HIGH-FRAME-RATE OIL FILM INTERFEROMETRY

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ABSTRACT

High-Frame-Rate Oil Film Interferometry

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This thesis presents the design and implementation of a high-frame-rate oil film interferometry technique (HOFI) used to directly measure skin friction in time dependent flows. Experiments were performed to determine the ability of a high-speed camera to capture oil film interferometry images. HOFI was found to be able to capture these interferometry images at frequencies up to 10^5 Hz. Steady laminar and turbulent flows were tested. Transient flows tested consisted of a wind tunnel ramping up in velocity and a laminar boundary layer which was intermittently tripped to turbulence by puffing air out of a pressure tap. Flow speeds ranged from 0 to 108 ft/sec and 10 and 50 cSt Dow Corning 200 dimethylpolysiloxane silicone oil was used. The skin friction was determined from the rate of change of the height of the oil film using lubrication theory. The height of the oil film was determined from the high speed camera interferogram images using a MATLAB script which determined fringe spacing by fitting a four-parameter sine wave to the intensity levels in each image. The MATLAB script was able to determine the height of the oil film for thousands of interferogram images in only a few minutes with sub-pixel error in fringe spacing. The skin friction was calculated using the oil film height history allowing for the direct measurement of skin friction in time dependent flows.

Keywords: High-frame-rate oil-film interferometry, shear stress, skin friction, lubrication theory, unsteady flow, high speed camera

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NOMENCLATURE

C_f	= Skin friction
τ_w	= Wall shear stress
q_∞	= Free stream dynamic pressure
h	= Height of oil film
λ_l	= Wavelength of light source in air
n_0	= Index of refraction of oil
θ_l	= Angle of incident light beam (measured from vertical)
θ_0	= Angle of light beam in oil film (measured from vertical)
μ_0	= Viscosity of oil
$\mu_{o,T}$	= Viscosity of oil at temperature T
μ_a	= Viscosity of air
ρ_0	= Density of oil
$\rho_{o,T}$	= Density of oil at temperature T
ρ_a	= Density of air
$\nu_{o,T}$	= Kinematic viscosity of oil at temperature T
γ_0	= Oil specific gravity
r	= Fringe visibility
$\frac{\Delta s}{\Delta t}$	= Change in fringe spacing vs. change in time

1. Introduction

The skin friction, defined as the local shear stress exerted by a viscous flow on a solid boundary, gives rise to crucially important flow phenomena such as viscous drag on air and ground vehicles, on wind turbine blades, and losses in internal flows. Measurement of skin friction is important in providing insight into these flows as well as validation for computational fluid dynamics techniques. Skin friction measurements are carried out in a variety of methods^{1,2}. These methods can be classified as either direct or indirect depending on whether the method is sensitive to shear stress directly or must be related to shear stress through an analogy or calibration; Figure 1.1 provides a taxonomy of skin friction measurement methods.

Skin Friction Measurement Methods	
<u>DIRECT</u>	<u>INDIRECT</u>
- Floating Element	- Velocity/Pressure
- Oil Film	- Clauser Plot
- τ Liquid Crystal	- Wall V (PW, HW, LDV)
	- Preston/Stanton/Fence
	- Heat Transfer
	- Wall Wire/Film
	- T Liquid Crystal
	- Electrochemical
	- Mass Transfer
	- Sublimation
	- Evaporation

Figure 1.1: Taxonomy of skin friction measurement methods

Among the skin friction measurement techniques only a few have been used to measure *unsteady* skin friction. These techniques include the hot wire/hot film, mass transfer, floating element, and τ liquid crystal. To date, oil film interferometry has only been used for measurement of steady or time-averaged skin friction. The objective of this thesis was to adapt the oil film interferometry method for use as a direct method of *time-dependent* skin friction measurement. This new *direct* measurement of *time resolved* skin friction would enable new applications to flows on vehicles during maneuver, rotorcraft blades, turbomachines, and pulsatile duct flows and measurement of flow fluctuations associated with large-scale vortex shedding, separation and stall, and perhaps even small-scale boundary layer turbulence.

The first practical implementation of the oil film method was developed by Tanner and coworkers in the 1970s⁶⁻¹². Being a direct measurement method, the oil film technique is widely applicable because it may be used without having knowledge of the state of the flow, such as: if the boundary layer is thick or thin, if the flow is laminar or turbulent, compressibility, three-dimensionality, or the rheology of the fluid. The oil film method is performed by applying oil to a surface and as fluid passes over the surface the oil thins into a thin film. Tanner and Blows⁶ established that the motion of an oil film is due to the forces of gravity, pressure gradients, surface tension, acceleration of the surface, and skin friction; and in most cases the skin friction is the dominant force. If an accurate thinning rate of the oil can be measured, lubrication theory can be used to find the skin friction acting on the oil. Fizeau interferometry¹³ is used to make the thickness

measurements and to determine the thinning rate of the oil film. Figures 1.2 shows a schematic of the technique.

Figure 1.2: Oil film interferometry schematic

A fraction of the light coming from the light source is reflected from the air-oil interface and combines with light reflected from the oil-surface interface to form either constructive or destructive interference depending on the relative phases of the two light waves. As the oil film thins it creates a wedge shaped cross-section which produces alternating light and dark fringes. Figure 1.3 shows an example of this.

Figure 1.3: a) On the left is an example of the light adding constructively to produce a light fringe and on the right an example of light adding destructively to produce a dark fringe b) fringes created by Fizeau interferometry

Each fringe represents a thickness difference in the oil of λ_o , equal to^{15,20}:

$$\lambda_o = \lambda_l / (2n_o \cos \theta_o) \quad (1)$$

where λ_l is equal the light source wavelength in air, n_o the index of refraction of the oil, and θ_o equal to:

$$\theta_o = \sin^{-1} \left(\sin \theta_l / n_o \right) \quad (2)$$

where θ_l is equal to the angle of the incident light beam measured from vertical.

If N is the number of optical fringes at some point in the film then the oil film thickness is:

$$h(x, t) = \lambda_o N(t, x) \quad (3)$$

In his paper in 1961, Squire³ derived the thin-oil-film equation from a control volume analysis of an oil film with air flow applied to its upper boundary. These concepts were applied by Tanner and co-workers⁶⁻¹² in their implementation of the oil film technique. Other underlying principles of the oil film method were also known before Tanner's work and should be noted^{4,5}. Since its development, the measurement of time-averaged skin friction from the measurement of the thinning of an oil film has become a well-established and widely used method².

Several varieties of the oil film interferometry (OFI) method exist and they are called laser interferometry skin friction (LISF), fringe imaging skin friction (FISF), global imaging skin friction (GISF), and surface imaging skin friction (SISF) techniques. The variety of these techniques have been well described by Naughton and Sheplak² in a review paper on oil film interferometry. Of particular interest for the present purpose is the work done by Murphy and Westphal¹⁴ in which it was shown that the rate of change in the height of the oil film *instantaneously* responds to changes in skin friction. The paper proposed that if it were possible to instantaneously measure the oil thinning rate it would provide an instantaneous measurement of skin friction. With the recent advances in the technology of imaging devices it is now possible to use a high speed camera to make these high-rate direct measurements of time dependent skin friction using the oil film interferometry method.

Highly Viscous Flow (Lubrication) Theory

Squire³ derived the thin-oil-film equation by applying a control volume analysis on an oil film with its upper boundary subjected to an external shear flow.

$$\frac{\partial h}{\partial t} = \frac{1}{\mu_0} \left\{ \frac{1}{3} \frac{\partial}{\partial x} \left(h^3 \frac{\partial p}{\partial x} \right) - \frac{\mu_a}{2} \frac{\partial}{\partial x} \left[h^2 \left(\frac{\partial u_a}{\partial y} \right)_{y=h} \right] + \frac{1}{3} \frac{\partial}{\partial z} \left(h^3 \frac{\partial p}{\partial z} \right) - \frac{\mu_a}{2} \frac{\partial}{\partial z} \left[h^2 \left(\frac{\partial w_a}{\partial y} \right)_{y=h} \right] \right\} \quad (4)$$

Where h is the height of the oil, μ_o and μ_a are the viscosity of the oil and air respectively, p is pressure, and u_a and w_a are the velocity components of the air.

If the pressure gradient terms are sufficiently small and by aligning the direction of the flow in the x-direction, Equation (4) reduces to:

$$\frac{\partial h}{\partial t} = \frac{1}{\mu_0} \left\{ -\frac{\mu_a}{2} \frac{\partial}{\partial x} \left[h^2 \left(\frac{\partial u_a}{\partial y} \right)_{y=h} \right] \right\} \quad (5)$$

If the velocity of the air is much greater than the velocity of the oil, then $(\partial u_a / \partial y)_{y=h} = \tau_w / \mu_a$ and Equation (2) further reduces to:

$$\frac{\partial h}{\partial t} = -\frac{1}{\mu_0} \frac{\partial}{\partial x} \left[\frac{h^2}{2} \tau_w \right] \quad (6)$$

If it is assumed the shear stress, τ_w , is spatially constant and constant in time then a linearized solution exists if it assumed the oil height is infinite at time of zero.

$$\tau_w = \frac{\mu_0 x}{ht} \quad (7)$$

Although τ_w is not always spatially constant it has been shown to be a valid assumption for the oil film skin friction meter technique by Zilliac¹⁷ who used a finite difference numerical model to show the analytical and numerical models were in close agreement. Existing oil film interferometry methods use equation

(7) or a similar form to determine the shear stress over a large period of time for flows where the skin friction is assumed constant over that time. Murphy and Westphal¹⁴ proposed a different solution for the case of time dependent skin friction. If it is again assumed τ_w is spatially constant then Equation (6) can be solved for τ_w which gives:

$$\tau_w = \frac{\frac{\partial h}{\partial t}}{\frac{\partial}{\partial x} \left(\frac{1}{\mu_0} \frac{h^2}{2} \right)} \quad (8)$$

Using a high speed camera and Fizeau interferometry to measure the thickness of the oil film as a function of space and time, equation (8) may be solved to determine the time dependent skin friction.

The objective of this thesis was to adapt the oil film interferometry method for use as a *direct* measurement method of *time-dependent* skin friction. The recent advances in the technology of imaging devices now makes it possible to use a high speed camera to make the high-rate measurements needed to measure the thinning rate of an oil film under the influence of time-dependent skin friction to determine the instantaneous skin friction acting on the surface. Being a direct method of skin friction measurement, the high-frame-rate oil film interferometry technique, or HOFI, requires no knowledge of the state of the flow, such as: if the boundary layer is thick or thin, if the flow is laminar or turbulent, compressible, three-dimensional, or the rheology of the fluid whose skin friction is to be measured. The new technique will allow for new insight into complex flow phenomena over a variety of both forced and natural unsteady flows.

2. Instrument Design

Two versions of the HOFI (high-frame-rate oil film interferometry) instrument were designed and used to make skin friction measurements. The first was a proof-of-concept instrument, called v1.0 HOFI. The v1.0 HOFI instrument was designed from readily available equipment and used to better understand the challenges associated with making HOFI measurements. Deficiencies in the v1.0 HOFI instrument were identified and used to design an improved v1.1 HOFI instrument. To determine what equipment was to be used in the proof-of-concept v1.0 HOFI a review of past OFI techniques and their equipment was necessary and is presented below.

Many oil film interferometry techniques exist². Among them are point techniques, line techniques, and image techniques, however, there are some common components to all of the techniques. All require oil, an image acquisition device, a form of illumination, and a reflective test surface. A goal when choosing these components is to maximize the fringe visibility, r , which can be defined as¹⁷:

$$r = \frac{(I_{max} - I_{min})}{(I_{max} + I_{min})} \cdot 100\% \quad (9)$$

where I_{max} and I_{min} are the fringe intensity maximums and minimums respectively. The components for v1.0 HOFI were selected with the goal of maximizing the fringe visibility r as well as other considerations such as availability of equipment and optical access to the test surface.

Oil

Since the development of the oil film method silicone oil has been used. This is because its viscosity is relatively insensitive to temperature changes, it is clear, it is non toxic, easy to clean, and has a relatively large index of refraction. Evaporation of oil can be a problem because it would make the oil appear to thin faster than it really is and would result in an overestimation of the skin friction measurement. Silicone oil has a very low vapor pressure and in most testing cases does not pose a problem with evaporation^{2,21}. Dow Corning 200 dimethylpolysiloxane is a silicone oil available in a large range of viscosities, and is the oil of choice in most of the referenced reports; Table 2.1 lists its key physical properties.

Table 2.1: Physical properties of Dow Corning 200 oil at 25°C.²⁸

$\nu_{0,nom}$ [cSt]	10	50	100	200	500	1000	10000	30000
γ_0	0.934	0.960	0.964	0.967	0.969	0.970	-	0.971
n_0	-	1.4022	1.4030	1.4032	1.4034	1.4035	1.4036	1.4037
α_0 [(cc/cc)/°C]	0.00108	0.00104	0.00096	0.00096	0.00096	0.00096	-	0.00096

Although silicone oil viscosity is less sensitive to temperature change than most oils, it is still one of the leading sources of uncertainty in OFI measurement of skin friction. The temperature should be closely monitored during testing and the oil viscosity should be temperature corrected using an approach such as the one Zilliac¹⁷ proposed in which the viscosity at the temperature of the wind tunnel is calculated based on the viscosity at the calibration temperature:

$$\nu_{0,T} = \text{Exp} \left[\frac{c_1}{T+c_2} - \frac{c_1}{T_{cal}+c_2} + \ln(\nu_{0,cal}) \right] \quad (10)$$

where T is in Kelvin, $C_1 = 774.8622$, and $C_2 = 2.6486$. The oil's specific gravity can be corrected using the manufacturer provided equation:

$$\gamma_{0,T} = \frac{\gamma_{0,T=25^{\circ}\text{C}}}{1+\alpha[T-25]} \quad (11)$$

where T is in $^{\circ}\text{C}$ and α is the coefficient of expansion and is given in Table 2.1.

Image acquisition

In HOFI the need to capture large numbers of interferograms in a short period of time requires the use of a high speed imaging system. Vision Research's V310 is a general-purpose commercial high speed camera with microsecond exposure times and frame rates well over 10 kHz. The camera is an available resource at Cal Poly and so it was used in the high-frame-rate oil film interferometry method presented in this paper.

Light Source

To accurately measure the thickness of the oil film using oil film interferometry a monochromatic or quasi-monochromatic light source is required. Original methods used by Tanner et al.⁶⁻¹² used a He-Ne laser because of the advantages of it being a monochromatic source and having a long coherence length. A drawback of using lasers is that, when used to illuminate a large area, a speckle pattern can be introduced^{17,18}. Other non laser sources have been used and have the advantage of being lower in cost and are able to light a larger area without problems of speckle. If non laser sources are used, a filter can be used to

isolate a narrow bandwidth of the light. Table 2.2 lists several light source options.

Table 2.2: Light sources used in oil film interferometry²

Light Source	Wavelength (nm)
He-Ne laser	632.8
Fluorescent lamps	Green - use with filter
Sodium lamp	Strong peak at 589
Mercury lamp	Strong peaks at 435.8, 546.1
Xenon flash	Broadband - use with filter

Surface Type

To provide the necessary reflection properties for interferometry the test surface must be smooth and have a high index of refraction. The goal in choosing an index of refraction is to match the reflectance of the air-oil interface to the oil-surface interface. Reflectance is defined as the ratio of the reflected power to the incident power. This is achieved by having equal relative indices of refraction, n_{ti} , defined as²⁰:

$$n_{ti} = \frac{n_t}{n_i} \quad (12)$$

Where n_t and n_i are the indices of refraction of the transmitter and incident materials respectively. Silicone oil has an index of refraction of $n = 1.4$ with air having an index of refraction of $n = 1.0$, giving the air-oil interface a n_{ti} value of 1.4. To match this n_{ti} , the surface should have an index of refraction near 2.0.

Zilliac¹⁷ investigated several surface materials in a study in 1996. He found the best surface material to be a high flint content SF11 glass manufactured by Shott Glass Co. with an index of refraction of $n = 1.78$. He also

investigated spray-on surface coatings such as ElectraMates Epoxy and Zynolyte epoxy paint and found them both to produce fringes of high quality. Mylar film is another test surface which produced good quality fringes and is a cost effective solution. In his master's thesis, Ehrmann²⁹ investigated using a polyurethane enamel, true black Imron®. He found the coating to be very durable and produced better fringe visibility than polished stainless steel. Tanner¹⁹ and Westphal et al.¹⁵ reported that the best fringe visibility occurred on metal-coated glass surfaces. Westphal et al.¹⁵ chose to use chromium plated glass because of its optical qualities and its abrasion resistance to reduce degradation in surface reflection due to repeated use. The back of the glass surface was treated with an antireflective coating of MgF_2 . The authors also suggest pure sapphire as an alternative and expect it to give reasonably good fringe visibility.

Proof-of-Concept Instrument: v1.0 HOFI (High-Frame-Rate Oil Film Interferometry)

The proof-of-concept instrument used a high-speed camera, Vision Research's v310. The Vision Research v310 is a general-purpose commercial high-speed digital video imaging camera which can provide microsecond exposure and frame rates beyond 10 kHz. The proof-of-concept instrument also used self-ballasted mercury vapor lamps, a narrow bandwidth filter, chromium-coated glass test surface, the high speed camera with a general purpose lens, and a 1 ft diameter indraft low speed wind tunnel. Because of the low air speed

of about 45 ft/sec, 10 cSt Dow-Corning 200 dimethylpolysiloxane oil was used for its low viscosity. The lower the viscosity of the oil the faster the oil will thin and the changes in the height of the oil will be easier to measure. Mercury vapor lamps were chosen because of their ability to illuminate a large surface area. The lamps were reflected off a diffuse surface and onto the test surface. Figure 2.1 and 2.2 show a close-up of v1.0 HOFI including camera, illumination, and test surface and the 1 ft indraft wind tunnel.

Figure 2.1: Wind tunnel test section with camera, illumination, and test surface for v1.0 High-Frame-Rate Oil Film Interferometer trials. Not shown is the diffuse surface which reflected light onto the test surface.

Figure 2.2: 1-ft diameter indraft wind tunnel.

Because the wind tunnel was not fitted with an air filter, its flow was contaminated by particulates which compromised the quality of the interferograms. And, the optics and illumination used limited the spatial resolution and frame rates that could be employed. Nonetheless, the interferograms obtained occasionally displayed regions of particulate-free oil flow which persisted for a few seconds. One such sample interferogram is shown in figure 2.3, obtained with turbulent flow and 10 cSt Dow-Corning 200 dimethylpolysiloxane oil flow on a chromium-coated glass test surface. On average, the fringe visibility for v1.0 HOFI was 15%, where the fringe visibility is again defined as shown in equation (9).

Figure 2.3: Oil film interferogram acquired using mercury vapor lamp illumination, taken with Vision Research v310 general-purpose high-speed digital video camera.

The frame rates and spatial resolution from v1.0 HOFI were not sufficient to attempt differentiating the interferogram data to compute instantaneous thinning rate, but it appeared likely that improved optical resolution, illumination, and a cleaner flow facility would allow higher frame rates and provide the improved image quality and signal-to-noise ratio that would lead to differentiable results.

v1.1 HOFI (High-Frame-Rate Oil Film Interferometry)

Deficiencies in the v1.0 HOFI instrument were identified and used to design an improved v1.1 HOFI instrument with improved optical resolution, illumination, and a cleaner flow facility. The v1.1 instrument used the same Vision Research v310 high speed camera and chromium-coated glass test surface but a diode laser light source, a reversed 50 mm camera lens, and a 2' by 2' wind tunnel. A pressure tap, located upstream of the test surface, was plumbed with a syringe pump to intermittently puff air to trip turbulence. This gave control over when the flow would be laminar or turbulent. The same 10 and 50 cSt Dow-Corning 200 dimethylpolysiloxane oils were used. Higher viscosity oil was tested but the 10 and 50 cSt oils produced the best results due to their low viscosities. Figure 2.4 shows a schematic of v1.1 HOFI.

Figure 2.4: Wind tunnel test section schematic for v1.1 HOFI

In place of the mercury vapor lamps, a laser line generator was used. The intensity of the light from the mercury vapor lamps was not high enough to operate the high speed camera at exposure times faster than 1200 μsec and consequently frame rates were limited to about 800 Hz. A laser light source was therefore chosen for its high intensity which allowed the camera to operate at frame rates in excess of 10 kHz. A low power, 1 mW 635 nm red diode laser was expanded into a line using a cylindrical lens and a double-convex lens. Figure 2.5 shows a schematic of the optical setup of the laser line generator. The approximate dimensions of the laser line were 0.5 in. long and 0.05 in. wide. Also, neutral density filters were attached to the camera lens. The ND filters were

necessary to attenuate the high intensity laser light which would saturate the camera's photo detector without attenuation.

Figure 2.5: Laser line generator

A camera lens which would provide more magnification and spatial resolution was chosen. A standard Nikon 50 mm focal length lens was mounted in reverse using a reversing ring. The reversing ring screwed into the filter threads on the front of the lens and mounted to the camera using a standard f-mount. This created a fixed focal length lens with magnification of nearly 1:1. When a lens is reversed the ability to focus using the focusing ring on the lens is

lost and the entire camera must be moved to bring the object into focus. For the lens used here, the working distance (the distance from front of lens to the object) became very small, about 3.75 inches for the 50 mm Nikon lens. The flat plate was therefore moved close to the top of the wind tunnel test section. A frame constructed from aluminum extrusions secured the camera and laser line generator above the wind tunnel test section. The frame was easily adjusted in order to line up the laser line and camera. Figure 2.6 shows a schematic of the camera, lens, and laser line generator.

Figure 2.6: Optical set-up of v1.1 HOFI

The 1 ft diameter indraft wind tunnel was replaced by Cal Poly's 2' x 2' wind tunnel. The 2' x 2' wind tunnel was a much cleaner facility than the 1 ft. wind tunnel and trouble with particulate laden flows was greatly reduced. The 2' x 2'

wind tunnel also had the advantage of being able to control the air speed during test runs. This allowed for testing of multiple speeds during the same run and allowed for certain transient conditions to be tested.

The chromium-coated glass test surface was set into an elliptical nose aluminum flat plate which is shown in Figure 2.7. The flat plate was mounted using brackets in the wind tunnel test section.

Figure 2.7: Chromium coated glass insert in aluminum flat plate

Sample interferograms from the same flow at three different times obtained with laminar flow at a distance of 8 inches from the leading edge and a free stream velocity of 54 ft/sec are shown in Figure 2.9. 10 cSt Dow-Corning 200 dimethylpolysiloxane oil was used on a chromium-coated glass test surface. Due to the improvement in light source the fringe visibility increased from 15% for v1.0 HOFI to 25% for v1.1 HOFI.

Figure 2.9: Oil film interferogram acquired using laser-line illumination, taken with Vision Research v310 general-purpose high-speed digital video camera.

3. Fringe Spacing Identification

In order to extract the oil thickness information stored in the interferograms, accurate fringe spacing measurements had to be made. In the past this procedure was performed using many different methods. Original methods were tedious, requiring manual measurement of photographs either by hand or by using an image processor such as Photoshop. Zilliac²² developed a computer application which partially automated the task of determining the fringe spacing from the interferometric intensity records. The method used a nonlinear regression model to accurately determine the fringe spacing. The method requires the user to locate the beginning of the fringe as well as a point two fringes downstream. Decker and Naughton²³ developed an automated method using a windowed Fourier transform and a correlation technique capable of locating fringes in an image. The authors report the technique is able to identify approximately seventy percent of the fringes in the image.

High-frame-rate oil film interferometry produces huge numbers of interferograms. Therefore, the technique chosen to determine the fringe spacing had to be accurate, completely automated, and rapid. It was evident a new technique for determining the fringe spacing had to be developed to be able to accomplish the fitting of such a large number of interferograms in a reasonable amount of time. A MATLAB script was written to determine the fringe spacing, because of its ability to quickly and autonomously process many interferograms in a short amount of time. A description of how the algorithm was implemented is given below and a copy of the MATLAB script can be found in Appendix A.

The Vision Research v310 high speed camera has internal volatile memory in which videos are recorded to. After each wind tunnel run the recorded video was transferred from the video camera to a personal computer where it was processed. The Vision Research *.raw* video file type was converted to a single multipage *.tiff* file which was used by the MATLAB script file.

The MATLAB script required a minimal amount of input from the user who decided what region of the interferograms was to be fitted. This was usually an area near the leading edge of the interferograms roughly 10 pixels tall and 50 to 100 pixels long, in the spanwise and flow directions respectively. Figure 3.1 shows an example interferogram with the chosen region to be fitted.

Figure 3.1: Sample interferogram showing the region to be fitted highlighted in blue and reproduced in an enlarged image (Note: flow is from left to right)

The MATLAB script took the region to be fitted and averaged the spanwise pixels to create the data set which was then fitted. The data set had the form of averaged intensity values vs. the x-coordinate values. Because the thickness of the oil film varied linearly with distance from the leading edge, the

interferometry fringes were equally spaced and the interferogram's light intensity variations were periodic. An example data set from the averaged spanwise intensity values vs. x-location (flow direction) from the region to be fitted is shown in Figure 3.2 below.

Figure 3.2: Sample data set taken from an interferogram

The MATLAB script fit a four-parameter sine wave of the form $f(x) = C_1 \sin(C_2x + C_3) + C_4$ to the data set by using a function which minimized the rms error between the values of the data set and the sine wave. The MATLAB minimizing function used was `fmincon`, a constrained nonlinear multivariable function.

As with most optimization techniques, adequate initial estimates for the four parameters of the sine wave were required for the function to find the global minimum in rms error as opposed to a local minimum in rms error. In a sine wave of the form $f(x) = C_1 \sin(C_2 x + C_3) + C_4$, C_1 represents the amplitude of the sine wave. An initial guess for this parameter was made by finding the range of the intensities and dividing it in half. C_3 represents a phase shift in the sine wave, and an initial guess of zero was chosen for this parameter. C_4 is an offset from the x-axis and represents an average pixel intensity value. An initial guess for this parameter was easily made by averaging the intensity values of the first interferogram.

C_2 represents the frequency, or wavelength, of the sine wave. This is the parameter of most importance because it is the fringe spacing in the interferograms. An initial guess was made using a fast Fourier transform algorithm. Many other OFI fringe measurement techniques use a FFT to entirely determine fringe spacing. However for the case of HOFI the FFT does not give the accuracy desired because an FFT only has spatial resolution of half a pixel. Because the high speed camera does not allow for the same spatial resolutions and amount of pixels as a still camera, higher fringe fitting accuracy was needed.

The initial guesses for C_1 , C_2 , C_3 and C_4 were then used by the `fmincon` function as the starting point in its minimization of the first interferogram's fit error. The function varied the four parameter values until a minimum in the rms error was found. Lower and upper bounds were placed on the parameters and were chosen based on physical constraints. This prohibited the minimizing

function from varying a parameter too far in one direction which could lead to finding a local minimum in the rms error. Because there was such a small time step between subsequent interferograms the values for the four parameters did not change drastically from interferogram to interferogram. Therefore, once the first interferogram was fitted using the calculated guesses for the four parameters of the sine wave, each subsequent interferogram used the previous interferogram's fitted values as new initial estimates for the new interferogram's fit. Figure 3.3 shows an example of the four parameter sine wave fitted to the data from Figure 3.2.

Figure 3.3: Sample data set fitted with the four-parameter sine wave

After an interferogram was fit using the minimizing function, the fringe spacing was determined from the fitted value of the frequency, C_2 , parameter. The fringe spacing, s , was found by taking the inverse of the frequency and

multiplying by 2π , or: $s = 2\pi/C_2$. The change in the fringe spacing between two subsequent interferograms was then used to determine the skin friction acting on the surface during the time between the two interferograms.

4. Wind Tunnel Results

After construction and implementation of the v1.1 High-frame-rate oil film interferometry instrument, testing was done to determine the instrument's ability to measure *time-dependent* skin friction. Testing involved three parts; first, v1.1 HOFI was used to measure the skin friction in a steady laminar flow. Next, skin friction measurements were taken while the wind tunnel was ramped up, providing a transient flow and a time-dependent skin friction. Finally, a second time-dependent scenario was tested which consisted of a laminar boundary layer being intermittently tripped to turbulence by puffing air out of a pressure tap upstream of the test surface.

Testing of a steady laminar flow provided time-independent skin friction and a chance to prove the instrument's capability of capturing oil thinning histories with sufficient optical resolution for fringe spacing identification. Testing was performed with wind tunnel velocities ranging from 27 ft/sec to 108 ft/sec. The results from one such test is shown below in figure 4.1. The wind tunnel velocity was 54 ft/sec giving a dynamic pressure of 3.4 psf and a local Reynolds number of about 3×10^5 . The distance from the plate leading edge to oil was 8 inches. The air temperature during the test remained at a constant 19.5 °C. 10 cSt dimethylpolysiloxane oil was used and the high speed camera captured 100 frames per second. A 50 mm focal length Nikon lens was mounted on the camera in reverse and a 0.3 neutral density filter was used to attenuate the laser

light (Note: a 0.3 neutral density filter blocks 30% of the light passing through the filter).

Figure 4.1: Fringe spacing vs. time: steady laminar flow, 54 ft/sec wind speed, 100 frames per second, 50 mm reversed Nikon lens, 10 cSt dimethylpolysiloxane oil. The time origin does not refer to when the wind tunnel was turned on but to when the camera was turned on. (Note: 1 pixel = 0.756×10^{-3} inches)

Because the air flow was steady, the oil thinned at a constant rate and the slope of the line in the figure 4.1 is constant. One pixel from the camera corresponded to 0.756×10^{-3} inches or 1323 pixels per inch. The slope of the line

in the plot is used to determine the skin friction acting on the surface. The calculation of the skin friction is shown below:

$$C_f = \frac{\tau_w}{q_\infty} = \frac{2n_o\mu_{o,T} \cos \theta_o \Delta s}{\lambda_l \left(\frac{1}{2} \rho_{air} V_{air}^2 \right) \Delta t}$$

where n_o is the index of refraction of the oil, $\mu_{o,T}$ is the viscosity of the oil at the testing temperature T , θ_o is the angle of refraction of the light in the oil, λ_l is the wavelength of laser light in air, and $\frac{\Delta s}{\Delta t}$ is the change in fringe spacing over the change in time, or the slope of the fringe spacing vs. time curve. The viscosity of the oil at the testing temperature T , is determined using temperature corrected values from table 2.1. The temperature corrected viscosity calculation is shown below where $\rho_{o,T}$ and $\nu_{o,T}$ are the temperature corrected density and dynamic viscosity of the oil respectively.

$$\mu_{o,T} = \rho_{o,T} \nu_{o,T}$$

Where:

$$\rho_{o,T} = \gamma_{o,T} \rho_{water}$$

$$\rho_{o,T} = \left(\frac{\gamma_{o,T=25^\circ\text{C}}}{1 + \alpha_o(T - 25^\circ\text{C})} \right) \cdot (\rho_{water})$$

$$\rho_{o,T} = \left(\frac{0.934}{1 + 0.00108(19.5 - 25^\circ\text{C})} \right) \cdot \left(1.94 \frac{\text{slug}}{\text{ft}^3} \right)$$

$$\rho_{o,T} = (0.940) \cdot \left(1.94 \frac{\text{slug}}{\text{ft}^3} \right)$$

$$\rho_{o,T} = 1.82 \frac{\text{slug}}{\text{ft}^3}$$

and using Zilliac's¹⁷ proposed temperature correction for $\nu_{0,T}$:

$$\nu_{0,T} = \text{Exp} \left[\frac{C_1}{T + C_2} - \frac{C_1}{T_{cal} + C_2} + \log_{10}(\nu_{0,cal}) \right]$$

$$\text{with } C_1 = 774.8622 \text{ and } C_2 = 2.6486$$

$$\nu_{0,T} = \text{Exp} \left[\frac{774.8622}{292.65 + 2.6486} - \frac{774.8622}{298.15 + 2.6486} + \ln(10 \text{ cSt}) \right]$$

$$\nu_{0,T} = 10.5 \text{ cSt}$$

Substituting these values into the viscosity equation gives:

$$\mu_{o,T} = \rho_{o,T} \nu_{o,T}$$

$$\mu_{o,T} = \left(1.82 \frac{\text{slug}}{\text{ft}^3} \right) \cdot \left(10.5 \times 10^{-6} \frac{\text{m}^2}{\text{sec}} \cdot \frac{(3.28 \text{ ft})^2}{\text{m}^2} \right)$$

$$\mu_{o,T} = 0.000206 \frac{\text{lb}_f \cdot \text{sec}}{\text{ft}^2}$$

The skin friction is then:

$$C_f = \frac{\tau_w}{q_\infty} = \frac{2n_o \mu_{o,T} \cos \theta_o \Delta s}{\lambda \left(\frac{1}{2} \rho_{air} V_{air}^2 \right) \Delta t}$$

$$C_f = \frac{2 \cdot 1.4 \cdot \left(0.000206 \frac{\text{lb}_f \cdot \text{sec}}{\text{ft}^2} \right) \cos(3.6^\circ)}{\left(635 \times 10^{-9} \text{ m} \cdot 3.28 \frac{\text{ft}}{\text{m}} \right) \left(3.4 \frac{\text{lb}_f}{\text{ft}^2} \right)} \cdot \left(0.2513 \frac{\text{pixels}}{\text{sec}} \cdot 0.063 \times 10^{-3} \frac{\text{ft}}{\text{pixel}} \right)$$

$$C_f = 0.00129$$

This value of skin friction is close to the estimated value of skin friction on a laminar flat plate with x-location = 8 inches and $U_\infty = 54 \text{ ft/sec}$ of $C_f = 0.0015$.

Because v1.1 HOFI was capable of making measurements in a steady laminar flow with acceptable frame rates and spatial resolution for the fringe spacing identification MATLAB program to work more complex transient flows were tested. The first transient test was a ramping up of the wind tunnel. An oil film was pre-thinned and then the wind tunnel was shut down. The wind tunnel was then restarted and ramped up to a velocity of 108 ft/sec or a dynamic pressure of 13.5 psf. Oil thinning histories were recorded during the ramp using the v1.1 HOFI instrument and results of the MATLAB fringe spacing program are shown in figure 4.2 below. 50 cSt dimethylpolysiloxane oil was used and 100 frames per second were recorded with the high speed camera. A 50 mm reversed Nikon lens and 0.3 neutral density filter were used.

Figure 4.2: Fringe spacing vs. time: laminar flow being ramped up in velocity from zero to 108 ft/sec, camera capture rate at 100 frames per second, 50 mm reversed Nikon lens, 50 cSt dimethylpolysiloxane oil.

At the beginning of the wind tunnel ramp, when the air velocity was low, the change in fringe spacing from one frame to the next is small — corresponding to a low skin friction. However, when the wind tunnel velocity increased so did the skin friction and the change in fringe spacing from one frame to the next began to increase. The fringe spacing vs. time curve then reached a constant slope at 48 seconds. This was due to the wind tunnel reaching and holding at its final dynamic pressure of 13.5 psf. Figure 4.3 is a reproduction of figure 4.2 with the initial zero velocity section of the ramp in

green, the ramping up of the wind tunnel velocity in blue, and the final steady-state velocity section in red.

The slope of the final steady-state portion of the curve is shown on the plot. The slope was used to determine the skin-friction acting on the test surface. The initial portion of the curve has no slope meaning the oil film height was not changing and there was no skin friction. The final steady-state portion of the curve has a constant slope corresponding to a constant skin-friction of $C_f = 0.001$. Although the MATLAB script was able to find the fringe spacing with sub pixel accuracy the interferograms were not of sufficient resolution to be able to differentiate the change in fringe spacing at a rate of 100 Hz. One second averages gave good slope accuracy and the skin-friction for the ramp portion of the curve could be accurately determined across the time step of one second.

Figure 4.3: Fringe spacing vs. time: laminar flow being ramped up in velocity from 0 to 108 ft/sec with the initial and final steady-states having lines fitted showing the slope of the curve. This slope corresponds to the rate of change of the height of the oil film.

A second time-dependent scenario was tested which consisted of a laminar boundary layer being intermittently tripped to turbulence. Figure 4.4 shows the v1.1 HOFI schematic which was described in the instrument design chapter. The test surface was placed downstream of a pressure tap which was plumbed to a syringe pump. The syringe pump was used to puff air out of the pressure tap which tripped turbulence in the downstream region. By controlling when the syringe pump puffed air, tests were performed to find the time-

dependent skin-friction in a flow which transitioned back and forth from laminar and turbulent flows.

Figure 4.4: Wind tunnel test section schematic for v1.1 HOFI

Figure 4.5 shows the results obtained from a test in which the boundary layer was repeatedly tripped to turbulence. The plot resembles a stair-step pattern with the steeper portions coming from when the boundary layer was turbulent and the less steep portions from the laminar boundary layer. The test case in figure 4.5 was performed at an air speed of 54 ft/sec corresponding to a dynamic pressure of 3.4 psf. The local Reynolds number at the pressure tap was greater than 10^5 to ensure the disturbance created from the puff of air tripped

turbulence. A 105 mm macro Nikon lens with a 0.6 neutral density filter was used and a high speed camera captured 1000 frames per second. 10 cSt dimethylpolysiloxane oil was used.

Figure 4.5: Fringe spacing vs. time: initially laminar flow being tripped to turbulence using air puffs, 54 ft/sec wind speed, 1000 frames per second, 105 mm macro Nikon lens with 0.6 neutral density filter, 10 cSt dimethylpolysiloxane oil

Figures 4.6 and 4.7 show the results of a second test performed with the same conditions stated above: air speed of 54 ft/sec corresponding to a dynamic pressure of 3.4 psf, 10 cSt oil, 105 mm macro Nikon lens with a 0.6 neutral density filter, and a frame rate of 1000 frames per second. Figure 4.6 shows the

fringe spacing vs. time curve with the turbulent and laminar flow regions labeled.

In figure 4.7, lines have been fitted to the laminar and turbulent regions. The skin frictions were calculated using the slopes of the fitted lines and are shown in Table 4.1.

Figure 4.6: Fringe spacing vs. time plot with turbulent and laminar flow portions labeled: 54 ft/sec wind speed, 1000 frames per second, 105 mm macro Nikon lens with 0.6 neutral density filter, 10 cSt dimethylpolysiloxane oil

Figure 4.7: Fringe spacing vs. time plot with fitted lines to the laminar and turbulent regions: 54 ft/sec wind speed, 1000 frames per second, 105 mm macro Nikon lens with 0.6 neutral density filter, 10 cSt dimethylpolysiloxane oil

Table 4.1: Skin friction results for flow repeatedly tripped to turbulence

Region	Skin Friction
Laminar Region #1	0.0014
Laminar Region #2	0.0019
Laminar Region #3	0.0014
Turbulent Region #1	0.0116
Turbulent Region #2	0.0113
Turbulent Region #3	0.0117

After HOFI was shown to be able to measure the time dependent skin friction in a laminar boundary layer tripped to turbulence by puffing air from a pressure tap, a scenario was tested to extend HOFI to multiple spatial measurements at the same time. The test demonstrated HOFI's ability to gather skin friction information from multiple regions in an oil film. A video from these tests was submitted to the American Physical Society's Division of Fluid Dynamics 63rd annual meeting where it was put on display³⁰. A permanent link to the video can be found in Reference 30. The same instrument from v1.1 HOFI was used with the exception of mercury vapor lamps used in exchange for the laser line generator because of their ability to illuminate a larger surface area. A trip disk was attached to the aluminum flat plate at the same streamwise location as the pressure tap. Figure 4.8 and Figure 4.9 show a side and top view of the wind tunnel set up.

Figure 4.8: Side view of wind tunnel with optical equipment and syringe pump used to puff air out of pressure tap

Figure 4.9: Top view of wind tunnel with locations of pressure tap and trip disk shown upstream of oil film

The pressure tap and trip disk created a non uniform skin friction distribution. The area downstream of the trip disk was turbulent, the area downstream of the pressure tap was either laminar or turbulent dependent on the syringe pump puffing air, and the region not affected by the trip disk or the pressure tap remained laminar. Figure 4.10 shows a sample interferogram from a test with an air speed of 54 ft/sec, corresponding to a dynamic pressure of 3.4 psf. The local Reynolds number at the pressure tap was larger than 10^5 to ensure the disturbance created from the puff of air tripped turbulence. A 105 mm macro Nikon lens with a narrow bandwidth green filter was used with a camera frame rate of 24 frames per second. 10 cSt dimethylpolysiloxane oil was used. The three colored rectangles in figure 4.10 highlight three regions in the oil film chosen for the MATLAB script to determine oil thinning histories for.

Figure 4.11 shows the results of the MATLAB script for the three regions in the oil film. Lines were fitted to the linear portions of the curves and the corresponding skin frictions are labeled on the plot. The turbulent and laminar skin frictions of the transient stair step plot were close to the values of the fully turbulent and fully laminar plots. The differences between skin friction values from one laminar or turbulent region to the next in the transient plot are possibly due to the oil film being highly three dimensional in the area trailing the pressure tap. It is possible if the thickness gradients are large enough the gravitational effects may need to be reexamined and no longer assumed to be negligible.

Figure 4.10: Interferogram showing pressure tap, trip disk, and regions analyzed for skin friction data.

Figure 4.11: Plot of fringe spacing [10^{-3} in] vs. time [sec] for three different locations on the oil film. The red data is from steady turbulent flow, the blue data from steady laminar flow, and the orange data from laminar flow intermittently tripped to turbulence. Slopes of the fitted lines to the data are shown as well as corresponding skin frictions.

5. Conclusion

The oil film interferometry method for measuring skin friction, first developed by Tanner and coworkers in the 1970's⁶⁻¹², was adapted for measurement of *time-dependent* skin friction. This was done by using a high speed camera to capture large numbers of interferograms recorded at a high frame rate. A proof of concept v1.0 and an improved v1.1 high-frame-rate oil film interferometry instruments were designed and used to perform skin friction measurements in a variety of flows.

The proof of concept instrument, called v1.0 high-frame-rate oil film interferometry, was constructed from readily available equipment. The v1.0 HOFI instrument used self-ballasted mercury vapor lamps, a narrow bandwidth filter, a chromium-coated glass test surface, 10 and 50 cSt Dow Corning 200 dimethylpolysiloxane oil, Vision Research's high speed camera with a general purpose Nikon lens, and a 1 ft diameter indraft low speed wind tunnel. The average fringe visibility for v1.0 HOFI was 15%. Because the wind tunnel was not fitted with an air filter, the flow was contaminated by particulates which compromised the quality of the interferograms. The optics and illumination used limited the spatial resolution and frame rates that could be employed. Nonetheless, the interferograms obtained occasionally displayed regions of particulate-free oil flow which persisted for a few seconds.

Deficiencies in the v1.0 HOFI instrument were identified and used to design an improved v1.1 HOFI instrument with greater optical resolution, illumination, and a cleaner flow facility. The v1.1 instrument used the same Vision

Research v310 high speed camera, chromium-coated glass test surface, and 10 and 50 cSt Dow Corning 200 dimethylpolysiloxane oil. In place of the mercury vapor lamps, a laser line generator was used for most of the testing of v1.1 HOFI. The intensity of the light from the mercury vapor lamps was not high enough to operate the high speed camera at fast exposure times and consequently high frame rates. A laser light source was therefore chosen for its high intensity which allowed the camera to operate at frame rates in excess of 10 kHz. To increase the spatial resolution a Nikon 50 mm focal length lens was mounted in reverse using a reversing ring. This created a fixed focal length lens with magnification of nearly 1:1. As a result of these improvements the fringe visibility increased from 15% to 25%.

Once oil thinning histories were recorded with the high speed camera the fringe spacing was determined for each interferogram. Because of the large number of fringe spacing calculations needing to be performed, a MATLAB script was written to autonomously calculate the fringe spacing in each interferogram. The processing step involved selecting a rectangular slice of the interferogram and processing each slice to obtain fringe spacing by fitting a four-parameter sine wave to the data using a minimizing function in MATLAB.

Testing with v1.1 HOFI was performed in Cal Poly's 2' x 2' square cross section wind tunnel to determine the instrument's ability to measure *time-dependent* skin friction. Testing involved three parts; first, v1.1 HOFI was used to measure the skin friction in a steady laminar flow. Next, skin friction measurements were taken while the wind tunnel was ramped up, providing a

transient flow and a time-dependent skin friction. Finally, another time-dependent scenario was tested which consisted of a laminar boundary layer being intermittently tripped to turbulence by puffing air out of a pressure tap upstream of the test surface.

The air speeds during tests ranged from 0 to 108 ft/sec. The frame rates of the camera ranged from 24 frames per second up to 10^5 frames per second. For the case when turbulence was intermittently tripped using air puffs, the frequency at which the air was puffed was as high as 1 Hz. HOI was shown to be capable of making multiple spatial measurements at the same time within a single oil film. For all of these ranges, all three testing scenarios produced quality interferograms, and the MATLAB script was able to find the fringe spacing to sub-pixel error resulting in the ability to accurately measure skin friction in transient flows.

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Appendix A

MATLAB script for fringe spacing identification

```
%This program fits a four parameter sine wave to interferogram images using
%fmincon, a MATLAB function used for constrained nonlinear optimization, and
%records the wavelength of the sine wave fitted to each frame.
%
%It first crops the image to the desired area.
%It then averages the pixel intensity in each column
%and fits a sin wave to the data. It does this by minimizing the error
%using the function, fmincon. It fits the first frame using guesses which
%come from the range, fft, phase, and mean of the data. Each following
%frame uses the previous frame's fitted coefficient values as a starting
%point for its fit.

%The User is required to do the following 3 steps:
%Step 1) Change the file name of the video
%Step 2) Change the number of frames to be fit
%Step 3) Change the size of the cropped image

clear all;
format compact
hold off;

Nframe=4; %change to number of frames to be fitted

%size of cropped image, origin is at top left corner of image
xmin=325; %x minimum
ymin=80;  %y minimum
wid=20;   %width
ht=10;    %height

%This For loop takes the average of only the red intensities of each
%column of ImgCrop and places them into the rows of the new matrix a
a = zeros((wid+1), Nframe);

for i = 1:Nframe
    ImgVertical = imread('VideoFileName',i); %**change file name**
    imgtranspose=ImgVertical(:,1); %takes the transpose of the image
    Img = flipdim(imgtranspose,2); %flips the columns of the matrix
    ImgCrop = imcrop(Img,[xmin ymin wid ht]);
    a(:,i) = mean(ImgCrop(:,1),1); %change '#' in (:,1) to...
    %1=red. 2=green, 3=blue
end;

%This section fits the first frame
options = optimset('Algorithm','interior-point','Hessian',{'lbfgs'},...
    'Display','off','MaxFunEvals',1e6,'MaxIter',1e6,'tolcon',1e-8,...
    'tolfun',1e-8,'tolX',1e-8,'FinDiffType','central');
opt=options;
xdata=1:wid+1;

guess1= range(a(:,1))/2;
```

```

%this uses the fft to pull out the dominate frequency to the nearest
%1/2 pixel
y=fft(a(:,1));
guess4= y(1)/(wid+1);
y(1)=[];
n=length(y);
power = abs(y(1:floor(n/2))).^2;
nyquist = 1/2;
freq = (1:n/2)/(n/2)*nyquist;
plot(freq,power);
index=find(power==max(power));
guess2=2*pi*(freq(index));

coeffguess = [guess1 guess2 0 guess4];
%guess1=Amplitude; guess2=frequency; guess3=phase;
%guess4=offset(Average);
lb = [(guess1-5) (guess2-1) -3.5 (guess4-1)];
ub = [(guess1+5) (guess2+1) 3.5 (guess4+1)];
ydata=a(:,1);

[coeff rmsResult]= fmincon(@rmscalc, coeffguess, [], [], [], [], lb,...
    ub, '', opt, xdata, ydata);

xsmooth = linspace(1,wid+1,10000);

Fpred = sinecurve(coeff(1,:), xsmooth);

Wavelength(:,1)= 2*pi/abs(coeff(1,2));
subplot(2,1,1);
plot(xdata, a(:,1),'x', xsmooth,Fpred)
axis tight; %makes the axis values equal to range of data
xlabel(1); %Displays the Frame # on the plot
disp(1); % Frame Number
disp(rmsResult); %RMS result
disp(coeffguess); %Coefficient Guesses
disp(coeff); %Coefficients chosen
disp(Wavelength(:,1)); %Fitted Wavelength of Sine Curve

ImgV = imread('VideoFileName.tif',1); %**change file name**
imgt=ImgV(:,:,1)';
Img = flipdim(imgt,2);
lcrop = imcrop(Img,[xmin ymin wid ht]);
subplot(2,1,2);
imshow(lcrop);

pause

%This section fits the remaining frames using the previous frame's coeff as
%starting point guesses
for i=2:Nframe
    coeffguess = [coeff(i-1,1) coeff(i-1,2) coeff(i-1,3) coeff(i-1,4)];
    %guess1=Amplitude; guess2=frequency; guess3=phase; guess4=offset(Avg)
    lb = [(coeff(i-1,1)-3) (coeff(i-1,2)-1) (-1000) (coeff(i-1,4)-10)];
    ub = [(coeff(i-1,1)+3) (coeff(i-1,2)+1) (1000) (coeff(i-1,4)+10)];
    ydata=a(:,i);

```

```

[coeff(i,:) rmsResult]= fmincon(@rmscalc, coeffguess, [], [], [],...
    [], lb, ub, "", opt, xdata, ydata);

xsmooth = linspace(1,wid+1,101);

Fpred = sinecurve(coeff(i,:),xsmooth);

Wavelength(:,i)= 2*pi/abs(coeff(i,2));
subplot(2,1,1);
plot(xdata, a(:,i),'x', xsmooth,Fpred)
axis tight; %makes the axis values equal to range of data
xlabel(i); %Displays the Frame # on the plot
disp(i); % Frame Number
disp(rmsResult); %RMS result
disp(coeffguess); %Coefficient Guesses
disp(coeff(i,:)); %Coefficients chosen by fitting function
disp(Wavelength(:,i)); %Fitted Wavelength of Sine Curve (in # of pixels)

%This displays the image below the data fit
ImgV = imread('VideoFileName.tif',i); %**change file name**
imgt=ImgV(:,:,1)';
Img = flipdim(imgt,2);
lcrop = imcrop(Img,[xmin ymin wid ht]);
subplot(2,1,2);
imshow(lcrop);

pause
end

plot(Wavelength, '.');
xlabel('Frame #');
ylabel('Fringe Spacing (pixels)');

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%The function sinecurve is shown below

function Fpred = sinecurve(x,xdata)

Fpred = x(:,1)*sin(x(:,2)*xdata+x(:,3))+x(:,4);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%The function rmscalc is shown below

function rmsErr = rmscalc(x,xdata,ydata)

Fpred = sinecurve(x,xdata);

resid = ydata-Fpred';

N=length(ydata);

rmsErr = sqrt(sum(resid.^2)/N);

```


Appendix B

In cooperation with Ms Anne Bender of Northrop Grumman Corporation, the high-frame-rate oil film interferometry method was used to make measurements in NGC's 7' x 10' wind tunnel located in El Segundo, CA. The goal of the test was to determine at what dynamic pressure transition occurred on a specific model. Mylar strips were applied to the model to provide a surface with good optical properties on which to apply the oil. A mercury vapor lamp was used to illuminate the surface and a Vision Research v310 general purpose high speed camera with a Nikon 105 mm macro lens fitted with a green filter were used to capture the images.

To determine at what dynamic pressure transition occurred the wind tunnel was ramped up to a speed known to be laminar and was held for a few minutes until the oil film was sufficiently thin. The dynamic pressure was then increased a little bit at a time, holding at a given dynamic pressure for 1 minute intervals. An example interferogram taken from the test is shown in figure B.1. Figure B.2 shows a plot of the dynamic pressure vs. time for the wind tunnel test. The MATLAB script was used to determine fringe spacing for the oil film thinning history. Figure B.3 shows the results of the MATLAB fit along with the dynamic pressure displayed on the same plot. The point of transition from laminar to turbulent flow is labeled on the plot as well as the equations of fitted lines to the laminar and turbulent portions of the fringe spacing vs. time curve.

Figure B.1: Interferogram taken in Northrop Grumman's 7' x 10' wind tunnel using 50 cSt dimethylpolysiloxane oil and varying dynamic pressures

Figure B.2: Plot of dynamic pressure [psf] vs. time [sec]

Figure B.3: Plot of fringe spacing [pixels] vs. time [sec] and dynamic pressure [psf] vs. time [sec]

The Mylar test surface and mercury vapor lamps allowed for a fringe visibility of only 5%. The low fringe visibility made the MATLAB fit less accurate than when a chrome-coated glass test surface is used; however the time of transition was still able to be determined due to an abrupt change in slope of the fringe spacing vs. time curve. The dynamic pressure at that time was then the dynamic pressure at which transition occurred.