two beams, namely the reference beam and the object beam. The object beam is the one in which the test section is placed and the reference beam is the beam to which no changes occur.

L1 is a diverging lens, which allows for the light to then be distributed uniformly across a ground glass plate. The test section is placed after the glass plate.

L2 acts as the imaging lens for the system. Its job is two fold it redirects the light onto the CCD chip and determines the mean speckle size in conjunction with the aperture.

L3 enables the light from the reference beam to diverge from the center of the viewing lens aperture, this enables interference between the object and reference beams.

Bs2 is a non-polarizing beamsplitter, which combines both the object and reference beams and redirects them both onto the CCD chip, this allowing for interference to occur between the two beams.

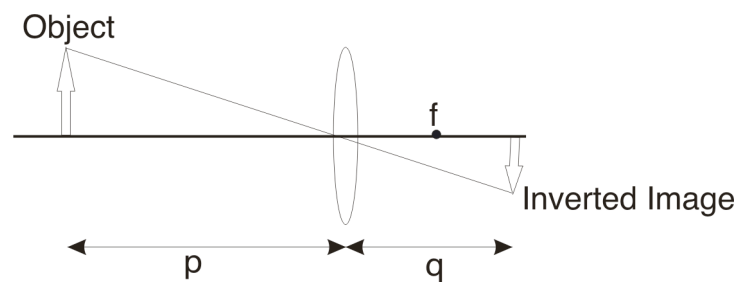
### 3.5 Optics calculations

The following calculations illustrate the steps needed in designing a basic ESPI set-up. Calculations of the following will be done:

Reference beam expansion  
Object beam expansion  
Speckle size determination  
Imaging lens

#### 3.5.1 Thin Lens equation

The thin lens equation will be used to determine the distances and focal lengths of the optics used in the ESPI system.



**Figure 3.5 – Thin lens**

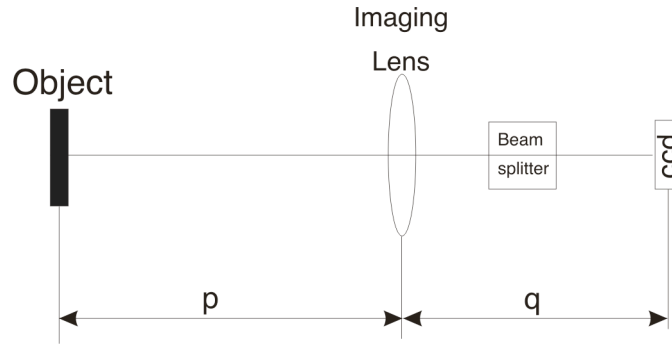
By means of the thin lens (Figure 3.5) equation it is known that:

$$\frac{1}{p} + \frac{1}{q} = \frac{1}{f} \quad (3.3)$$

#### 3.5.2 Imaging lens

The imaging lens is used to refocus the object beam onto the CCD chip.

The following calculations outline the necessary steps taken when designing the imaging lens system.



**Figure 3.6 – Imaging lens**

The magnification of the system is given by the diameter of the CCD chip divided by the diameter of the image.

$$M = -\frac{q}{p} \quad (3.4)$$

The relative position of the image whether it be upright or inverted will not affect the results of these calculations and therefore the minus sign in the above equation can be ignored.

Combining equations 3.3 and 3.4 produces the following equations:

$$\frac{q}{f} = 1 + M \quad (3.5)$$

and:

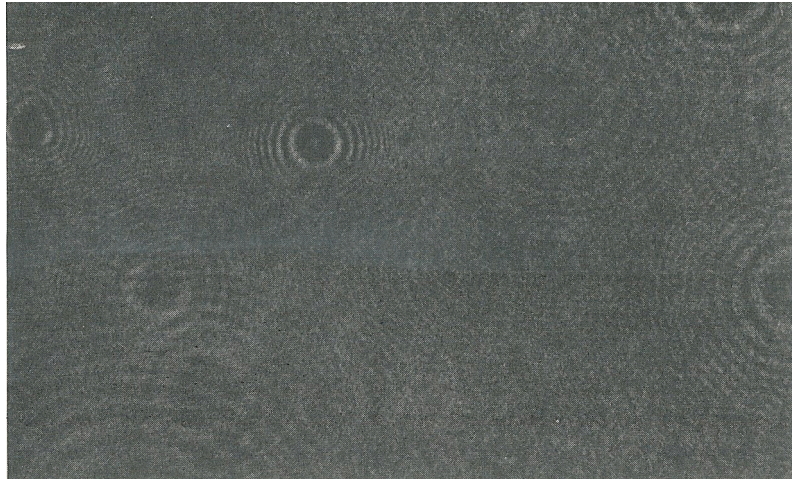
$$\frac{p}{f} = 1 + \frac{1}{M} \quad (3.6)$$

With the above equations one can then determine the distances needed for the layout of the imaging lens set-up.

For a detailed discussion of the optical set-up with sample calculations consult Andrag (2000).

### 3.6 Dust Diffraction Patterns

An optical difficulty encountered throughout ESPI is that of dust particles being amplified. It is therefore necessary to minimize dust and dirt on all optical surfaces, however it is impossible to remove all of it.



**Figure 3.7 – Dust Diffraction Patterns (Klein, 1970)**

Figure 3.7 shows a typical diffraction pattern formed by dust particles on the optics.

Chapter 4 deals with the image post processing techniques that can be employed to reduce these types of patterns.



## 4. Chapter 4

### *Image processing*

#### 4.1 Interferogram generation by Image subtraction

In order to derive the fringe pattern a picture needs to be taken before the disturbance is introduced and one thereafter. These two images are then subtracted from one another.

The original and the disturbed images are recorded as separate files and read into computer memory, the files are read in as matrices with values ranging from 0 – 255, with 0 representing pure black and 255 pure white (the values in between are differing levels of grey).

Once the matrix is read into computer memory, matrix manipulation can occur by making use of any mathematical matrix program.

The original image is read in as image\_1 and the disturbed image as image\_2. The disturbed picture is subtracted from the original image, i.e.  $\text{image\_2} - \text{image\_1}$ , resulting in image\_3 being produced. Image\_3 is the interferogram (see Section 5 for sample pictures).

The code for MATLAB would be:

```
image_1 = imread('DSCF0001.jpg');  
image_2 = imread('DSCF0002.jpg');  
image_3 = image_2 - image_1;
```

image\_3 has now been read into memory and image manipulation and filtering techniques can be employed to enhance the visibility of the fringes.

Image subtraction is one of many types of specific processes used to generate interferograms, others are image addition and multiplication (Fomin, 1998).

## 4.2 Introduction to pixel size

A pixel is a single area in a graphic image; it is basically the smallest size to which a portion of the image can be recorded.

There are three main types of processes (algorithms) used with image processing (McAndrew, 2004):

- Image enhancement
- Image restoration
- Image segmentation

Once an image has been acquired it then has to be digitally processed into computer memory, once it is saved in a digital format (jpeg, bitmap etc) it can then be used and manipulated by one of the three methods mentioned above. The above processes are only used once the images have been subtracted from one another. ESPI images tend to have a lot of noise and diffraction patterns, thus the subtracted images still have a lot of the noise, and therefore image processing is needed.

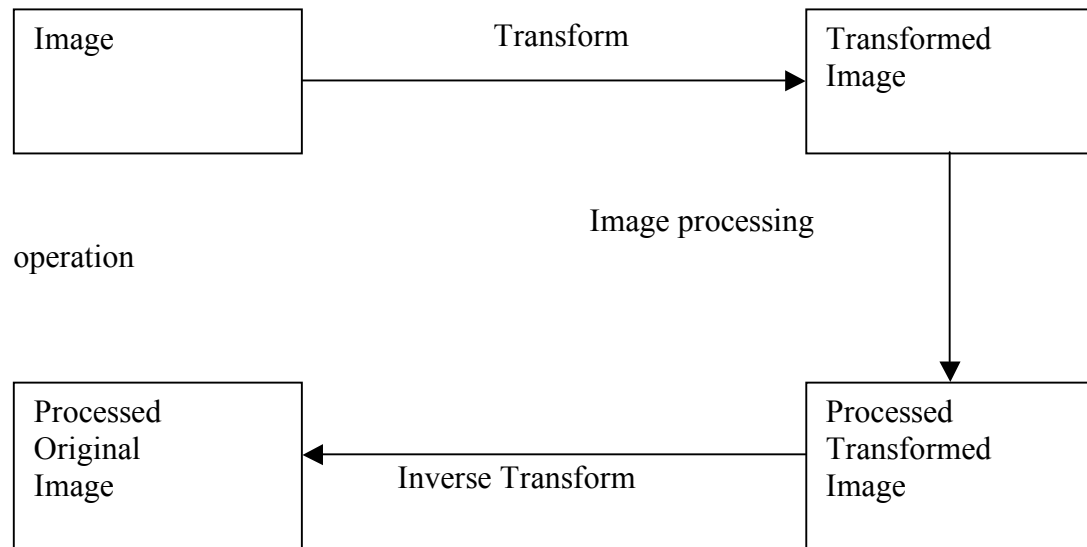
The image processing procedure used attempts to remove the background noise and to reduce the visibility of the diffraction patterns. This can be done by utilizing all three of the above mentioned procedures.

Since ESPI only deals with monochromatic light, the discussion in the following chapters will only deal with light recorded on the grayscale level. This means that when an image is recorded it will be recorded in a  $n \times m$  matrix (where  $n$  represents number of pixels in image height and  $m$  the number of pixels in the image width) with values ranging from 0 (black) to 255 (white) and in between will be the varying shades of gray (0-255). Each pixel is represented by a byte (8 bits).

An image is typically recorded on a digital device such as a digital camera, then that image (jpeg, bitmap, raw, etc.), can be imported into a mathematical program such as MATLAB for further processing. The image is recorded as an array of values, and thus one can manipulate the matrix values in order to derive the desired result whether it be contrast enhancement, filtering etc.

### 4.3 Transformations and point processing

A transformation allows one to reassign a value to a pixel by means of a specific function, therefore the transformed value is of a different value but in an equivalent form, this procedure is highlighted below (figure 4.1) (Mcandrew, 2004).



**Figure 4.1 – Transformation**

The above figure depicts the typical steps taken in a transformation; this type of process is a very powerful tool and can allow for a broad base of linear and non-linear filters to be applied. The steps depicted above show an image being transformed into a specific domain to which an image processing operation can occur (for example before an image can be manipulated by a Fourier transform it must be in the frequency domain), the operation is then carried out, and the image is inverted back to reveal the processed image.

Specific types of transformations will be discussed further on in this chapter.

### 4.4 Filters

As opposed to applying the same function to the entire pixel range, a filter can be applied which enables a neighborhood of pixels to be adjusted according to a specific function.

A mask, which is normally a rectangular shape, is placed over a certain section of the picture, a function is then applied to that specific area (mask) and the new values are then calculated for those specific pixels. This combination of mask and function is called a filter. There are two types of filters, which can be applied namely, linear filters and non-linear filters (Mcandrew, 2004).

### 4.4.1 Linear Filters

A linear filter is when the values calculated for the pixels under the mask have a linear relationship between all of them.

There are many types of linear filters such as spatial filtering, low and high pass etc.

#### 4.4.1.1 Spatial Filter

A spatial filter is one of the simplest types of linear filters that are used in image processing, a spatial image has a mask applied to it and then the product of the mask and its corresponding pixel values are summed. This is done to every pixel in the image.

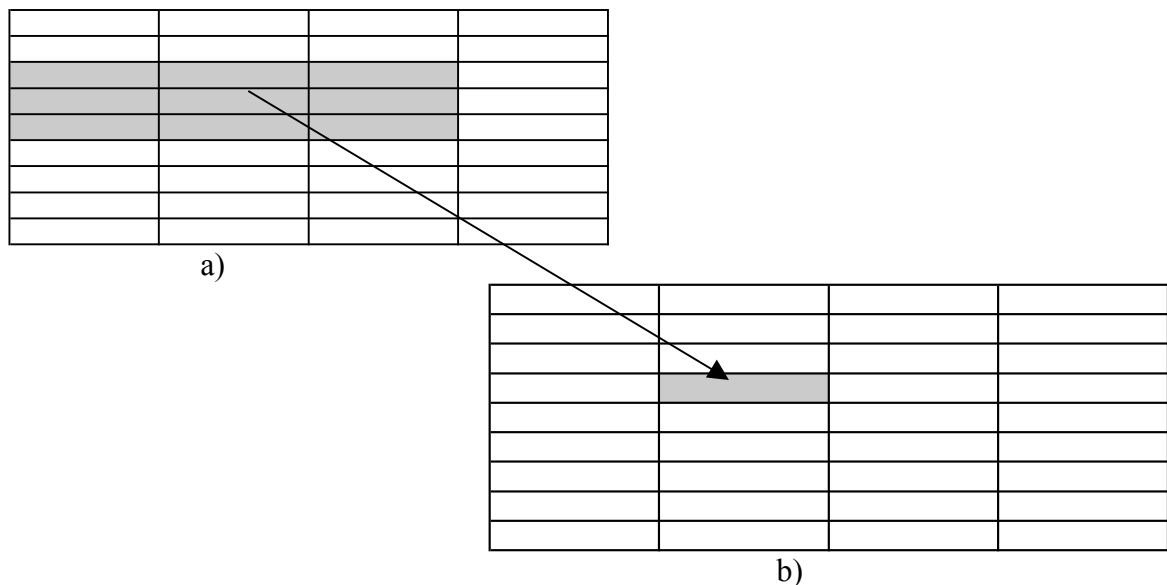
The spatial filter's sum notation is given by ( $s$  refers to the masks matrix row number and  $t$  its column number,  $i$  (row) and  $j$  (column) refer to the pixel matrix):

$$\sum_{s=-1}^1 \sum_{t=-2}^2 m(s,t) p(i+s, j+t) \quad (4.1)$$

Where:

$m$  = Mask matrix

$p$  = Corresponding pixel matrix



**Figure 4.2 – a) Original pixel values with mask applied b) Output matrix**

The figure (figure 4.2) above depicts a mask (grey are Figure 4.2 a) being applied to a range of pixels and the corresponding output matrix (Figure 4.2 b) due to the function being applied to the specific set of pixel values underneath the mask. The grey area in figure 4.2 a is the range of values used to determine the output function which will be applied to a single pixel in Figure 4.2 b.

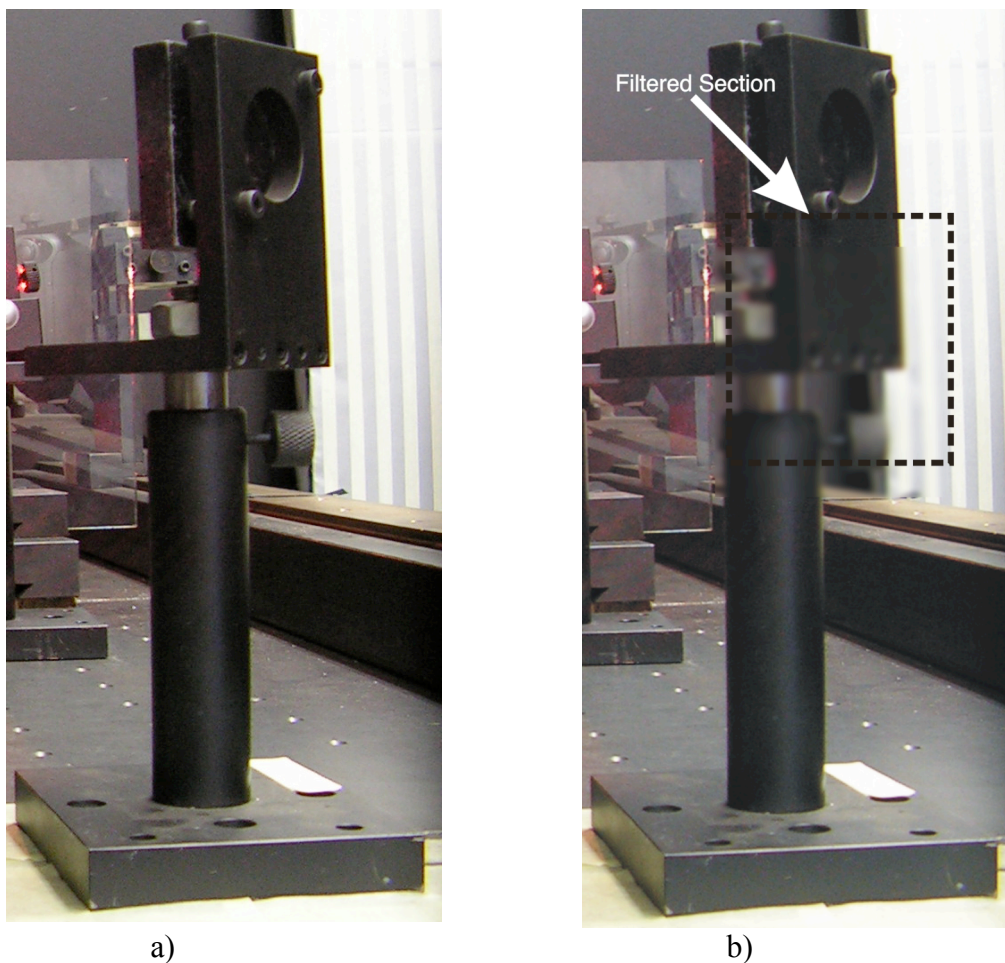
#### 4.4.1.2 Gaussian filters

A Gaussian filter is a low-pass filter, which is based upon the Gaussian probability distribution function of the form:

$$f(x) = e^{-\frac{x^2}{2\sigma^2}} \quad (4.2)$$

Where:

$\sigma$  = Standard deviation



**Figure 4.3 – a) Unfiltered Image b) Filtered image using Gaussian blur**

Figure 4.3 highlights the effects of applying a mask and then a Gaussian filter to the highlighted area, as is evident from the picture, there is a clear blurring of the sectioned image, this type of filter can prove to be very useful to remove noise from an image, and therefore is used in improving ESPI images.

## 4.4.2 Non linear filters

A non-linear filter is derived by applying a nonlinear function of the pixel values under the mask.

The median filter is a commonly used non-linear filter, and is generally used to reduce noise in an image. Depending on the mask or neighborhood specified will determine the severity of smoothness applied to the newly processed image ([http://www.cee.hw.ac.uk/hipr/html/hipr\\_top.html](http://www.cee.hw.ac.uk/hipr/html/hipr_top.html)).

Consider the following 6 x 5 matrix (Figure 4.4), which represents the pixel values of an image

|     |     |     |     |
|-----|-----|-----|-----|
| 112 | 117 | 114 | 119 |
| 114 | 109 | 104 | 110 |
| 116 | 101 | 190 | 108 |
| 107 | 111 | 107 | 119 |
| 109 | 122 | 124 | 123 |
| 115 | 116 | 120 | 109 |

**Figure 4.4 – Image matrix**

If a 3 x 3 mask or neighborhood is applied to the above matrix starting at row 2 column 2, the following matrix (Figure 4.5) is derived:

|     |     |     |
|-----|-----|-----|
| 109 | 104 | 110 |
| 101 | 190 | 108 |
| 111 | 107 | 119 |

**Figure 4.5 – 3 x 3 mask**

As is evident the middle value (190) of the above matrix (figure 4.5) is not in the same range as its surrounding values (109, 104, 110 etc).

A median is therefore taken of the above values and the newly calculated median value replaces the original value (190 – Original value is replaced by 109 – median value).

This procedure is done to the entire range of pixel values in an image, resulting in a smoother image.

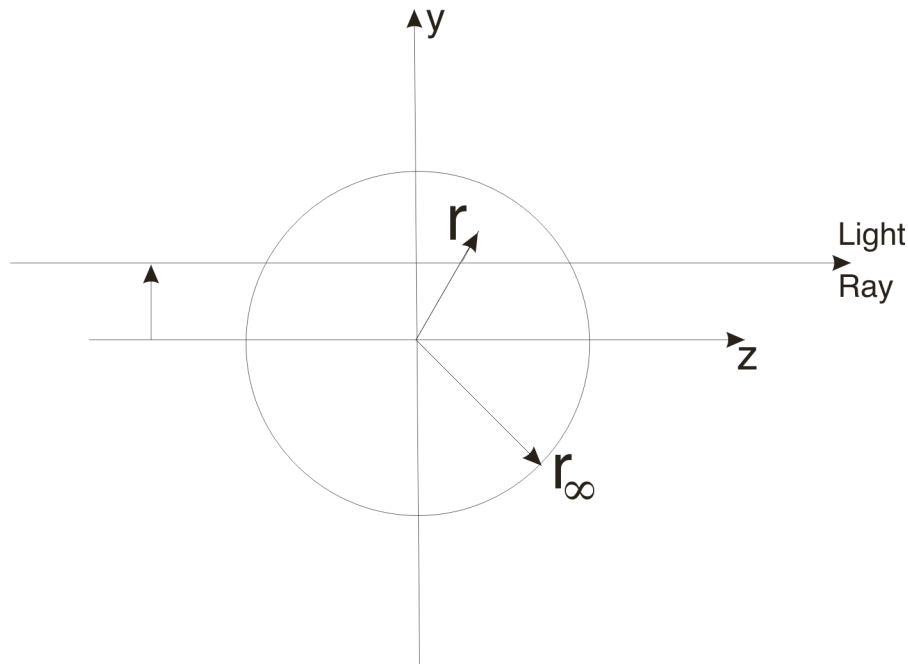
## 4.5 Fourier transforms

The Fourier transform allows for highly accurate processing of images. The efficiency of a Fourier transform is far greater than that of a spatial filter. The Fourier transform allows for the isolation of a particular frequency and thus enables high-pass and low-pass filtering to occur to a greater extent than normal spatial filtering.

## 4.6 Abel Transform

A useful tool in terms of fringe analysis had been highlighted for special types of flows, namely axis-symmetric flows. Two-dimensional information that is derived from an interferogram can be used to determine the density of a three dimensional flow-field providing it is axis-symmetric (Merzkirch, 1987).

The Abel transform is a mathematical function that allows for mapping of a two-dimensional onto a mono-dimensional one (Hamed et. al, 1983)



**Figure 4.6 – Light ray passing through test field**

Figure 4.6 depicts the typical interaction as a light wave passes through an axis-symmetric flow field.

The z axis represents the optical path of the light (i.e. object beam axis), the y axis represents the vertical height, and the x axis is the axis of rotational symmetry.

An observer will see the following when looking at Figure 4.6 at an infinite distance from the origin:

$$F(y) = \int_{-\infty}^{\infty} f(r) dz \quad (4.3)$$

Since  $r = \sqrt{y^2 + z^2}$  then dz becomes:

$$dz = \frac{r dr}{\sqrt{r^2 - y^2}} \quad (4.4)$$

Substituting equation 4.4 into 4.3 and then taking the inverse of it (derived by theory of Laplace functions) yields the following result (equation 4.5), which is called the inverse Abel transform (Shakher 1999):

$$f(r) = \frac{-1}{\pi} \int_r^{\infty} \phi \frac{dy}{\sqrt{y^2 - r^2}} \quad (4.5)$$

By making use of the above equation it is then possible to derive quantifiable data from a fringe pattern by noting that  $f(r)$  is equal to the change in refractive index given by:

$$\frac{n(r) - n_{\infty}}{n_{\infty}} \quad (4.6)$$

Substituting equation 4.6 into 4.5 results in the following:

$$\frac{n(r) - n_{\infty}}{n_{\infty}} = \frac{-1}{\pi} \int_r^{\infty} \phi \frac{dy}{\sqrt{y^2 - r^2}} \quad (4.7)$$

Equation 4.7 thus allows for quantitative full field density measurement.



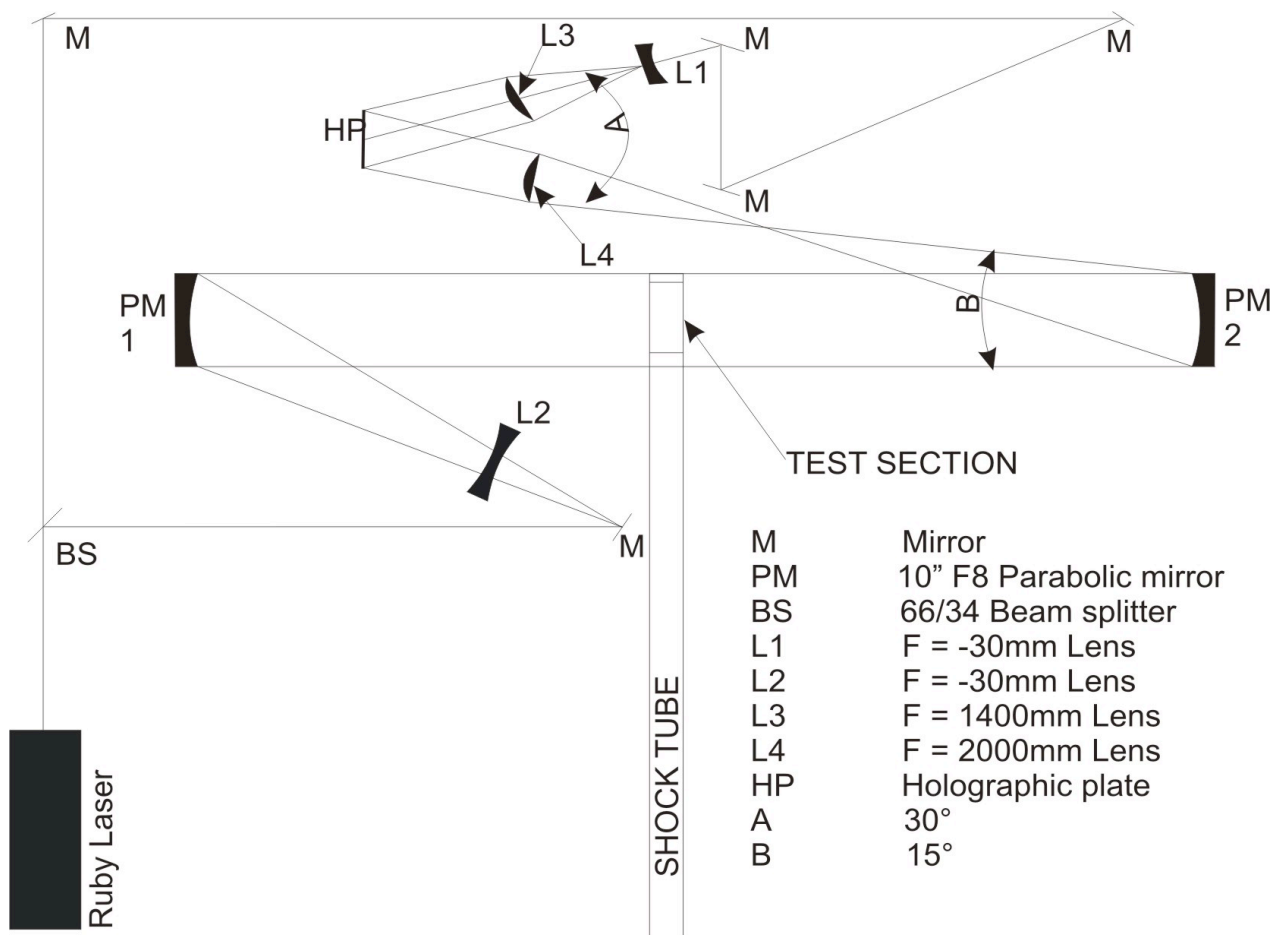
## 5. Chapter 5

### *Experimental Set-up*

#### 5.1 Holographic Interferometry

The author registered for an MSc in January 2007, the original research topic was Flow Visualisation by means of Holographic Interferometry. The proposed project was to apply holographic interferometry to flow visualisation as previously conducted by Barbosa at the University of the Witwatersrand.

The proposed experimental set-up was of this form (Figure 5.1).



**Figure 5 – Holographic Interferometry set-up**

The flow field that was to be explored by this technique was that of the two-dimensional diffraction of a shock wave over a convex surface, with particular attention to flow separation. This is a largely unexplored field and one in which the correlation between experiment and computer simulation is weak.

All of the equipment needed for this project had been purchased by Barbosa for his thesis, however the Double pulsed Ruby Laser Apollo 22HD purchased from Apollo Photonics had not been used in approximately 10 years. The main reason for this being that the film needed to take holographic pictures, previously made by AGFA, had been discontinued.

Holographic film became available in 2005 and hence the attempt to revive the holographic interferometer.

The first step was to recommission the laser, which in itself was a complex task as the control systems used for it are exceptionally outdated, and therefore an intensive evaluation of the manuals was done. Problems encountered were that of a firing system that is electronically controlled by an IBM xt computer, which sends commands out by the serial port. The commands make use of the gwBasic programming language which is very old and dissimilar to modern programming languages

Several laser experts from the CSIR and private practice investigated the laser initially, however none of them were fluent in the gwBasic programming language and thus they could not setup the communication device (IBM xt) in order to control the firing system of the laser. The author therefore began to learn the gwBasic programming language in order to troubleshoot the communication device errors that the computer was reporting.

The author was eventually able to locate the bug in the communications program by analyzing the source code, the printer had to be disabled as a communication device in order for the program to write to the serial port and communicate with the laser.

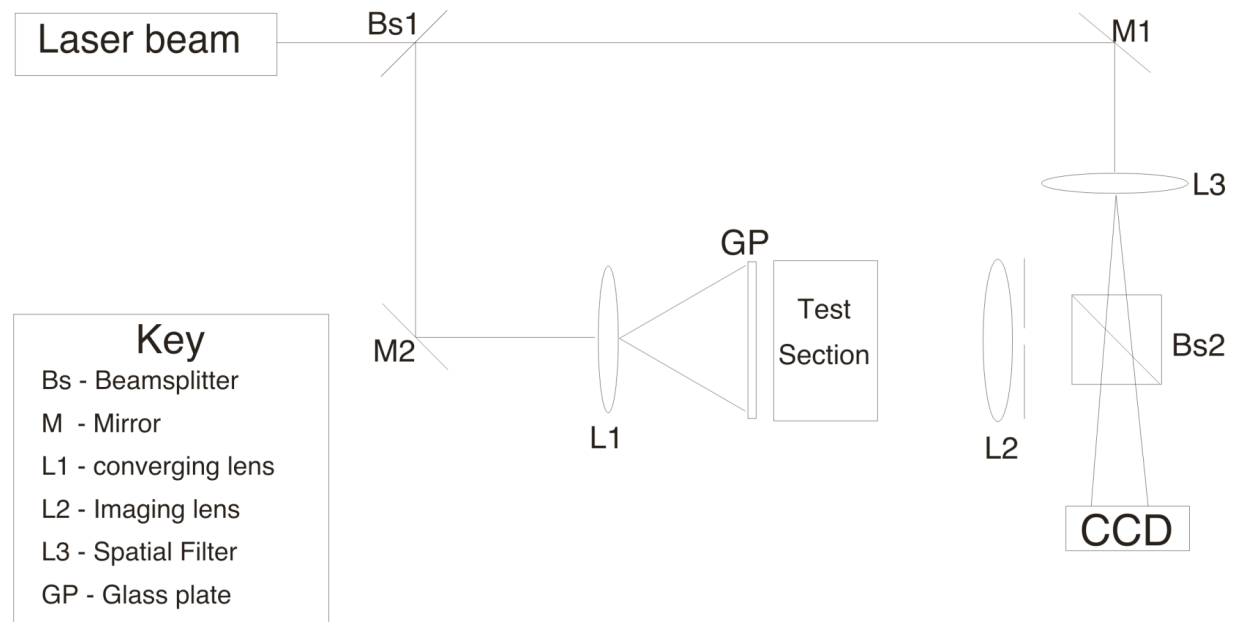
As the control system was working for the laser a laser expert was called in to attempt to fire the laser, however they encountered numerous problems including flashlamp decay and misalignments of the ruby.

They came to the conclusion that one of the service engineers that were part of the Apollo Photonics group was needed to come and recommission the laser. This problem was twofold as Apollo Photonics had declared insolvency and budgetary constraints also did not allow for an expert to be brought to South Africa from the U.S.A.

After ten months of work conducted on the Ruby laser it was decided to rather focus on another flow visualisation technique namely that of ESPI (Electronic speckle pattern interferometry). The rest of this chapter details the experimental process followed in conducting ESPI.

## 5.2 Out of plane interferometer

The following diagram depicts the set-up used for all ESPI tests conducted at the University of the Witwatersrand.



**Figure 5.1 ESPI Set-up**

Beamsplitter one, Bs1, was a variable beamsplitter

M1 and M2 were fully reflective optics mirrors.

The converging lens was an Edmund Scientific spatial filter with just the microscope objective attached

The ground glass plate was typical window glass 3mm thick which was roughened by means of carborundum as highlighted in 3.2

The spatial filter used acted as a diverging lens much the same as L1 which expanded the reference beam onto the ccd chip

The Laser beam was a HeNe laser 5mW.

L2 was a 121.5mm focal length lens.

The digital camera was a FujiFinepix S3 pro with a ccd size of 23 x 15.5 mm.

### 5.2.1 Test specimens

The initial tests that's were conducted made use of a soldering iron, candle and a compressed air nozzle, to generate flowfields with density change.

The soldering iron was used to complement the results achieved by Andrag. However these results did not lead to high-quality fringes, as the density gradients produced were not steady.

Therefore a candle was used as this produced high-quality fringe patterns. Due to the steady state nature of the candle, improvements and optimisation of the system was possible. The candle highlighted all the problems areas encountered with the ESPI set-up. A detailed account of the different set-up configurations is given in chapter 6.

A nozzle from a typical spray gun was also used to highlight the fringe patterns that occur due to flow (pressure changes), as opposed to that of thermal changes (candle). This allowed for flow visualisation.

A high aspect ratio nozzle (Menon, 2005) was also used as well as a model rocket nozzle (Lafleur, 2006).

### 5.2.2 Set-up details

A generalized description is outlined below for the ESPI set-up. For an in-depth discussion consult Andrag.

A laser is placed on a solid surface (to ensure stability).

The first beamsplitter is then added to the system resulting in one beam traveling in the same direction as the original (reference beam) and the other beam running perpendicular to it (object beam).

The first mirror is then placed so that the object beam is now parallel to the reference beam.

The second mirror is now added to the system resulting in the two beams intersecting – care must be taken throughout that the reference beam length and the object beams length are the same.

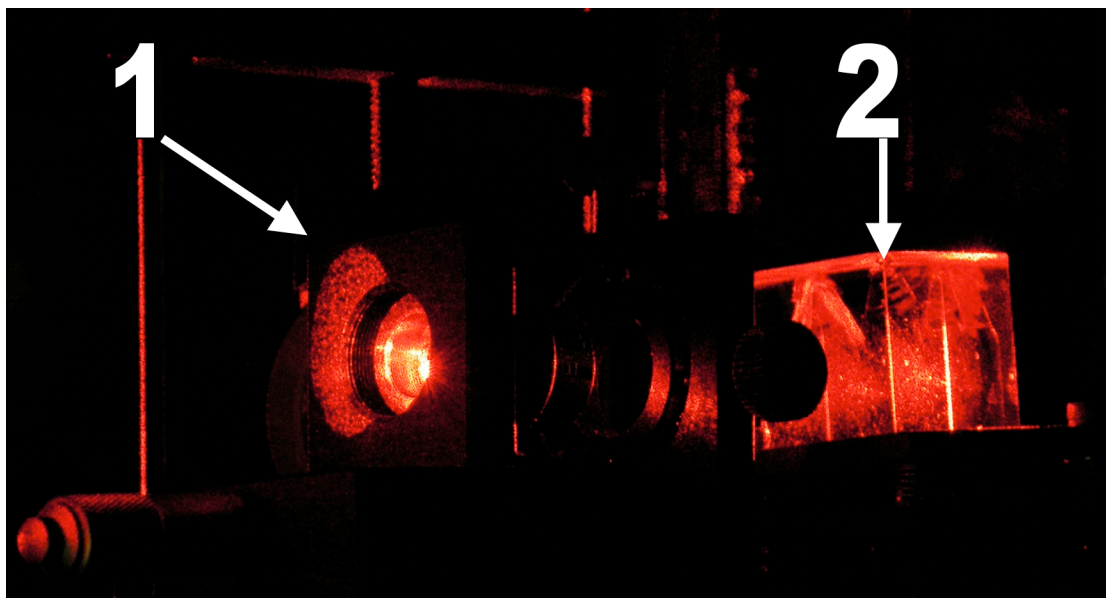
The combining beamsplitter is now added at the intersection point. Fringes should be visible now, if they are not the set-up must be checked to ensure that all the heights are the same and the path lengths of each beam are the same and that the system is placed in a rigid manner.

The spatial filter and the imaging lens components are placed in their calculated positions (Section 3.6).

The ground glass plate and the converging lens and the camera are then added.

In reality an ESPI set-up can take hours or even days sometimes, care has to be taken that high quality fringes are seen.

The picture below (Figure 5.2) shows the reference beam being focused (by the spatial filter - 1) onto the beamsplitter (2).



**Figure 5.2 – Spatial Filter and Beamsplitter**

### 5.2.3 Image processing details

In order to produce an ESPI interferogram image processing is needed. The following technique was employed during experimentation.

Images were recorded before the introduction of the disturbance and after (i.e. for the candle a picture was taken before it was lit and after). In order to ensure that pictures with true fringes were taken two pictures were always taken of the undisturbed system and then those two images were subtracted and the result had to yield no fringes in order for the real ESPI images to be relied upon. As sometimes fringes would occur if the system was bumped, therefore the abovementioned technique was used.

Once the images had been recorded into the cameras memory, they then had to be transferred onto a computer in order for the image processing to take place. The images were read into memory.

Matlab and Adobe Photoshop were the software programs used throughout this report; the images that were going to be subtracted were read into memory (in Matlab) as matrices. Two images were read in as matrices, the image matrices were then subtracted from one another and the result yielded an ESPI image.

The following steps summarise the process:

- Record undisturbed image on digital camera
- Record disturbed image on digital camera
- Read images into computer memory
- Read images into Matlab's memory as a set of matrix values
- Subtract disturbed image from undisturbed image
- View ESPI image
- Write ESPI image to file

### 5.3 Optimisation of set-up

Since ESPI is a very sensitive visualisation technique, optimisation of the technique was needed before it could be applied to more complex flow fields. Therefore many different test specimens were used

The soldering iron was used, as this was the test specimen used by Andrag for his ESPI experimentation at the University of the Witwatersrand, much of the optics that were used in that experiment were also used for the current experiment.

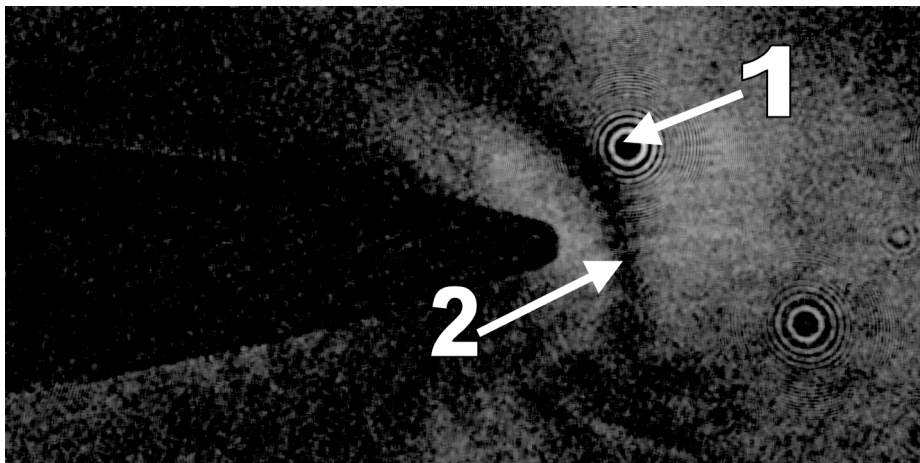
Once a suitable test specimen was found that would produce high-quality fringes, then optimisation and configuration was needed of the set-up, since the candle experiment produced the best quality fringes (with the unoptimised set-up) it was decided to optimize and configure the set-up with that particular test specimen.

Configuration and optimisation of the set-up included the following:

- Etching, grounding of glass plate
- Distance configuration
- Reference and object beam intensities
- Light exposure

#### 5.3.1 Soldering iron

A soldering iron was used to complement and compare to the results of Andrag, since a different soldering iron was used the results were not exactly the same, the resolution differences are clearly seen as the camera used in these experiments was a 12 Mega pixel whereas Andrag's was  $\pm 1$  Mega pixel.

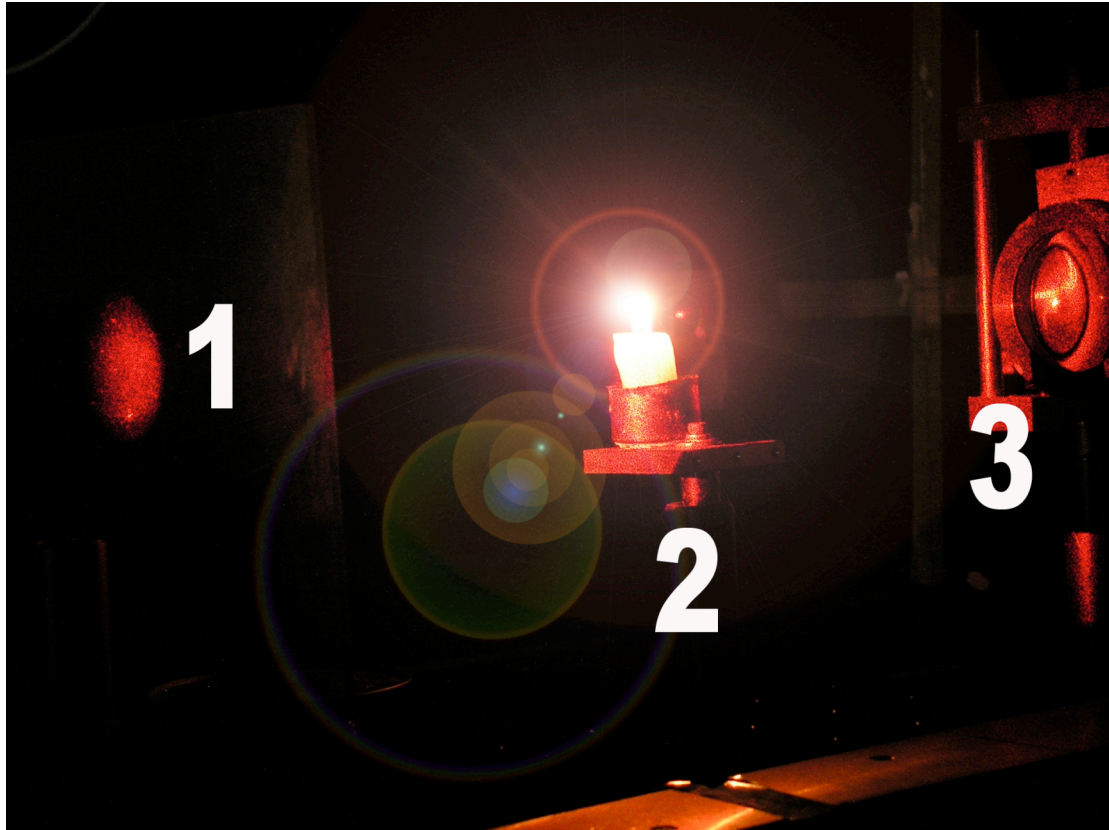


**Figure 5.3 – ESPI image of soldering iron**

In figure 5.3, 1 represents a dust diffraction pattern and 2 a fringe. The soldering iron produced mixed results and therefore was not used as the test specimen for optimisation of the set-up.

### 5.3.2 Candle

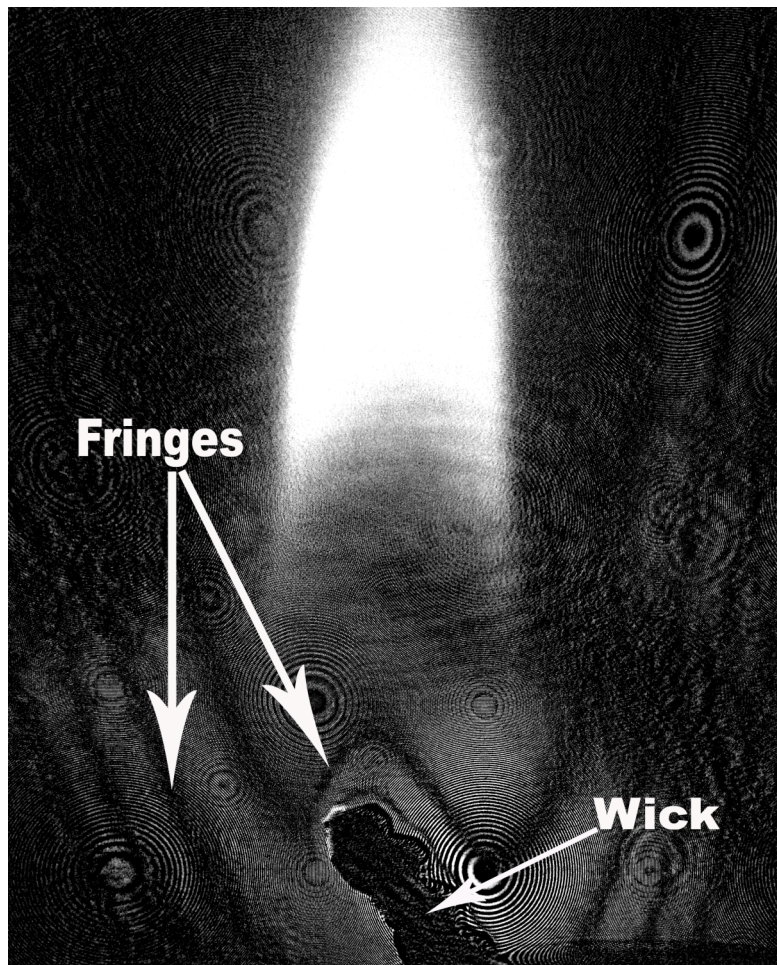
A candle was then used as the test specimen. It was decided that the candle would produce the best symmetrical and consistent fringes (due to its flow-field being axis symmetric) and therefore would prove to be the best test specimen to use as a baseline for the set-up.



**Figure 5.4 – ESPI Set-up with candle**

The figure above (Figure 5.4) is a picture taken of the ESPI set-up with a candle as the test specimen (2), the ground glass plate (which produces the speckle effect) can be seen to the left of the picture (1). The imaging lens (which is used to focus the image onto the CCD chip) can be seen in the right of the picture (3).





**Figure 5.5 – ESPI candle interferogram**

The above figure (Figure 5.5) was one of the initial ESPI pictures taken, the resolution is fairly consistent and the fringes seem symmetrical. The ground glass that was used was window glass that had no etching or grinding yet done to it. The round concentric circles that can be seen in this picture are an indication of diffraction patterns forming (as explained in section 3.6).

The above picture (figure 5.5) illustrates the need for optimisation in terms of resolution and focusing, thus the first step in basic optimisation of the setup was to refocus the image by modifying the object and camera lengths, once the imaging lens has been placed it can not be moved (Andrag 2000).

Different imaging lenses were used in order to refocus the image, as well as manually changing the object and image lengths in order to achieve the best result. Since the camera was inverted one could not manually check to see if the object was in focus, as well as the fact the digital camera was not be able to view an image in real time digitally (i.e. the LCD screen on the camera only shows taken pictures). Therefore a simple and effective technique was employed to manually check and see if the object was in focus by lighting the candle. A piece of white paper was then held and brought forwards and backwards till the flame was perfectly in focus, that specific point was marked and the camera was placed in that position. A picture was then taken to

confirm whether or not the object was in focus. If the object was not in focus then the camera was finely adjusted till the object was in focus. Throughout the experiments the candle flame technique was employed.



**Figure 5.6**

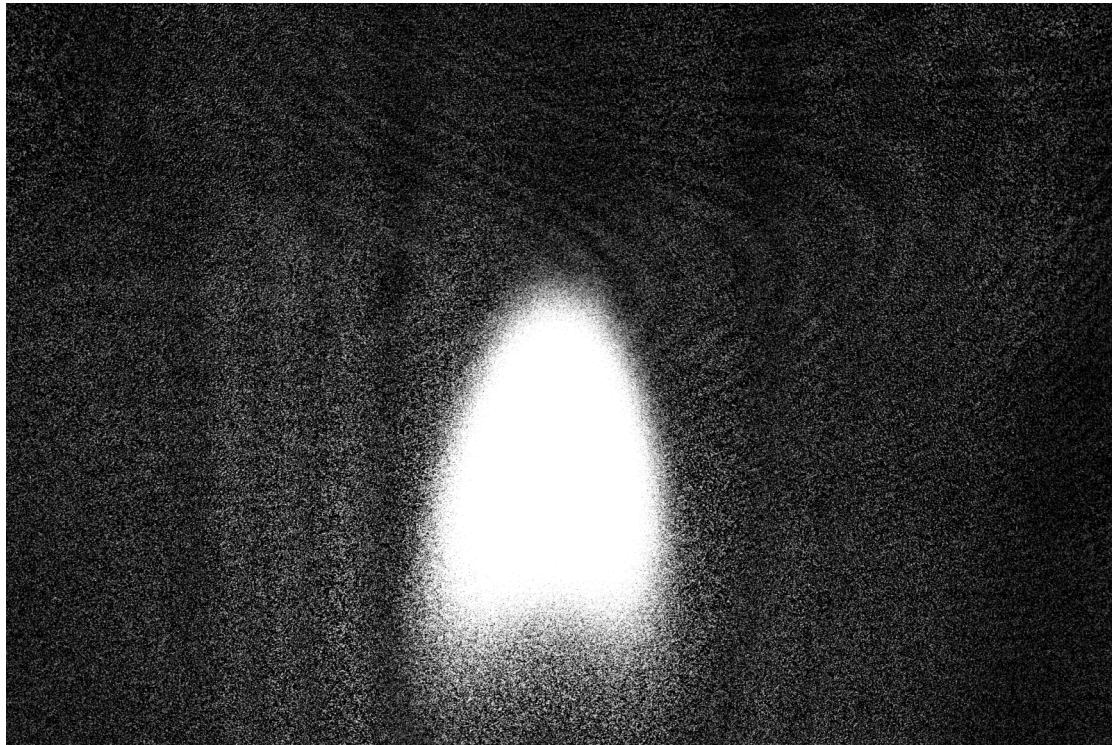
The above picture (Figure 5.6) shows a clearer and sharper image; there are more fringes shown and the flame is in sharp focus.

The next step in the optimisation process was to test different types of speckle producers (glass plates) (Section 3.2). Several methods are discussed by Fomin (1998) and Andrag (2000). Several methods were experimented with such as sandblasting the glass, sanding it and grinding it.

Since Andrag had used hydrofluoric acid to etch the glass (Coyne 1997), it was decided that that would be used as the etching agent for the speckle generator. However the fume hoods in the Laboratory at North West Engineering were not of the correct specification needed for hydrofluoric acid. It was thus decided to try other methods first before resorting to using outside research agencies to etch the glass.



The first method used was to sandblast the glass, which was done by a professional glass company. The results were promising as the diffraction patterns that were typically found with normal ground glass had disappeared. However the resolution of the fringes was severely affected as the illumination had dropped quite dramatically due to the fact that the severe grating of the sandblasted glass did not allow for all the light to pass through it.



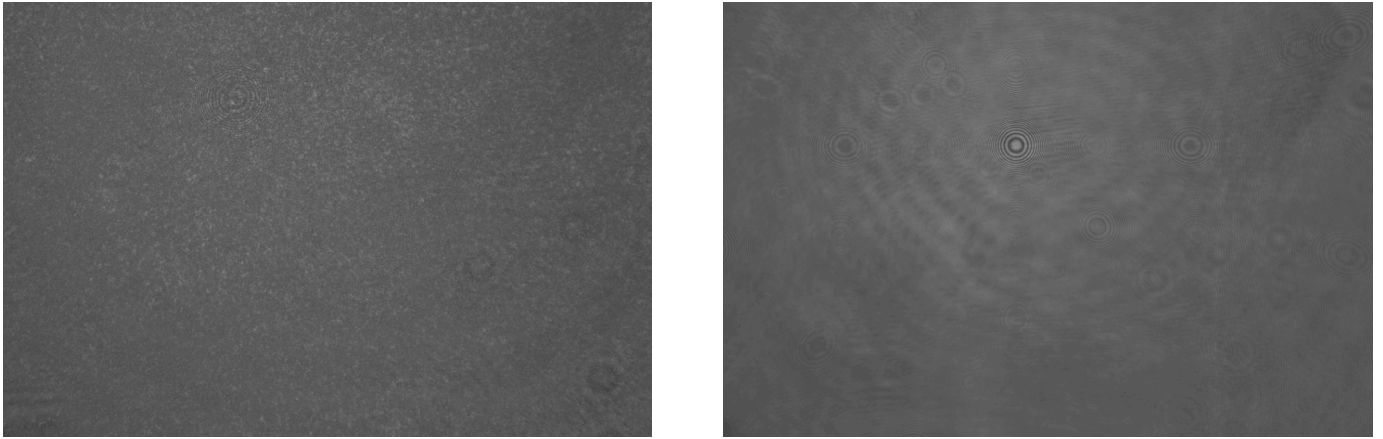
**Figure 5.7**

As can be seen in the above picture (Figure 5.7) the diffraction patterns have been removed, and the fringes are visible. However they lack the resolution of the pictures taken using the ground glass as the speckle generator.

The next step was to try and combine the resolution of the ground glass images (Figures 5.3 and 5.4) with that of the sandblasted ones. Since etching could not take place, it was decided to grind the glass with a carborundum powder commonly known as machinist's paste.

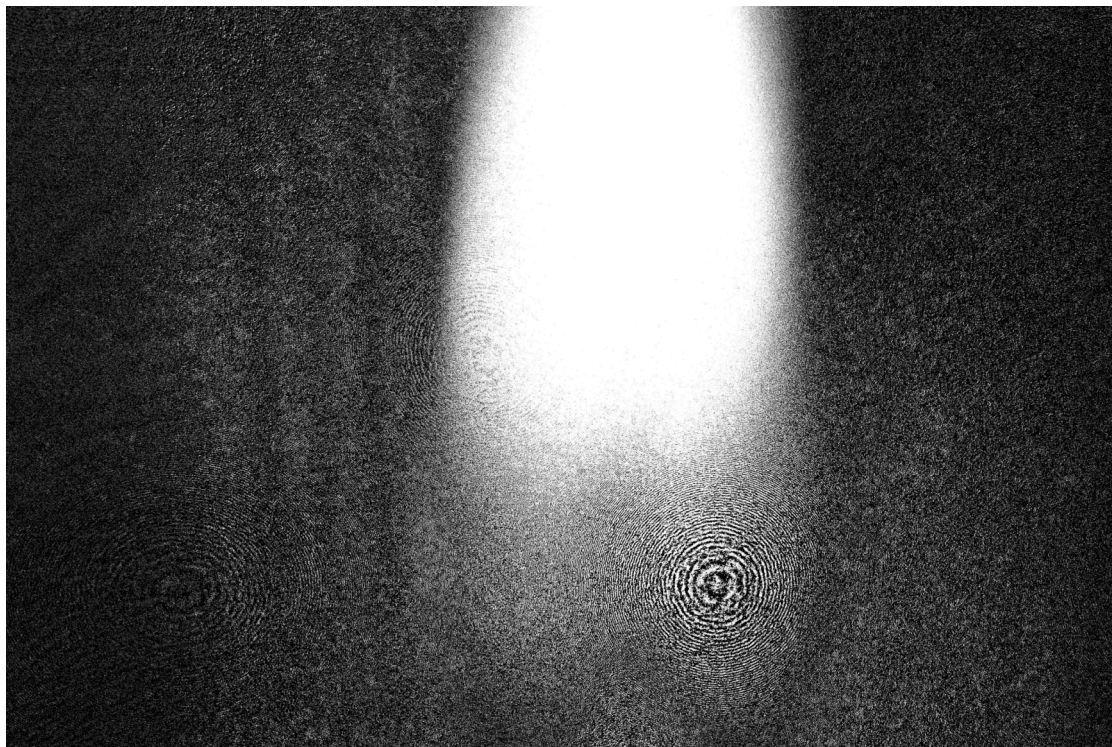
The paste was placed on top of a piece of glass and another piece of glass was placed on top as highlighted in chapter 3.2. The first piece of glass yielded the following results (Figure 5.8).





**Figure 5.8 a) Speckle pattern after paste applied    b) Before paste applied**

As can be seen above (figure 5.8 a) much of the diffraction patterns have been eliminated as opposed to that of b). The reason for that being that the once the glass has been ground the surface roughness of the glass has been increased and therefore magnification of dust does not occur. A detailed discussion of the diffraction patterns that occurred throughout the ESPI experimentation will be given in chapter 6.

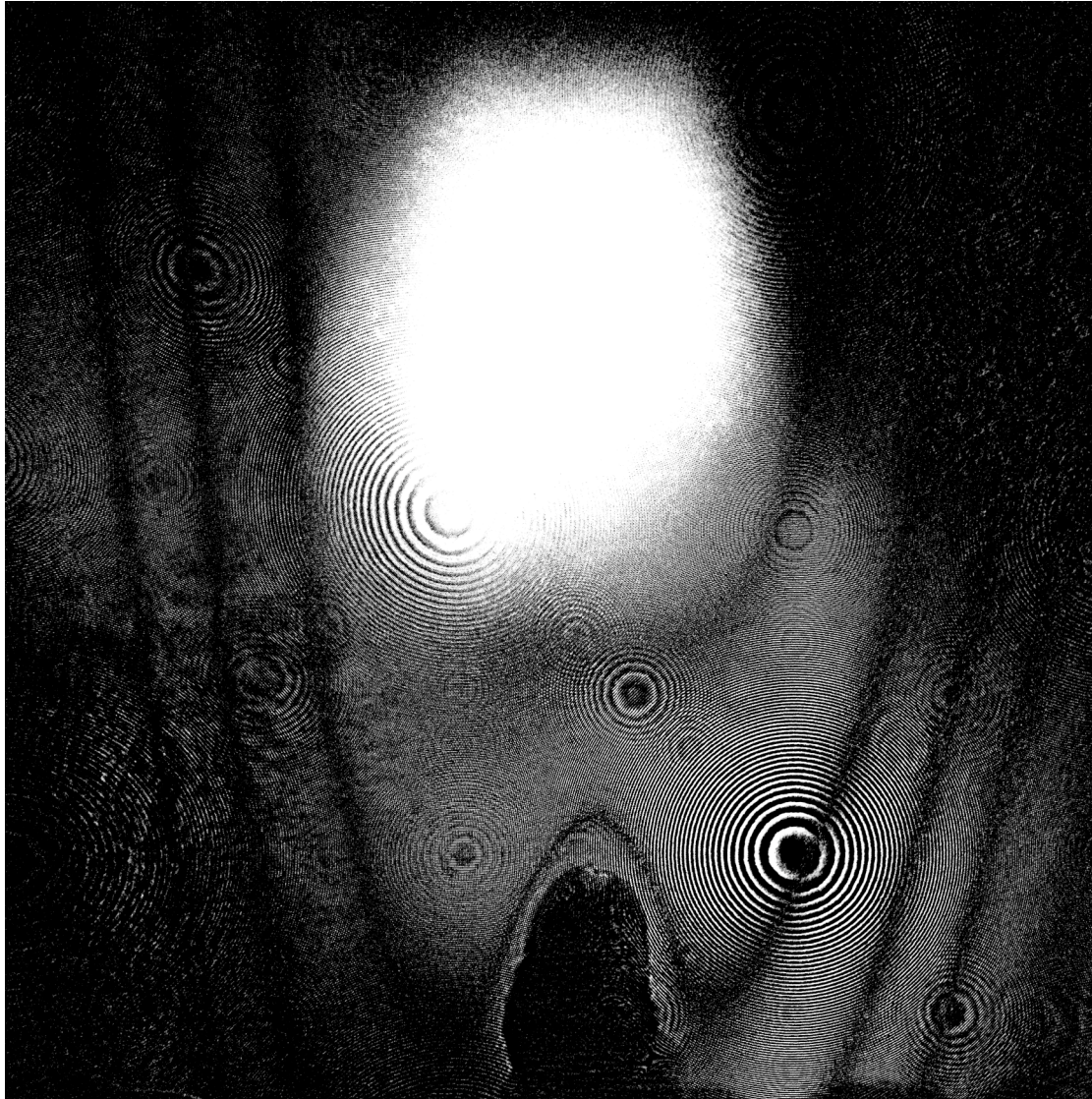


**Figure 5.9 – Subtracted ESPI image using the newly ground glass**

The above picture (figure 5.9) illustrates the result of the candle interferogram; the fringe visibility is slightly better than that of the sandblasted one (Figure 5.7). However the fringe visibility is still nowhere near that of the original pictures taken (figures 5.6 and 5.5), and majority of the diffraction patterns were also removed.



It was therefore decided to grind the glass very lightly, producing only a slight surface roughness and hence seeing then to what degree the diffraction patterns disappear, and the resolution of the fringes.



**Figure 5.10 – Candle Flame with best ground glass**

The above picture (figure 5.10) shows the result of the glass which was ground very finely, hence producing a low surface roughness factor; the picture illustrates a high fringe visibility as opposed to those of figures 5.7 and 5.9. However the diffraction patterns are clearly visible. Even though the diffraction patterns are prevalent, it was decided that the high fringe visibility was of utmost importance and with the use of image processing one could mask the diffraction patterns, producing high quality ESPI fringe patterns. Since the current ground glass configuration produced the best result, it would therefore be used for the rest of the ESPI experimentation conducted.

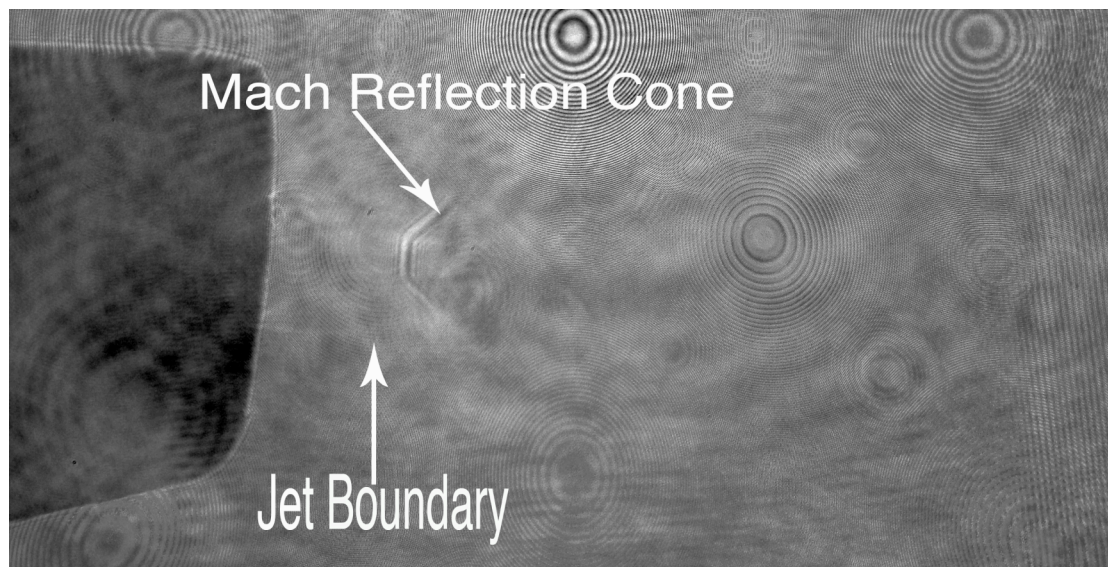
By making use of the candle flame to optimize the set-up it was possible to iron out all the glitches involved when making use of ESPI and applying it to flow visualisation. Hence all of the distances could be configured and the optimum components could be selected since the candle flame allowed for repeatable experimentation.

Since the set-up had been optimized and confidence had been gained in its ability to produce fringes it allowed for the application of ESPI to many other types of flowfields.

## 5.4 Axis-symmetric Air compressor Nozzle

Since the ESPI set-up had been proven to work, it was now possible to apply it to other flow fields. A nozzle from an air compressor gun was placed in the test section where the candle normally stood.

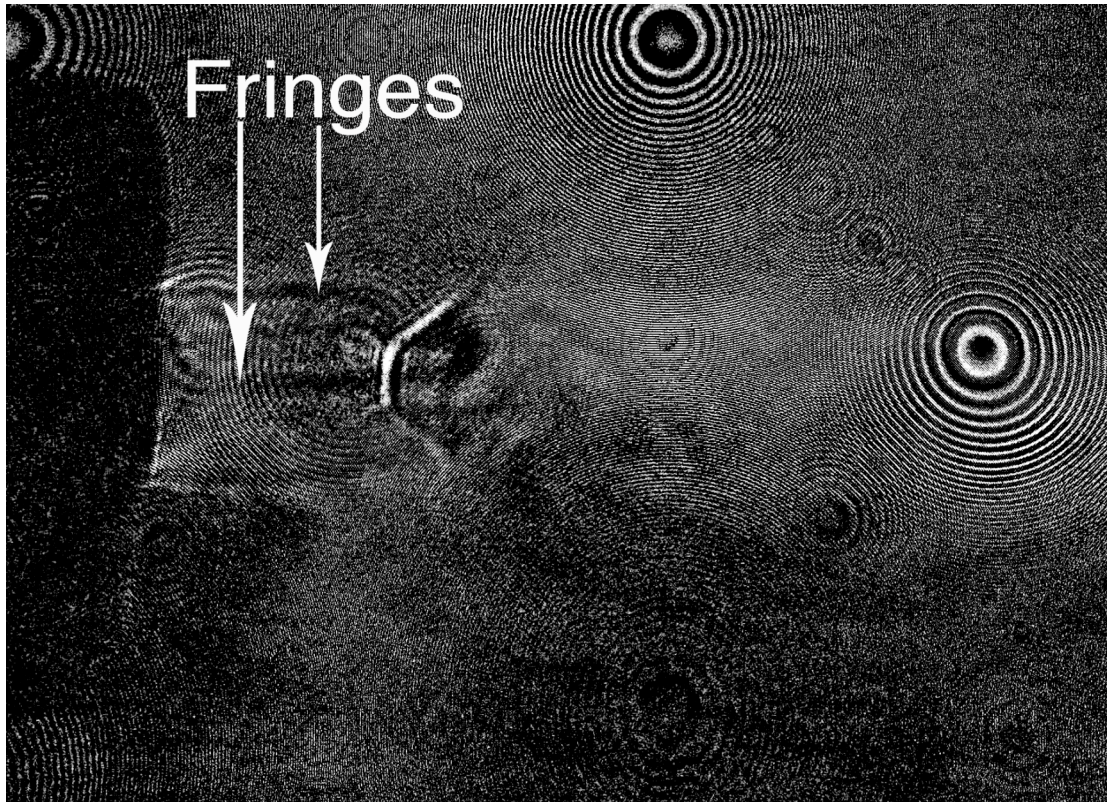
The nozzle was connected to the low-pressure (6 bar) line in the University of the Witwatersrand's flow research lab. A major concern of the author when setting up the rig was that the air exiting the nozzle would interfere with the optical set-up, however all of the components remained intact and steady throughout the nozzle experimentation.



**Figure 5.11 – Nozzle with a jet exiting**

The above picture (Figure 5.11) is of a nozzle with air exiting from its outlet. The picture shows the faint outlines of the jet boundary of the exiting fluid as well as the Mach reflection cone.





**Figure 5.12 – Nozzle interferogram**

Figure 5.8 was subtracted from a reference image of the nozzle and this yielded the above picture (Figure 5.12), i.e. a picture was taken with no flow in the system (reference picture) and then a picture with flow was taken (Figure 5.11).

Figure 5.11 yielded above average results in terms of fringe visibility, as they can be seen clearly. An in depth analysis of these images is given in chapter 6.

The diffraction patterns are highly visible again in the above image; these diffraction patterns would prove to be a major hindrance throughout ESPI experimentation. Image post processing allowed for manipulation/elimination of these diffraction patterns whilst still retaining high fringe visibility.

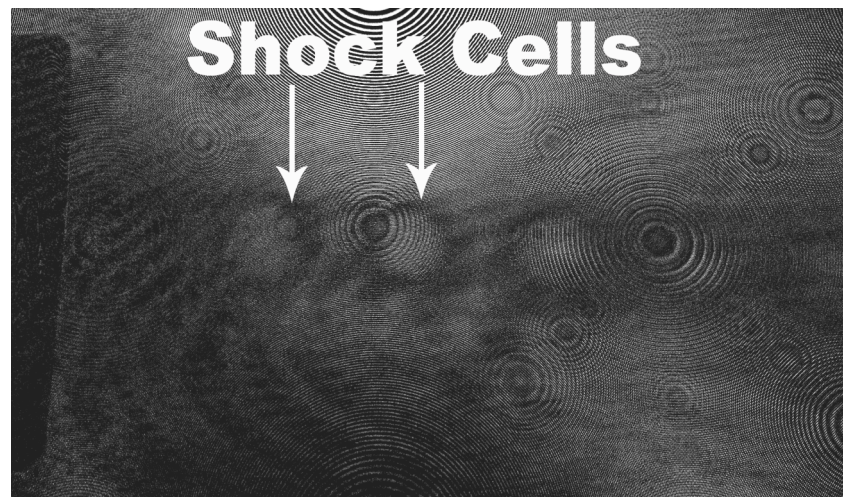
The diameter of the nozzle orifice was quite small, and the current optical set-up did not allow for further magnification and focusing of the nozzle onto the CCD chip and thus detailed information between the two jet boundaries was lost. Since the flow research lab did not have a large selection of lenses that had the exact focal lengths required for different test sections, thus certain geometries yielded better fringes, as the optical set-up suited them better.

## 5.5 Rocket Nozzle

Since the axis-symmetric nozzle produced positive results, it was decided to test another nozzle with a greater orifice diameter in order to increase fringe visibility, as a bigger diameter would enable a greater part of the image to be focused on the CCD chip. The current optical set-up would thus be more suitable to this nozzle as opposed to that of the former.

The rocket nozzle was designed and experimented with by Lefleur. as a fourth year research project at the University of the Witwatersrand, it was designed to be used on the supersonic wind tunnel.

Throughout the set-up of the rocket nozzle, the nozzle exhibited large amounts of air leakage, which could not be stopped.



**Figure 5.13 – Rocket Nozzle Interferogram**



**Figure 5.14 – Shock cells**

(<http://www.aerospaceweb.org/question/propulsion/q0224.shtml>)



As can be seen in the above pictures (Figure 5.13 & 5.14), there were shock cells emitted from the outlet of the nozzle. Faint fringes can be seen outlining the shock cells. Figure 5.14 shows the typical shock cells that are emitted from a nozzle, and thus confirms the result of Figure 5.13.

Since the rocket nozzle produced a positive result, it was decided to experiment with different geometries.

## **5.6 Non axis-symmetric nozzle**

The results of the axis-symmetric nozzle proved that the ESPI technique would work, however the results of the rocket nozzle were not optimal, therefore further experimentation needed to be done.

Menon designed and built an open-ended test chamber for non axis-symmetric nozzles, which he took shadowgraph images on (Menon, 2005).

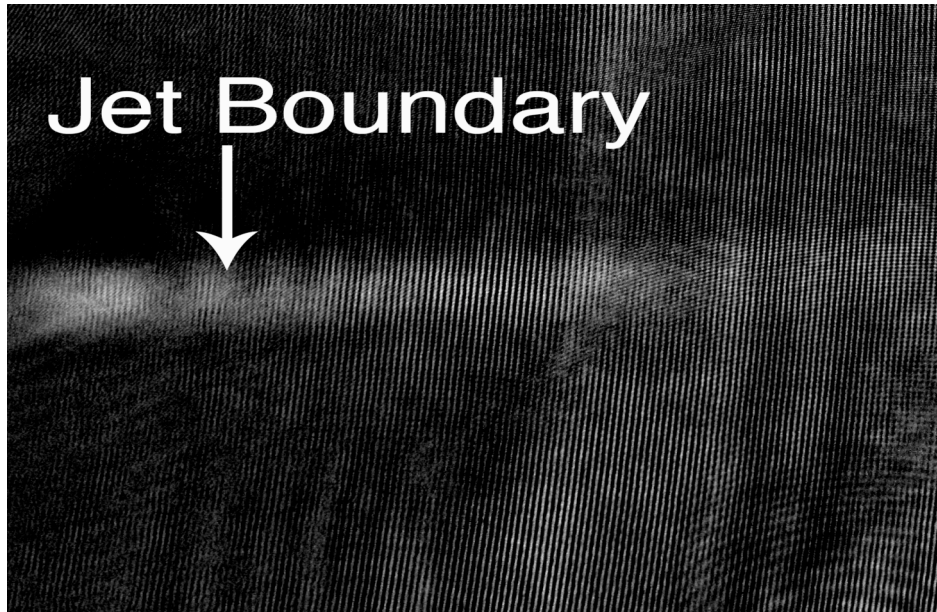
The ESPI set-up was moved to Menon's rig to perform further experimentation; the rig was moved there as the tests could be conducted under steady state, repeatable conditions.

All previous experimentation had been conducted in a designated optics room within the flow research lab; the optics room had an optics bench, which had vibration isolators attached to its legs. The optics bench was also flat, which enabled set-up to be conducted with relative ease. However the room in which the non axis-symmetric nozzle rig had been set up was not easily accessible, i.e. positioning of components was difficult as the rig took up the majority of space in the room, thus not allowing for easy access to the camera when testing, thereby making the process extremely labour intensive. Another major problem was that the optics have to be aligned extremely well as the ESPI set-up is extremely sensitive, and with the absence of an optics bench this caused several difficulties.

The other major problem area was that before, if the object appeared too high/ low it could easily be moved, as well as with focusing the object, it could be brought backwards and forwards, however the rig was stationary and therefore the degree of accuracy had to be very high during the placement of the optics components.

Once again focusing of the image onto the lens proved to be highly difficult as the focal lengths were not optimal to the geometrical layout of the room, therefore a great deal of reconfiguring needed to take place in order that the image could be recorded on the camera.

The purpose of this set-up was purely to see if this rig could produce better results than that of the two previous nozzles tested, and was done as a pure qualitative assessment of ESPI, as the geometries involved were not axis-symmetric and therefore quantitative data would not be derived.

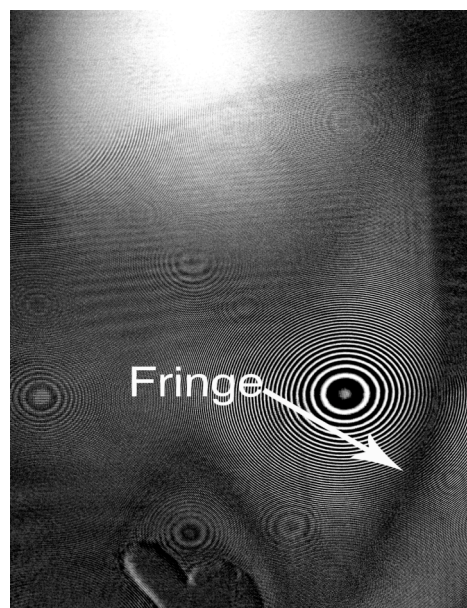


**Figure 5.15 – Non axis-symmetric nozzle**

The above picture (Figure 5.15) was one of the first interferograms taken on this rig, as one can see, only one jet boundary is visible and there are no fringes, this was due to the fact that the system still had to be realigned and focused for this specific geometry. As was highlighted above the processes involved proved to be highly labour intensive.

A major concern for the author after reviewing the above results was that perhaps the system was not configured correctly in terms of interferometry (as opposed to just a focusing issue) and therefore was not producing fringes.

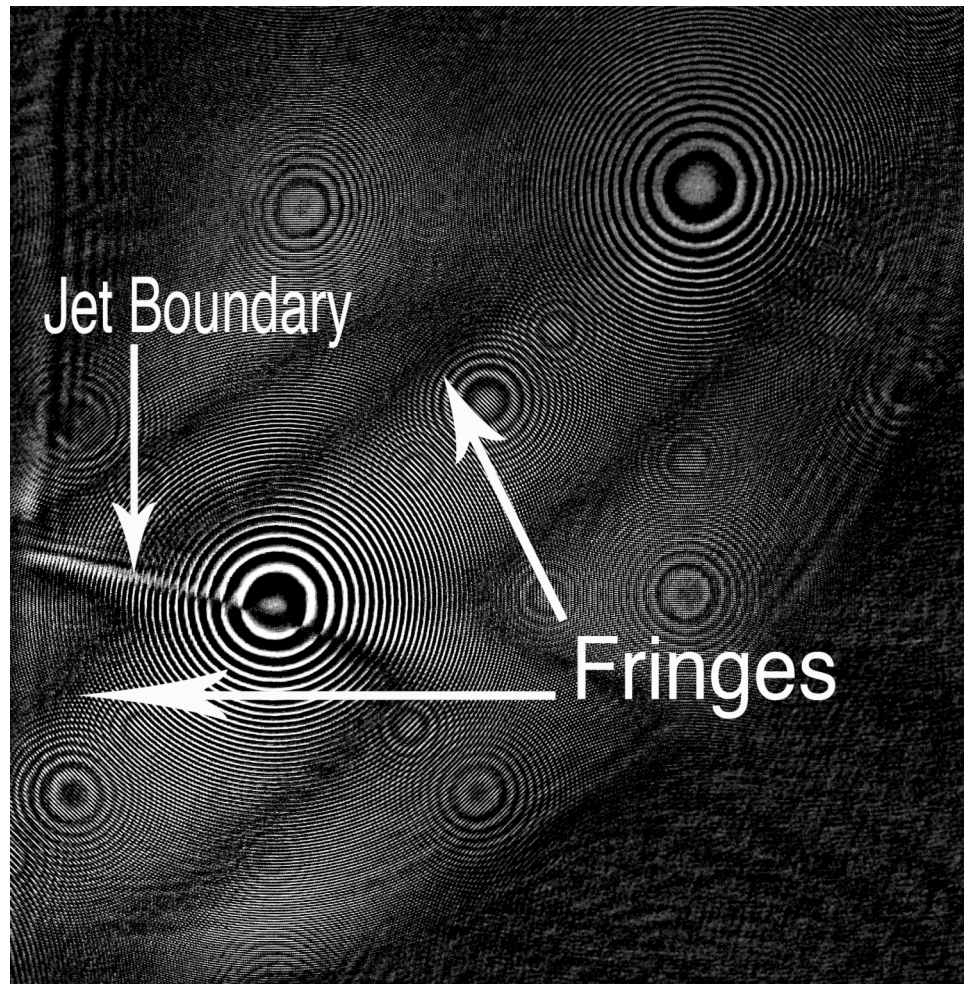
The candle was consequently positioned in place of the geometry, and depending if the candle could reproduce fringes on this set-up would thus prove if the set-up was incorrect or if there were other factors affecting the non-conformance of fringes.



**Figure 5.16 – Candle illustrating fringes**

The picture on the previous page (Figure 5.16) indicates that the set-up was interferometrically correct as fringes can clearly be seen, this indicated that further readjustment was needed for the nozzle area as the interference between the reference and object beams was sufficient (as shown by the fringes).

The following picture (Figure 5.17) was taken after some minor readjustments to the system.

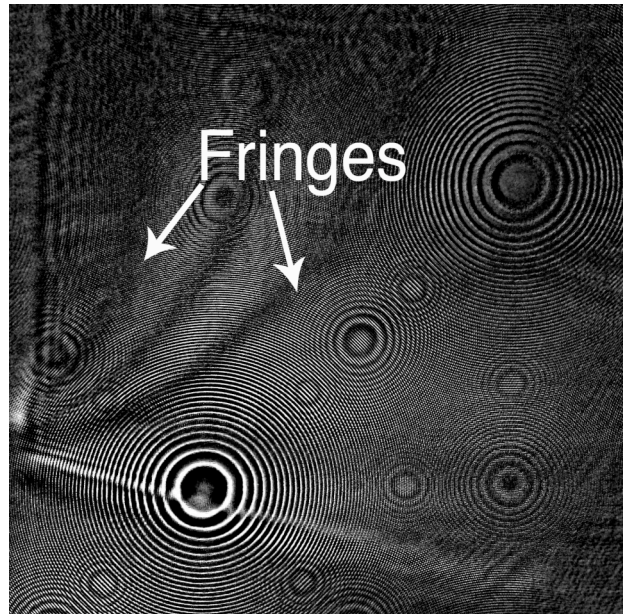


**Figure 5.17 – Improved image with fringes**

Figure 5.13 is a picture of one end point of the nozzle with fringes and a jet boundary, the fringes that are displayed are highly visible and the contrast between light and dark fringes is satisfactory. The next step was to focus on the entire outlet of the nozzle (as opposed to just one side of it), whilst still retaining high fringe visibility.

As explained before, refocusing and realignment of the optical system proved to be one of the major difficulties throughout the experimentation process, thus the following pictures (figure's 5.18 -5.22) were taken after several attempts at repositioning of the system. The main complexity was that a lens with the right focal length was not available and therefore much readjustment was needed to attempt to focus the entire nozzle area while still retaining high speckle information.

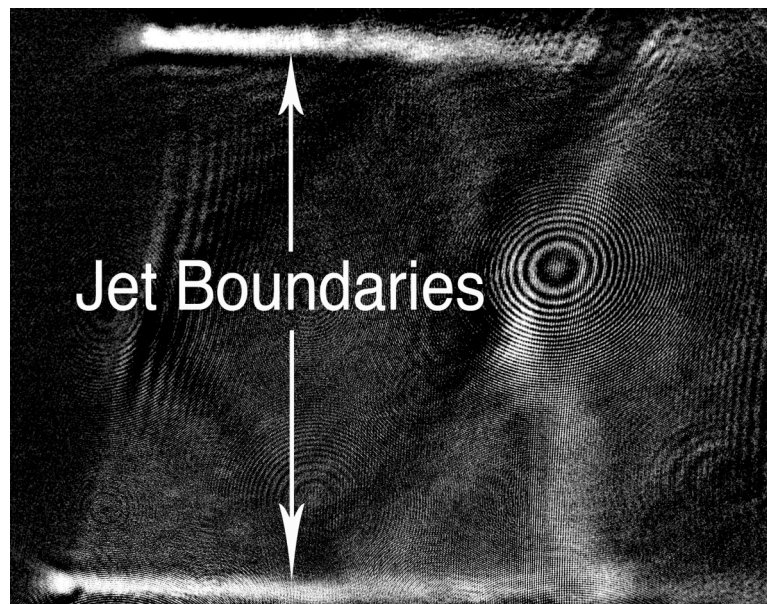




**Figure 5.18 – Constant fringes**

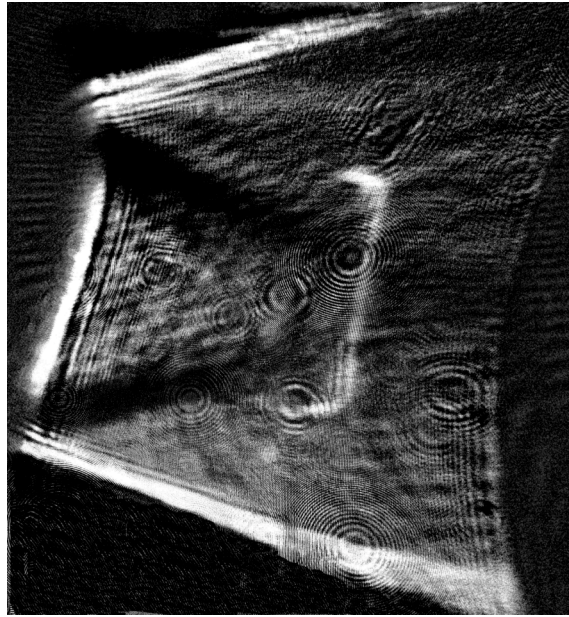
The above picture (Figure 5.18) is of the same size geometry as the previous pictures (Figures 5.15 and 5.17), however the fringe resolution is the greatest here with constant fringes being produced (as opposed to Figure 5.17). This is due to the fact that this picture was taken once the pressure ratio had stabilized, whereas with Figure 5.17 the picture was taken as the valve was opened.

Refocusing of the geometry took place and produced the following results initially.



**Figure 5.19 – Refocused image**

This picture (Figure 5.19) was taken as the valve was opened, the jet boundaries are clearly identifiable, however there are no visible fringes.

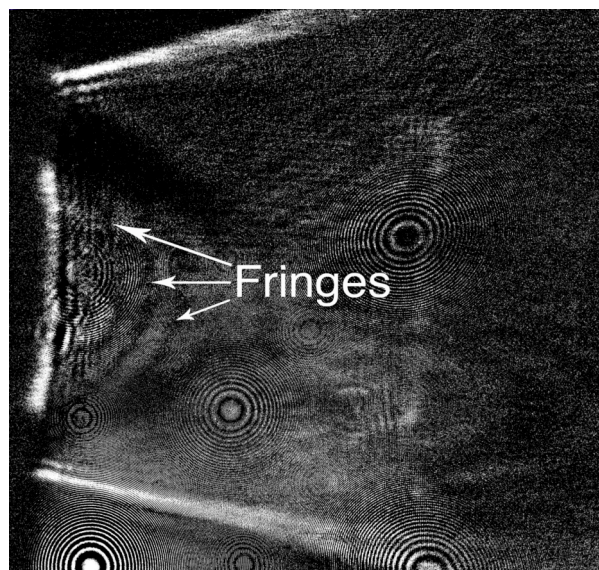


**Figure 5.20 – Refocused image after pressure increase**

Figure 5.20 is of the same geometry as that of figure 5.19, but it is taken after a pressure increase (i.e. the valve was opened further) and after a prolonged time.

Two distinct jet boundary layers can clearly be seen diverging from the end exit tips of the nozzle, the two converging black lines in the centre of the picture appear to be shock waves, and there is also a distinct resemblance to that of a Mach reflection cone in the middle of the picture. Further discussion of these results is given in chapter 6.

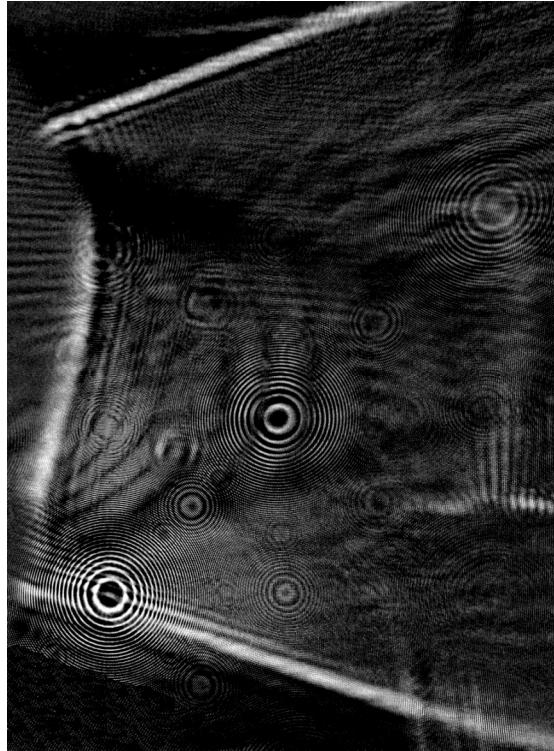
The image is in focus and the boundaries are clearly visible, but there are no visible fringes. The only possible explanation for this was that the beamsplitters intensity had to be adjusted very finely as opposed to that of the candle due to the drastic changes in density over a very small area.



**Figure 5.21 – Refocused image with fringes**

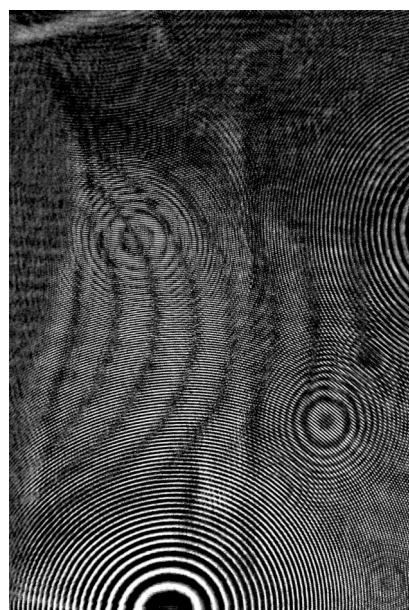


The picture on the previous page (Figure 5.21) was the first image that had the view of the full flow-field with fringes occurring. The reason the fringes were visible in Figure 5.21 as opposed to that of Figure 5.20 was due to the fact the intensity of the beamsplitter was adjusted finely allowing for the sensitive speckle information to be recorded. Four distinct fringes can clearly be seen between the two shock waves in Figure 5.21.



**Figure 5.22 – Higher fringe resolution**

The above picture (Figure 5.22) had the highest number of fringes visible of all the pictures taken on the non axis-symmetric rig. This picture resulted after many fine adjustments to the optics and pressure ratio.



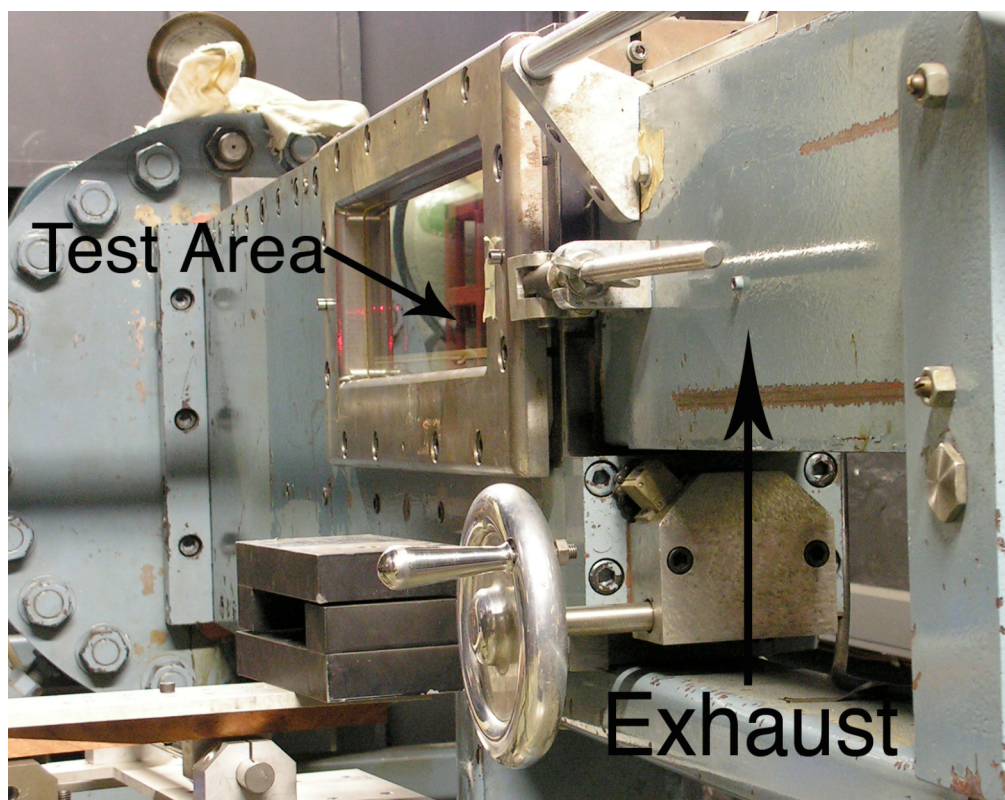
**Figure 5.23 – Best fringes**

The picture on the previous page (Figure 5.23) produced the clearest fringes out of all the pictures taken on the non axis-symmetric nozzle rig. The fringes are clearly distinguishable and visible and the contrast between light and dark fringes was the highest of all the images taken. There are five highly noticeable fringes emitting radially outwards from the left hand side of the image, as well as another two discernible fringes occurring after the initial five.

## 5.7 Missile Geometry

The positive results that were produced with the non axis-symmetric jet provided a catalyst to experiment the ESPI technique on other wind tunnels in the flow research lab. It was thus decided to conduct ESPI tests in the University of the Witwatersrand's supersonic blow down tunnel.

The tests were to be done with a symmetric model in the hopes of being able to extract quantifiable data from the pictures.

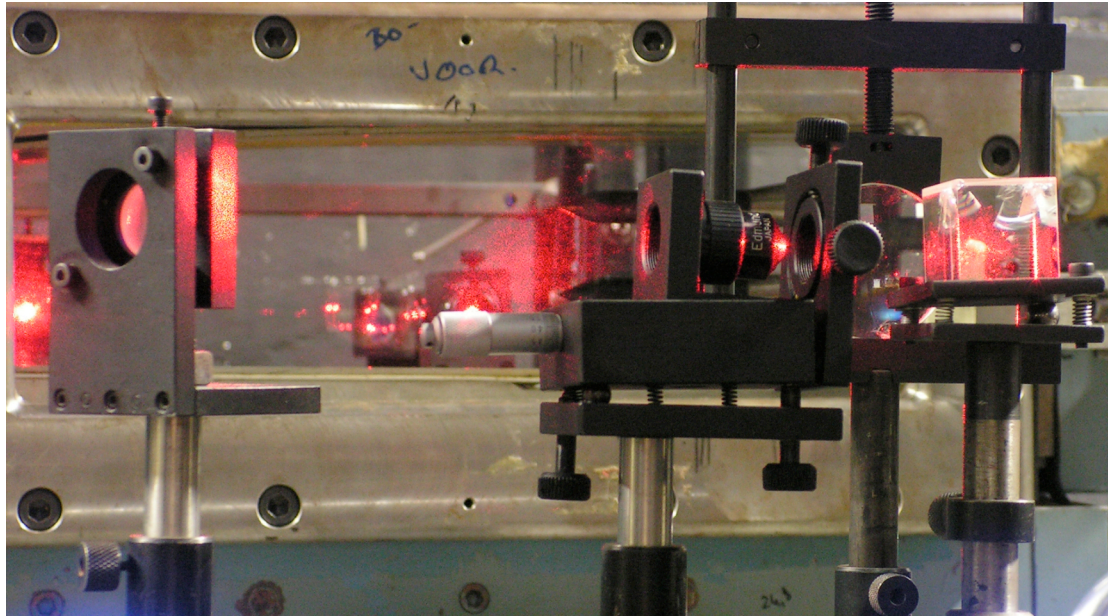


**Figure 5.24 – Super Sonic Blow Down Tunnel**

The ESPI set-up had to therefore be moved from the Menon's rig to the supersonic test section. Up until now there was place for the reference beam to pass on the outside of the test section and for the object beam to be the only light source that passes through the test section, but due to the specific design of the supersonic tunnel this was not possible as after the test section there is an exhaust connected to the outlet of the test section (see Figure 5.24). It was therefore impossible to place the reference beam on that side.



The glass area that allows for visualisation of the test section is fortunately relatively large, which thus allowed for placement of the reference and object beams to pass through it.

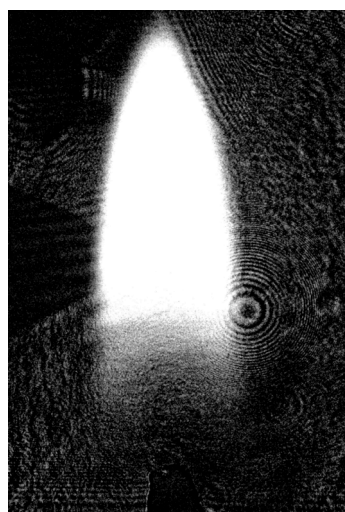


**Figure 5.25 – ESPI supersonic set-up**

The above picture (Figure 5.25) illustrates the interferometric set-up on the supersonic blow down tunnel. The left hand side of the image shows the reference beam passing through the glass test section; the right hand side is the object beam. Both beams intersect within the beamsplitter (transparent cube).

The ESPI set-up was placed with this new configuration, during the set-up process the glass viewing area of the test section proved to be a hindrance and adversely affected the fringes, as there were now four surfaces that the beam was passing through.

The candle was initially placed in front of the geometry as a control measure to ensure the production of sufficient fringes.



**Figure 5.26 – Candle Interferogram without fringes**

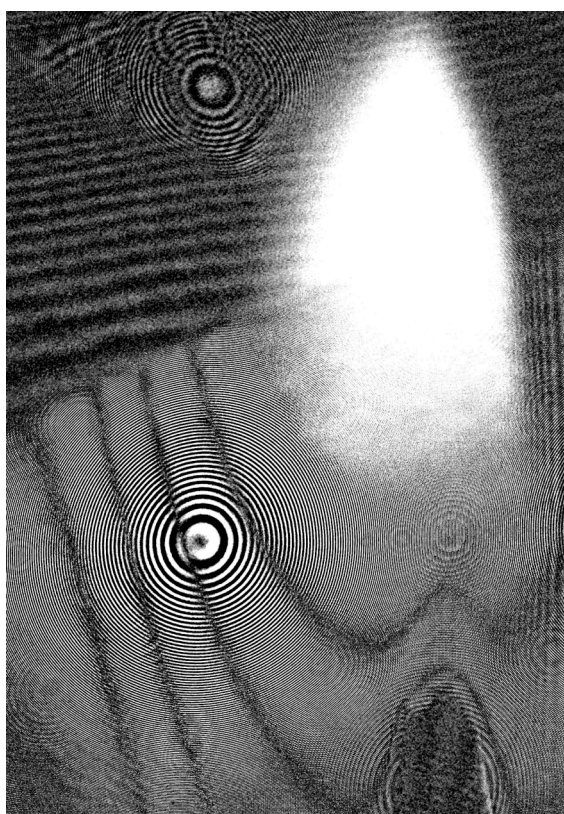
Figure 5.26 on the previous page is an interferogram of the candle flame, however no fringes were produced, this proved that the set-up was not interferometrically correct. Initially it was thought that this was due to the fact that the reference and object beams collectively were traveling through four optical surfaces (i.e. the glass test section).

There was one other potential area of concern, the optical path lengths for the reference and object beams were slightly different. The path lengths difference should ideally equal nil, however if they are not one only needs to ensure that the difference is at least below the coherence length of the laser.

During the set-up process special consideration of the above-mentioned problem was noted and therefore the optical path length difference was kept below the coherence length.

The negative result of figure 5.26 forced the set-up to be reevaluated and therefore a reconfiguration of the reference and object beams was done keeping in mind to keep the optical path difference closer to nil.

Since the area in this wind tunnel was limited and the fact that the reference beam could not pass on the other side of the object beam did not therefore allow for the laser to be placed in the same type of configuration as before. The variable beamsplitter had to therefore be inverted in order to allow for the laser to be placed on the other side. The fact that one had to invert the beamsplitter was the main reason why originally the laser had not been placed in this configuration and that would allow for optimal path length difference.

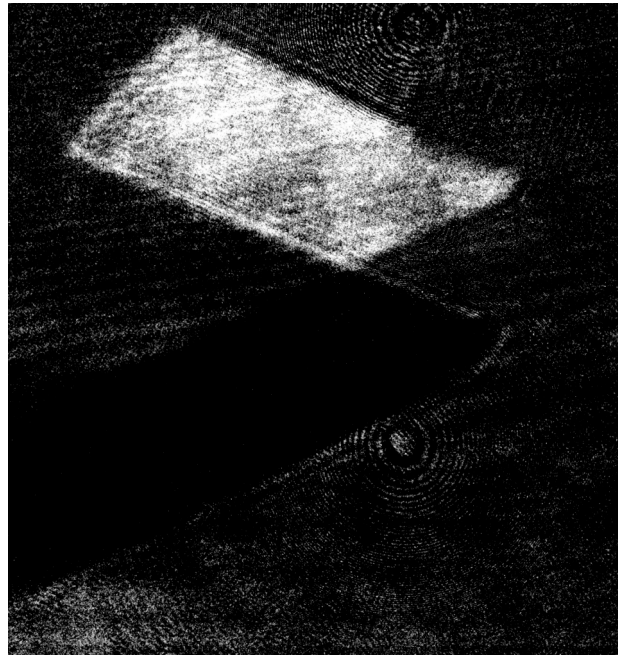


**Figure 5.27 – Candle Interferogram with Fringes**

The interferogram on the previous page (Figure 5.27) yielded a positive result as fringes were formed.

The candle verification method proved to be the best method of ensuring interferometrically correct set-ups.

The next step was to test an axis-symmetric geometry, it was decided to use a conical tip geometry with a cylinder attached to it (missile).



**Figure 5.28 – Missile Interferogram**

Figure 5.28 is an interferogram of the missile tip; there are no visible fringe lines. The main reason for the absence of fringes is due to the fact that the missile tip moves between the undisturbed and the disturbed image due to aerodynamic loading. This test arrangement is therefore unsuitable.



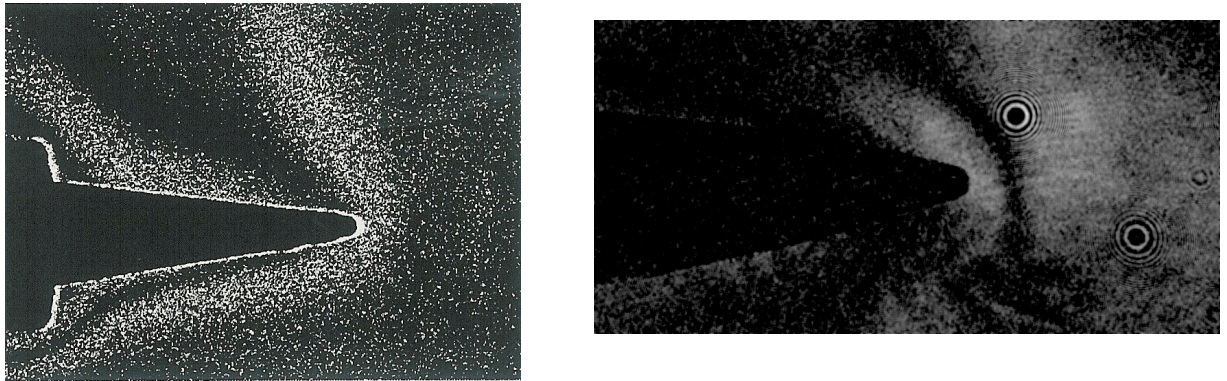
## 6. Chapter 6

### *Results and discussion*

#### 6.1 Soldering Iron

One of the main objectives of this thesis was to be able to develop an ESPI set-up that could be used in a variety of applications such as full flowfield and temperature analysis and to develop a rig that could be moved. Part of the verification process included reproducing the speckle interferograms that were done previously in the flow research lab at the University of the Witwatersrand.

At the time when speckle interferograms were first taken they used a one megapixel camera, whereas a twelve megapixel camera was used for the current work.



**Figure 6.1 – Comparative pictures**

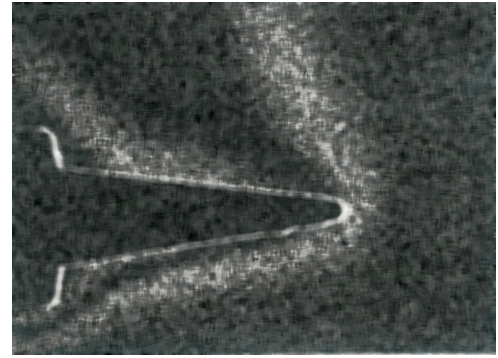
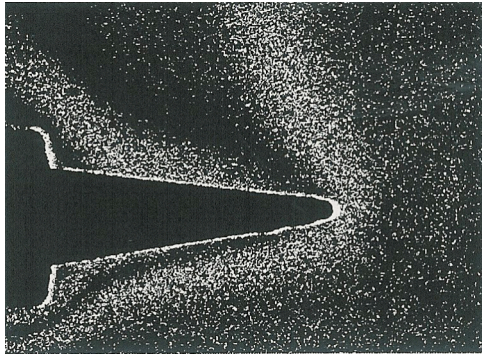
a)

b)

Figure 6.1 highlights the differences between ESPI images taken previously (Andrag – picture a)) and the ones that were taken for this report (picture b)).

The main difference can clearly be seen in the clarity of picture b to that of a, the main reason for this is simply due to the improved resolution of the digital camera used. The speckle in figure a is very high and simply by using a more advanced camera, one can drastically improve the resolution of speckle interferograms.

As explained in chapter 5, the soldering iron was replaced with a candle for optimisation of the set-up, and therefore further comparisons between the two pictures is not possible.



**Figure 6.2 – Filtered pictures**

**a) Original image**

**b) Filtered image**

The above pictures display the differences between an unfiltered and filtered image using the following filtering process:

The original image was read into Photoshop  
 Noise was added to the picture  
 A median filter was then applied

This simple set of post processing procedures greatly enhanced the contrast of the interferograms in terms of fringe visibility. These filtering procedures helped immensely with the fringe analysis of the interferograms that will be displayed in this chapter.

## **6.2 Candle**

A candle was used as the main specimen of analysis throughout this report; it was used to optimize the set-up, as well as a test specimen for fringe analysis. All the image post-processing was also optimized using the candle interferograms.

### **6.2.1 Calculations**

In order to show that the interferograms obtained were correct, the following calculations were done assuming that the flow-field was axis-symmetric and isopycnic:

By making use of  $P_1 = \rho_1 RT_1$  and  $P_2 = \rho_2 RT_2$  and combining them noting that  $P_1 = P_2$  results in:

$$\rho_2 = \frac{T_1}{T_2} \rho_1 \quad (6.1)$$

Using the following constants to substitute into equation 6.1  $T_2 = 1873 \text{ K}$  (Hamed, 1993)  $T_1 = 295 \text{ K}$  and  $\rho_1 = 1.0053 \text{ kg/m}^3$

Therefore  $\rho_2 = 0.15833 \text{ kg/m}^3$

By making use of equations 2.12 and 2.10 and rearranging them results in the following equation:

$$N = \frac{k(\rho_2 - \rho_1)dy}{\lambda} \quad (6.2)$$

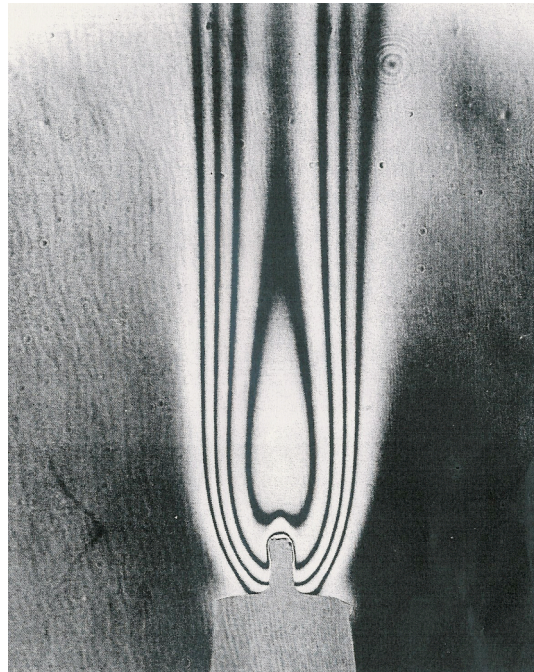
Resulting in  $N = -7.596$

Using  $k = 0.2271 \cdot 10^{-3}$ ,  $\lambda = 632.98 \cdot 10^{-9}$  and  $dy = 25 \text{ mm}$ .

Therefore an interferogram of a candle should produce 7 - 8 dark fringes.

Figure 6.3 is a holographic interferogram of a candle flame (Vest, 1977). This image shows 8 distinct fringes as predicted by equation 6.2. The experimental result of ESPI must therefore display similar results, as holographic interferometry and ESPI produce the same fringes (Andrag, 2000)

The following page displays an unfiltered interferogram (Figure 6.3), as one can see the contrast of the fringes is high, however there is still a lot of background noise due to the diffraction patterns. The diffraction patterns are due to dust being on the glass diffracting the light beam.

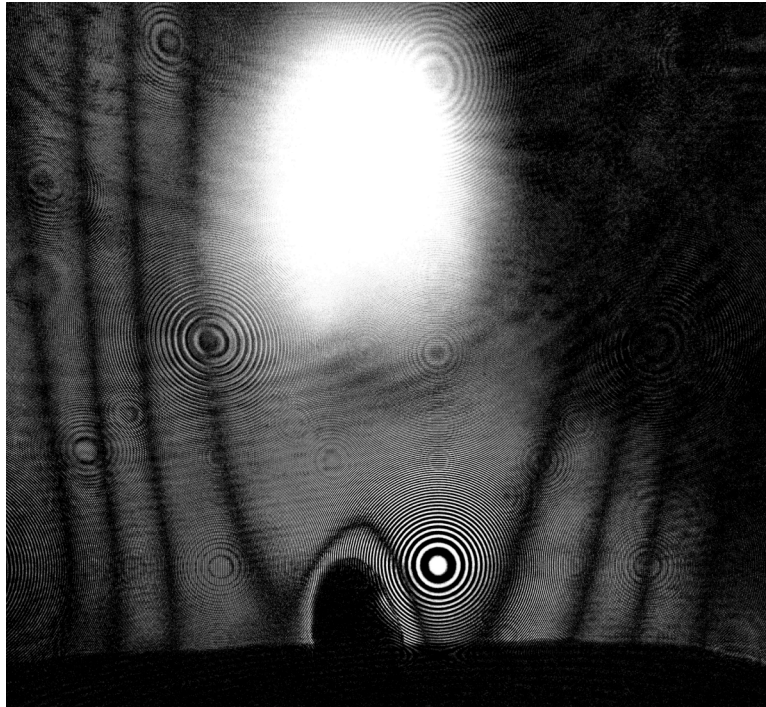


**Figure 6.3 - Holographic Interferogram of a candle flame (Vest, 1977)**

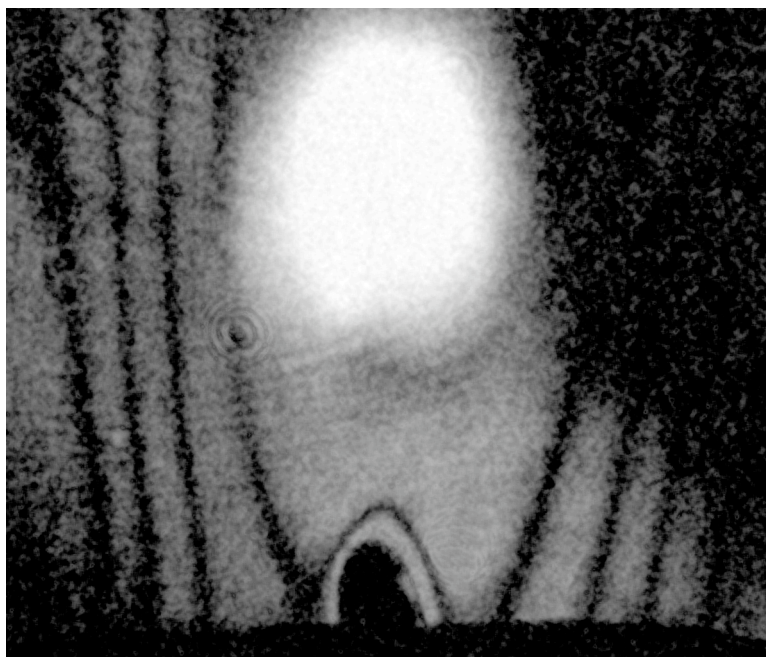


As explained in chapter 5 that in order to get the optimized fringe visibility, complete removal of the diffraction patterns was not possible. Image post processing therefore needed to be done i.e. the image needed to have a filter applied to it to remove the noise.

Figure 6.5 is a filtered image of figure 6.4. The diffraction patterns have been removed, and the fringes are clearly visible. Figures 6.4 and 6.5 produce the same results as that of figure 6.3, thus confirming the reliability of ESPI.



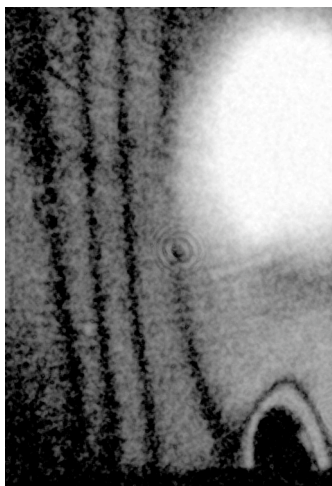
**Figure 6.4 – Original image**



**Figure 6.5 – Filtered Image**

### 6.2.2 Analysis

Equation 6.2 predicted that there should be 7 – 8 dark fringes visible in a candle interferogram. The fringes formed on the image represent lines of constant density/temperature (in 2-D). The fringes will occur between the maxima and minima temperatures (i.e. the fringes will represent the temperatures between 1600 K and 295 K).



**Figure 6.6 – Cropped image**

Since it was assumed for the calculation that the interferogram was axis-symmetric, it is then possible to assume that the fringes formed will be symmetrical about the candlewick.

The predicted number of fringes was 8 and therefore four fringes will be seen if only one side of the interferogram is analyzed. Figure 6.5 is a cropped image of figure 6.4 highlighting only those fringes in the left of that image.

As explained above that the fringes represent lines of constant temperature. The four visible dark fringes in figure 6.5 represent the temperature change, the outermost fringe at the edge of the picture represents ambient temperature (295 K) and the fringe directly above the wick represents the hottest part of the flame ( $\pm 1600$  K).

The fringe directly above the wick and the one directly to the left of it represent the same line of constant temperature, this is the blue part of the flame (Figure 6.7).



**Figure 6.7 – Candle with flame colours**

Figure 6.7 on the previous page is a picture of a candles flame, as can be seen that near the wick the flame is a blue colour, this is the hottest part of the candle flame (<http://hypertextbook.com/facts/1999/JaneFishler.shtml>), the colours of a candles flame range blue to yellow to orange to red.

These colours indicate the temperature range as blue has the shortest wavelength of the abovementioned colours hence the fact that the part of the flame that is blue in colour is the hottest part. This is due to the fact the blue colour indicates that more heat energy is being released as a shorter wavelength indicates higher energy. The other colours show the decreasing temperature range of the flame (yellow-orange-red), the wavelengths of these colours increase indicating a decrease in energy release.



**Figure 6.8 – Superposition of candle images with fringes**

The above picture (Figure 6.8) is of two pictures superposed one upon another, the bottom image is that of a candle with a flame, the superposed picture on top of it is an interferogram of a candle flame. The purpose of this picture was to highlight the fringe formation around the blue part of the flame.

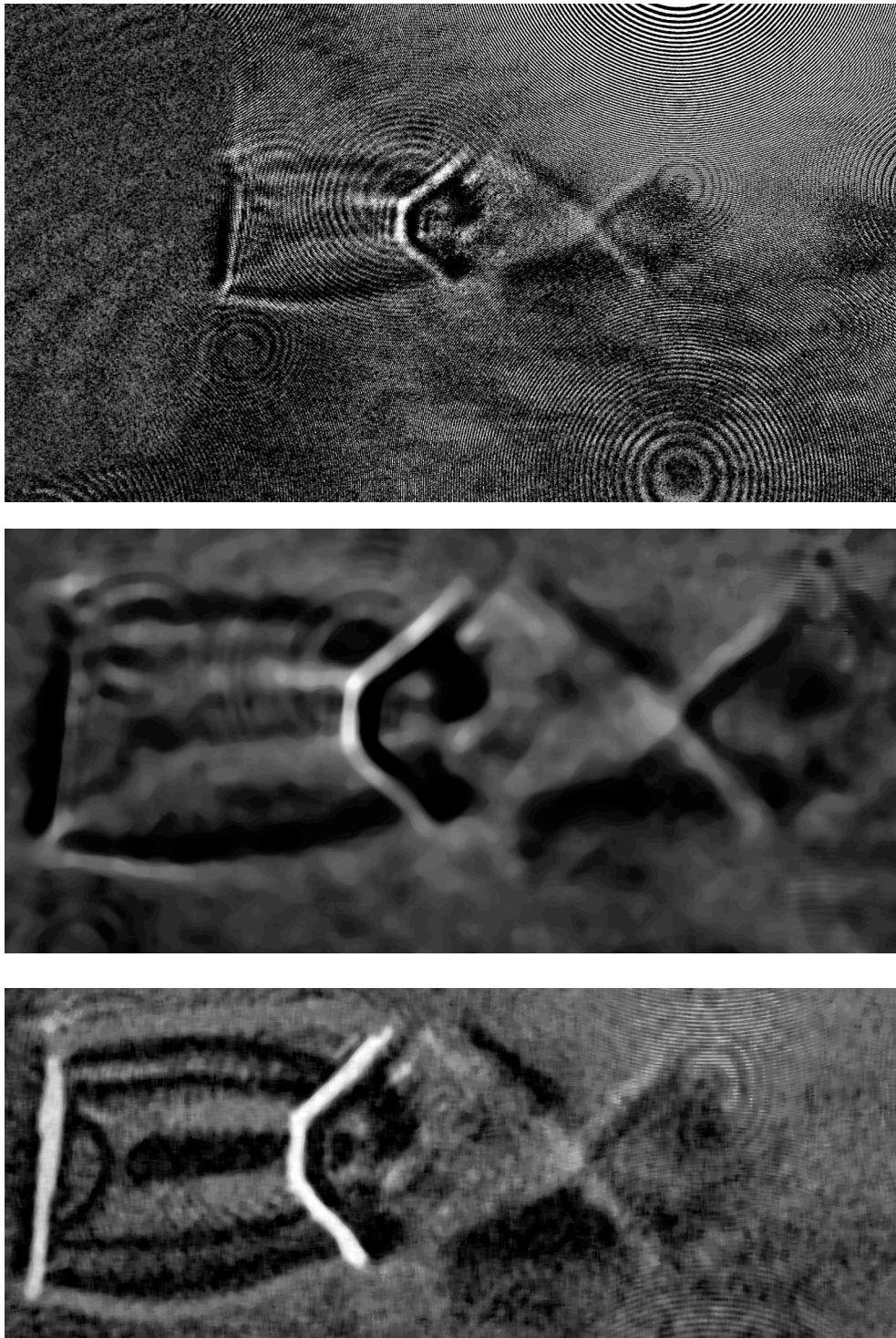
Since the blue part is the hottest part of the flame it would therefore be expected for a fringe to form around it. As is clearly evident that the first fringe (from the wick) is formed around the blue part of the flame. The blue part of the flame has the same temperature everywhere where it is blue and hence only one fringe is therefore formed around it. Figure 6.7 clearly shows the fringe formation at the exterior of the blue part of the flame.

An Abel transform (Section 4.5) must be used to quantitatively calculate the temperature at each individual fringe



### 6.3 Air Compressor Nozzle

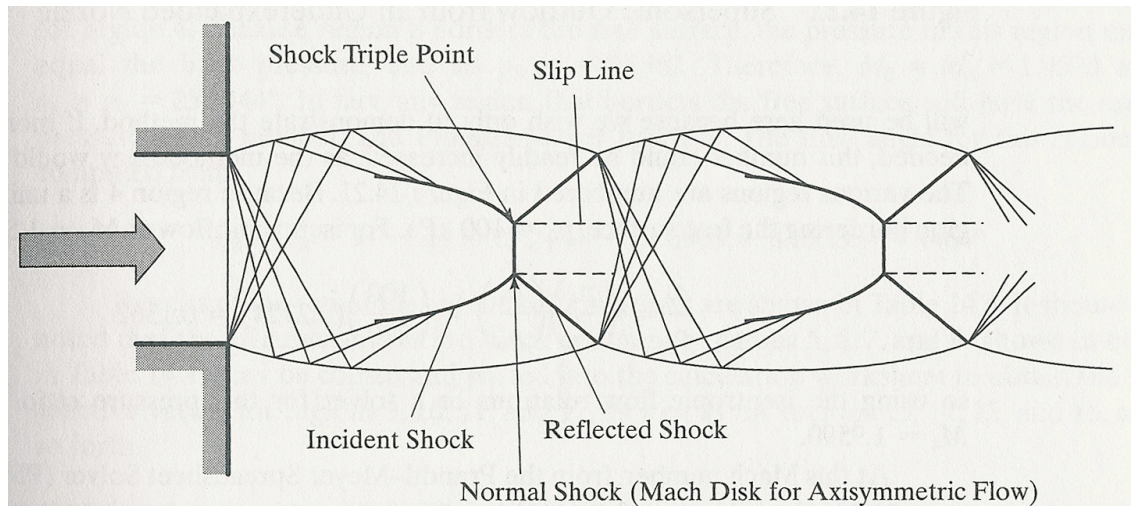
The air compressor nozzle produced the best results for axis-symmetric compressible flows.



**Figure 6.9 – Nozzle Interferogram with different filtering techniques**



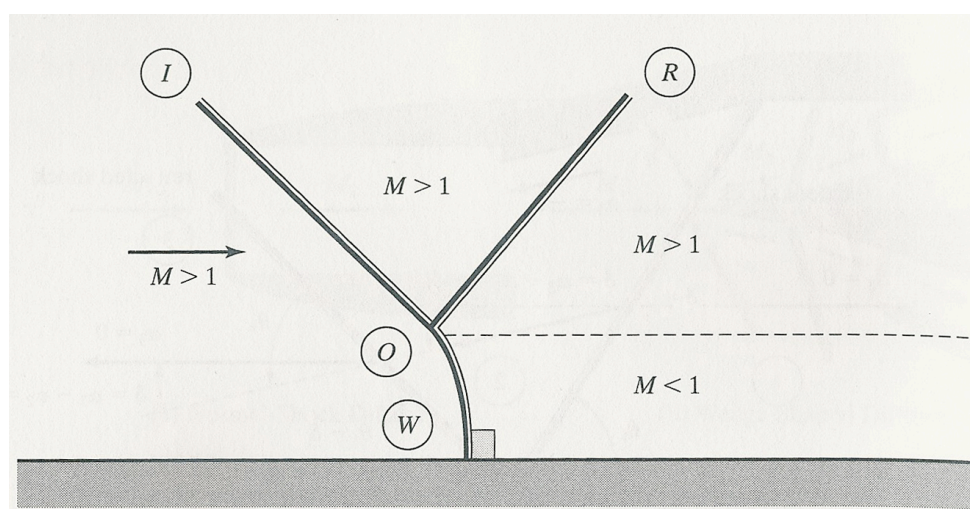
Figure 6.9 on the previous page details the different filtering techniques applied to the original interferogram (top picture). The middle and bottom pictures are post processed images of the top one, the middle picture had a larger radius applied to it when the filter median was applied, the bottom picture was enhanced slightly by applying a foreground colour to the defined areas of the interferogram (i.e. the Mach disk and its reflected shocks)



**Figure 6.10 – Underexpanded jet with a large pressure ratio (John, 2006)**

Figure 6.10 details the shock wave interaction typically found in an axis-symmetric underexpanded jet.

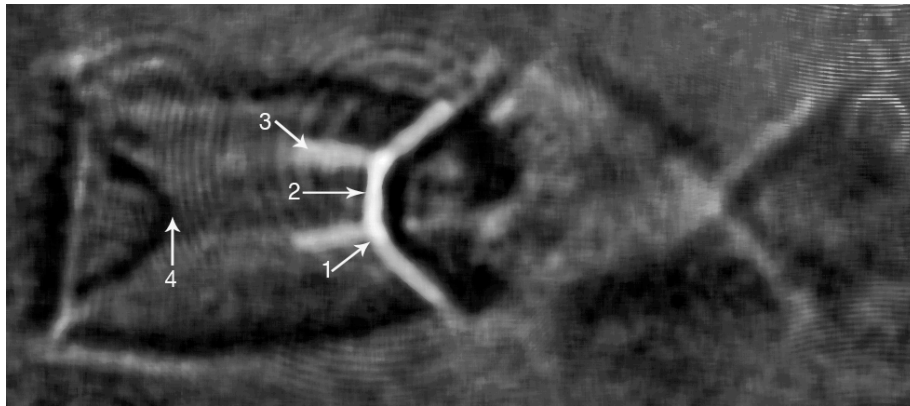
This phenomenon of a Mach disk with its reflected shocks occurs when the pressure mismatch at the orifice is large (steady state jets) For a detailed discussion of Mach disk and its reflections consult John (2006), Ben Dor (2001).



**Figure 6.11 – A Mach Reflection at a plane wall (John, 2006)**

Figure 6.11 on the previous page details the Mach reflection at a plane wall where I is the incident shock, R the reflected shock, O the oblique shock and W the wall. At O there is a triple point.

It would therefore be expected that at the Mach disk and at the incident and reflected shocks that fringes would occur



**Figure 6.12 – Nozzle interferogram for an underexpanded axis-symmetric jet**



**Figure 6.13 – Traced fringes**

The picture above (Figure 6.12) labels all the points of interest found in an underexpanded jet.

Point 1 is the shock triple point

Line 2 is the Mach disk

Point 3 is the incident shock

Point 4 is the first fringe formed as the fluid exits the nozzle

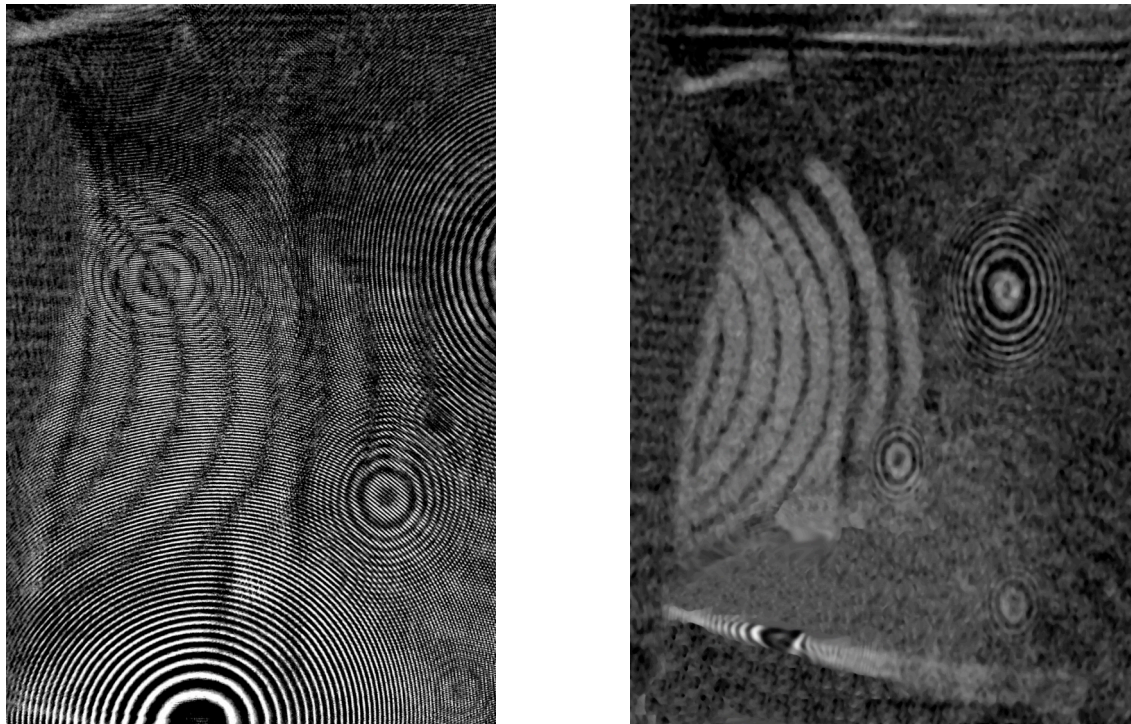
Figure 6.12 was an interferogram taken of an axis-symmetric underexpanded jet, thus one would expect fringes to occur at the boundary of the jet and at the points where the shocks interact as these are points at which steep gradient changes occur and therefore one would expect a phase shift to happen at these points.

Figure 6.13 was drawn to highlight the fringes that occurred in figure 6.12, the fringes were traced in Photoshop using the brush tool.

Figure 6.12 confirms the theoretical predicted result of figure 6.10 and thus confirms that for an axis-symmetric nozzle ESPI can be applied. Greater resolution is needed in order to derive fringe visibility between the boundaries of the jet. Point 4 (Figure 6.12) shows that fringes will occur in between the boundaries of the jet as opposed to only at shock waves and at there interaction points.

## 6.4 Non axis-symmetric jet

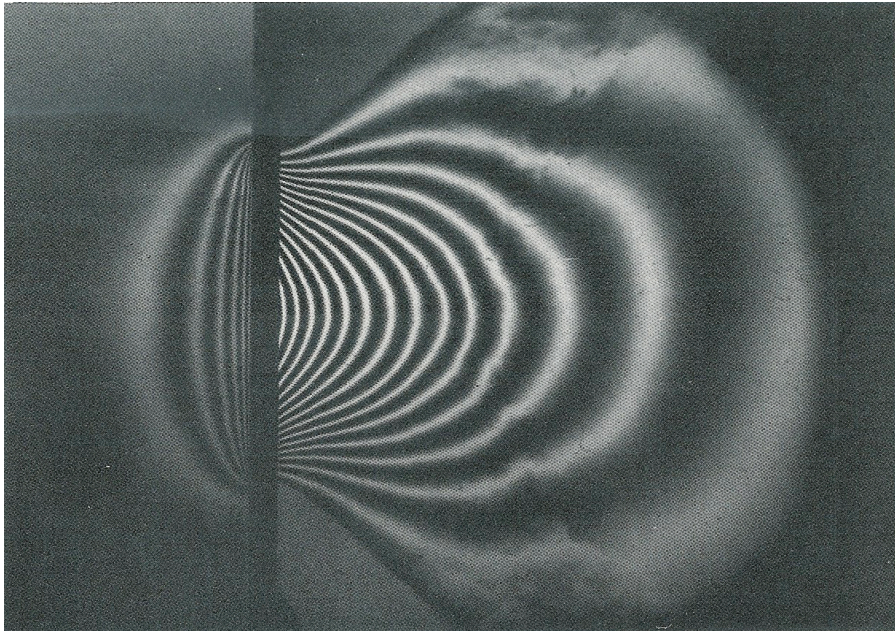
The non axis-symmetric jet produced the best fringes out of all the compressible flow experimentation, but due to it being non axis-symmetric the Abel Transform could not be applied to it in order to derive quantitative data from the fringes. However in view of the high aspect ratio of this nozzle , the flow of the exit will be approximately two-dimensional



**Figure 6.14 – Non axis symmetric Interferograms**  
**a) Original image** **b) Filtered image**

Figure 6.14 highlights the differences between the original and filtered image, the fringes exiting from the nozzle represent the constant density contours.





**Figure 6.15 – Circular orifice nozzle interferogram (Van Dyke, 1982)**

Figure 6.15 (Van Dyke, 1982) demonstrates the typical fringe dimensions and shape of a jet interferogram, and when compared to figure 6.13 it is clearly evident that the ESPI technique was applied successfully to compressible flow.

## Chapter 7

### ***Conclusion***

The main purpose of this study was to set up an interferometric flow visualisation technique that would be capable of taking interferograms of compressible fluid flows. Holographic interferometry was the first technique that was undertaken, however the laser was unfixable and therefore ESPI was the set-up that was chosen.

Once the system had been implemented the second purpose of the study was to improve on previous work done, as well as enhance the post processing of ESPI pictures as well as allowing for a movable set-up that could be used on any test rig.

The project proved to be successful, as ESPI verification occurred between previous and current work done in ESPI.

The technique was applied successfully to many different test rigs and specimens. The pictures of the candle flame proved that the technique had been set up successfully and provided the template for all other work done on compressible fluid flows.

The axis-symmetric jet (air compressor) nozzle showed the capability of ESPI in terms of full flow field analysis.

The non axis-symmetric jet proved the high sensitivity of the technique (indicated by the high fringe visibility) and its ability to be applied on different test rigs.

The missile geometry on the supersonic tunnel showed that ESPI has to have specific conditions for it to yield desirable results.

The interferogram pictures that were taken throughout this study showed that with advanced CCD technology, higher resolution pictures could be taken, which allow for greater fringe visibility and thus greater sensitivity.

The project overall was a success as it showed the versatility of ESPI in its ability to be applied to various test rigs and specimens and allow for a quantitative flow visualisation technique.

All the objectives of this study were met as an ESPI system had been built on various testing rigs, and interferograms have been taken on all of them

Improvements in image post processing have occurred resulting in better pictures.

The versatility of this system has been shown as the technique is sensitive and this project showed which types of flow visualisation tests yield the best results.



## References

Andrag, R. (2000), *Flow Visualisation using Electronic Speckle Pattern Interferometry (ESPI)*, MSc, The University of the Witwatersrand, Johannesburg, South Africa

Barbosa F.J. (2000), *Shock Wave and Shock Wave Vortex Interactions in a Bifurcated Shock Tube*, PhD, The University of the Witwatersrand, Johannesburg, South Africa

Ben Dor, G. & Igra, O., & Elperin, T. (2001), *Handbook of Shock Waves (Volume 2) Shock Wave Interactions and Propagation*, Academic Press, London

Coyne, G.S. (1997), *The Laboratory Companion*, John Wiley & Sons, New York

Dyson, J. (1959) Optical Diffusing Screens of High Efficiency, *Optical Society of America*, Vol. 50, pp. 519 – 520

Fomin, N.A. (1998) *Speckle Photography for Fluid Mechanics Measurements*, Springer – Verlag, Berlin

Hamed, A.M. & Sharaf, F. & El-Ghandour, H. (1993), Study of the Refractive index distribution around a candle flame, *Optics & Lasers*, Vol. 25 No. 2, pp. 113 – 116

John, J. & Keith, T. (2006), *Gas Dynamics*, Pearson – Prentice Hall, New Jersey

Jones, R. & Wykes, C (1989), *Holographic and Speckle Interferometry*, Cambridge University Press

Klein, H.A. (1970), *Holography*, J.B. Lippincott Company, Philadelphia

Klein, R. (1998), *Make your own Ground Glass*, Retrieved from <http://www.panphoto.com/Panorama/Panorama-December%201998.pdf>, pp 23.

Lafleur, T. *Design, construction and testing of a rocket model with a helium jet, for use in the supersonic wind tunnel*, Final year project report, School of Mechanical Engineering, University of the Witwatersrand, 2006.

McAndrew, A. (2004) Introduction to Digital Image Processing, Thomson, USA.

Menon N., Skews BW. Non-axisymmetric supersonic jet impingement. *25th International Symposium on Shock Waves*, Bangalore, India, 319-324, G Jagadeesh, E Arunan, KPJ Reddy (Eds.), Society for Shock Wave Research, IIS, 2005

Merzkirch, W. (1987), *Flow Visualization*, Academic Press, London

Serway, R.A. & Beichner, R.J. (2000), *Physics for Scientists and Engineers with Modern Physics*, Saunders College Publishing, Fort Worth

Shakher, C. & Nirala, A.K. (1999), A review on refractive index and temperature profile measurements using laser-based interferometric techniques, *Optics & Lasers in Engineering*, Vol. 31, pp. 455 – 491

Smith, F.G. & King, T.A. (2001), *Optics and Photonics*, John Wiley & Sons, New York

Tolansky, S. (1973), *An Introduction to Interferometry*, William Clowes & Sons, London

Van Dyke, M. (1982), *An Album of Fluid Motion*, The Parabolic Press, California

Vest C.M. (1977) *Holographic Interferometry*, John Wiley & Sons, New York

Weinberg, F.J. (1963), *Optics of Flames*, Butterworth & Co., London

<http://www.aerospaceweb.org/question/propulsion/q0224.shtml> retrieved 13th July 2007

[http://www.rpc Photonics.com/engineer\\_diffuser.htm](http://www.rpc Photonics.com/engineer_diffuser.htm) retrieved 20th March 2007

[http://www.cee.hw.ac.uk/hipr/html/hipr\\_top.html](http://www.cee.hw.ac.uk/hipr/html/hipr_top.html) retrieved 13th July 2007