MEMS Fabricated Optical Sensor for Measurement of Skin Friction

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Abstract—A MEMS fabricated optically-interrogated skin-friction sensor has been developed which will allow for accurate measurement of the skin friction distribution present on aerodynamic surfaces such as wind turbine blades. The basic concept of the sensor is briefly discussed. The experimental setup used to validate its performance is described, and experimental data is presented.

Index Terms—MEMs, sensor, optical readout, skin friction, drag reduction

I. INTRODUCTION

Research Support Instruments (RSI) has developed a MEMS fabricated sensor, which is thin and conforms to smooth curved surfaces without the need for an adhesive and is capable of measuring the distribution of skin friction (shear stress) present on aerodynamic surfaces. The film is passive and is interrogated using an optical system comprised of a directed light source and a standard CCD camera.

The design and development of efficient wind turbines requires that the pressure and skin friction distribution present on the aerodynamic surfaces be well understood. While the bulk of the design work can be accomplished using computational fluid dynamics techniques, there remains the need to provide these models with accurate experimental data for code validation. Pressure distributions are relatively easy to obtain using a variety of commercially available sensors, however, the accurate measurement of skin friction has been attempted by various means with varying means of success and remains an experimental challenge Ref [1,2]. The sensor film described herein is designed primarily for component testing that will be conducted under controlled conditions within a wind tunnel or similar experimental apparatus.

The skin friction sensor is fabricated from a silicon based organic polymer called polydimethylsiloxane (PDMS) which can be micro-molded using standard MEMS fabrication techniques. The sensor is currently produced in small lots in the form of 5cm x 5cm patches – both larger and smaller size configurations are possible. These PDMS patches are thin, with a design goal in the range of 10’s of microns, and flexible and can be applied in various patterns to resolve the skin friction distributions on the surface under investigation.

The PDMS material is both flexible and very smooth which allows the sensor patch to adhere to smooth polished surfaces without the need of an adhesive. During laboratory testing at RSI, the skin friction sensor films are placed onto a smooth test surface such as a glass slide, a Plexiglas sheet or a polished stainless steel fixture and are then gently rolled using a smooth metal cylinder to remove any air trapped under the film. Once the film is in place, it adheres to the test surface until it is removed. The patch material is not damaged when it is peeled from the test surface and can be easily repositioned or used on another test surface.

The molding process that produces the skin friction sensor yields a thin, flexible patch that is covered with a densely packed array of micro-optical elements. Under illumination from a source placed normal to the surface of the sensor, the micro-optic array produces a uniformly reflecting surface that can be monitored by a CCD camera. When subjected to a shearing stress resulting from a flow that is parallel to the sensor surface, the MEMS structures produce a shift in the angle of reflection that is proportional to the magnitude of the applied shear stress. The shift produces a change in the intensity of the reflected light and this change is recorded by the CCD camera. The relative change in the intensity of the signal can be used to obtain a quantitative estimate of the local shear stress. The processed image from a patch that is subjected to the shear produced by an air jet that is flowing parallel to the patch surface is shown in Fig. 1.

![Fig. 1: RSI MEMs shear stress sensor patch is capable of resolving the effect of the shear stress produced by a free air jet that flows parallel to the surface of the patch.](image-url)
II. Method of Use

The images obtained from the sensor patches provide qualitative information about the shear stress distribution. These qualitative images can also yield quantitative data about the magnitude of the shear stress by comparing the resulting images to a calibrated scale. This section describes the process which has been used to produce this calibration standard.

The calibration technique for the skin friction sensor utilizes an impinging air jet to provide a repeatable source of shear stress. In this method, the sensor patch is affixed to a smooth substrate and a collocated camera and light source are positioned on a line that is normal to the plane of the patch. A small diameter stainless steel tube, connected to a compressed air supply via a fast acting solenoid valve is used to produce a high velocity jet that is parallel to the surface of the sensor patch, see Fig. 2.

The impinging jet of air produces a localized area of shear on the patch which is directly proportional to the jet exit velocity. The jet velocity is controlled by varying the gas supply pressure upstream of the solenoid valve. The air jet can be moved to any desired x-y coordinate on the patch via a stepper motor controlled two axis linear stage. This experimental set-up is shown in Fig. 3.

The data collection procedure begins with the acquisition of a baseline (no-flow) image of the sensor. After obtaining the baseline image – the system can be used to collect either single frames or continuous video of the sensor as it is subjected to various flow conditions. While it is possible to make out some faint images from the patch sensor from just observing the flow images, the signal to noise ratio can be greatly increased through image division where the flow images are divided by the base line image. The portions of the image of the patch that remain unchanged obtain a pixel value that is close to one, the portions that produce less reflected light obtain a pixel value less than one and those regions that get brighter obtain a pixel value that is greater than one. This analysis procedure is shown in Figure 4.

Quantitative variation in the shear stress due to the action of the impinging jet can be obtained by defining a profile line on the image and plotting the variation of the pixel values that results from the image division process. An example of this is shown in Fig. 5. The variation in the divided pixel value varies from approximately 1.1 to 0.62. The values above one represent those locations of the patch that become more reflective due to the action of the shear stress – this is caused by slight variations in the micro-optical devices that results in a normal distribution of the angle of reflection about a mean orientation that is normal to the patch face. The lowest value that a pixel value can achieve is dependent on the fill ratio of the micro-optics and has a typical value of about 0.6. The reason for this is that the base surface of the patch is just as reflective as micro-optical structures and also contributes to the signal received by the camera. For a typical patch design the ratio of devices to open surface area is approximately 1:1 and thus approximately 50% of the signal from the patch does not change resulting in a minimum pixel value of about 0.5.

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**Fig. 2:** Schematic of test set-up used for calibration of the sensor patch.

**Fig. 3:** Experimental set-up used to collect calibration data from the shear-stress sensor patches.

**Fig. 4:** An example of the image division process used to increase the signal to noise ratio of the shear stress resolved by the sensor patch.

**Fig. 5:** Profile of the pixel values for the skin friction present along a line that bisects the region where the air jet impacts the sensor patch.
Linear Response of Sensor Patch

The first step in the calibration process was to establish experimental values for the relative response of the patch to an increasing level of shear. The experimental set-up shown in Fig. 3 was used to obtain the required data for a lot of ten sample sensor patches. The increasing level of shear was obtained by increasing the pressure of the air plenum upstream of the air-jet solenoid. During the testing the air plenum pressure was varied from between 30 psi to 120 psi in 10 psi increments. For each pressure an image of the patch being acted on by the jet was obtained and each image was then divided by the base image of the patch (as shown in Fig. 4).

For all tests conducted, the sensor patch was 25.4 x 25.4 mm and the camera was positioned such that the image of the patch filled a 480 x 480 px region. Yielding a resolution of 18.9 px/mm.

The average pixel intensity for each horizontal row of the resulting image (where the rows are parallel to the jet) was determined and the row with the maximum change was identified – for each patch this row well-correlated with the central axis of the jet tube. The response of the patch to the action of the jet was then determined by calculating an average pixel value for a 10px by 100px region that was centered on the row of maximum change (+5px to -5px) and 50 px to 150 px from the leading edge of the patch (Fig. 6). This average pixel value was then obtained for each of the ten specified plenum pressures.

The data was plotted as average change in pixel value as a function of plenum pressure (Fig. 7). Each of the ten patches tested demonstrated a linear response to the change in plenum pressure which, as will be discussed, correlates well to a linear change in the exit velocity of the jet. While each patch’s individual response is linear, the resulting linear curve for each patch shows slight variations in slope. The final calibration process will use this data to account these variations.

Data Collection – Patch Uniformity

The uniformity of each of the patches was determined experimentally by subdividing each patch into a 20 x 20 grid and subjecting each element of the grid to the same shear force. The shear force was supplied by an air jet that was oriented at a shallow angle of 22 degrees to the patch. The increase in angle was implemented to produce a slightly higher level of shear stress on the patch. The higher level of shear was desired to provide a higher dynamic range for the variation of the point to point variation across the face of the patch.

The air jet was mounted on a two axis linear motion stage that was controlled by a pair of stepper motors. The motion stage was used to move the jet to each cell of the 20 x 20 grid, where the solenoid valve would be actuated and a image of the patch would be collected by the CMOS camera. The process was automated and was controlled via a custom LabVIEW program. The resulting 400 images were then processed to yield a composite image of the patch that yielded the response function of the patch.

A sequence of 20 images that comprise the scan of a single column of the array is shown in Fig. 8. Each of the images has been post-processed by implementing an image division of each flow image by the initial baseline image and has been overlaid with the 20 x 20 grid. The white square on each image encloses a 24 x 24 pixel region and tracks with the motion of the free-jet. These 24 x 24 pixel regions are then used to develop a composite image that is used to show the degree of uniformity of the patch response to a constant level of applied shear.

The base image of each of the ten patches has inherent non-uniformities that result from the fabrication process. An example of how these non-uniformities are captured by the camera is shown in Fig. 9. Also shown in Fig. 9 are examples of a divided image, a composite image, and a binned image. The first row of the figure presents these images in the standard pixel range of 0 – 255. The second row of the figure is the same images having been contrast stretched – each image has been stretched by the same amount. The third row shows the histogram of the pixel intensity values for each image. Ideally the histogram for both the base image and the
Fig. 8: A composite image of the 20 images collected during the scan of a single row of a 25.4 x 25.4 mm patch.

The quantitative effect of applying the uniform shear to the entire patch can be obtained through a comparison of the histograms for the divided image and the composite image. The effect of applying the uniform level of shear to the patch is to reduce the average pixel intensity from 97.0 to 81.7. This change in pixel intensity can be used to directly determine the applied shear as will be discussed in the following section. For the conversion to shear the average pixel intensities will be normalized to the baseline image, for the case described here the normalized intensities, obtained by dividing by 97.0, would be 1 to 0.842 or a 15.8% reduction in pixel intensity. The final step in the process is to average each individual 24x24 px area in the composite image to produce a binned image that is a small 48 x 48 px intensity array.

III. SENSOR CALIBRATION

The exit velocity of the free-jet was controlled by adjusting the air supply pressure up-stream of the solenoid valve. The pressure was varied over a range from 30 psi to 120 psi. Since shear stress is a function of flow velocity, it was necessary to develop a model that could be used to predict the jet velocity profile as a function of the upstream pressure. The first step in developing this model was to obtain a limited set of experimentally measured flow velocities taken along the central axis of the jet. This was accomplished by positioning a pitot tube velocity meter (Flow Kinetics 1DP-PBM-E) at different axial locations in front of the jet allowing the jet exit velocity profile to be determined as the upstream pressure was varied. The data indicated that the jet velocity was a linear function of pressure.

The velocity meter used to obtain the experimental velocity data had an upper limit of 52 m/s and was not capable of determining the velocity at the exit plane of the jet. The experimental data, however, was useful in providing validation of a 2D axisymmetric CFD model of a free jet. This model was then used to estimate the actual velocity at the exit of the 2mm tube. The experimental data is shown plotted against velocity curves from the model in Fig. 10.

The model predicts a linear relationship between the jet supply pressure and the jet exit velocity. This linear relationship was then used to determine the jet exit velocities that corresponded to the specific supply pressures used during testing.

With the exit velocities of the free jet determine it was then possible to develop a 3D CFD model of the experimental configuration shown in Fig. 2. The model was then used to model the shear distribution present on a flat plate that is subjected to a free jet that is aligned parallel to the flat plate. The model geometry and the meshed planes of interest are shown in Fig. 11.

The model defines a fluid volume that is 25.4mm x 25.4 mm x 15 mm which conforms to the dimensions of the 25.4 mm² FRAP patch. The inlet velocity for the jet was derived from
Fig. 10: The 2D axisymmetric CFD model of the free-jet is used to determine the jet’s exit velocity.

The results of the axisymmetric jet model, the bottom boundary was defined as a no-slip wall, the exit plane boundary was defined as a constant pressure outlet, and the remaining boundaries where defined as pressure inlets to insure that mass continuity is achieved during the modeling process. The no-slip wall is the boundary of interest for the shear stress results, and a mid-plane boundary was defined to allow for visualization of the free jet velocity axial profile. The intersection of these two planes define the line of maximum shear stress.

With the 3D model it was possible to run numerous cases that provided data on the variation of the shear stress profile on the no-slip wall as a function of inlet velocity. Since the previous axisymmetric free-jet model was capable of relating the inlet velocity to the jet plenum pressure, the combination of the two models provided a means the correlate the shear stress present on the sensor patch to the plenum pressure used in the experiments.

The model just described was then used to provide a calibration for the patch that allows for a change in pixel intensity to be directly converted to a value of shear stress. The 3D model of the jet/patch interaction was used to obtain shear stress distributions for each of the nine experimental plenum pressures tested. The images from the experimental set are compared with the model results and, if necessary, are rotated to align the centerline of the experimental jet to the horizontal. An example of such a comparison is presented in Fig. 12.

The images are then “stacked” together and a small area (12 x 12 px) on the centerline of the jet is selected. This area is then averaged for each image in the stack allowing a shear value to be directly related to an intensity value. Ideally the response of the patch to the shear level should be the same for each location on the patch. To verify this, a number of 12px² areas along the centerline of the patch were analyzed. Fig. 13 shows the approximate location of were these areas were located.

The analysis of the data was then plotted with shear stress plotted as a function of intensity. The resulting plot is presented in Fig. 14. The data is collected into four sets that correspond to different locations of the 12px² averaging area along the center axis of the jet. These x-locations are the number of pixels as counted from the left edge of the figures. At locations very close to the jet exit (less than 39 px which is approximately 2 mm) the data of shear as a function of intensity is linear but the slope changes for different axial positions. Past the 2mm location (x > 39 px) the variation of the data from location to location begins to coalesce into a single function. The data also indicates that the sensor patches have a lower limit of resolution of 50 Pa.
Figure 14. The calibration yields a functional relationship between the reduction in normalized pixel intensity and the applied shear stress acting on the patch.

Fig. 15: Final calibration plot for a sensor patch.

Fig. 16: Calibrated image of the shear stress present on the sensor patch due to the action of the free jet.

This raw data can be further processed by collecting the data into bins that represent a 0.01 variation in the pixel intensity level. The resulting data sets can then be used to determine a mean values for the pixel intensity and the corresponding shear stress level and their respective standard deviations. This process is shown in the plot in Fig. 15 – where only the data from the spatial locations from x = 39 to x = 134 have been used. The plot displays two data sets – the first set referred to as “binned original intensity” is the data set as obtained using the process just described. There is however a slight variation in the uniformity of the patch response and the second set of data has been processed using a patch calibration array such as is shown in Fig. 9.

Using this calibration curve and the patch uniformity calibration array it is possible to convert the raw image data of the sensor patch to a calibrated image of shear stress. An example of one such result for the action of the free jet is presented in Fig. 16.

IV. Conclusions

The ability to accurately measure the distribution of skin friction on aerodynamic surfaces is needed to allow for the development of more efficient and effective wind turbines. Research Support Instruments has developed a MEMS fabricated sensor material that can be used to obtain quantitative measurements of shear stress. The sensor has been developed, fabricated and tested and the results have been promising. On-going work on the development of the sensor is concentrated on fine-tuning the calibration process and developing test procedures that can be used to obtain accurate data from curved surfaces.

V. References


VI. Biographies

Daniel J. Sullivan, PhD is a Principal Scientists with Research Support Instruments in Hopewell, NJ. He has a doctorate in aerospace engineering from Penn State. He is also an adjunct faculty member in the School of Engineering at The College of New Jersey.

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